PENNSTATE

1855

THE PENN STATE HYDROGEOPHYSICS FIELD EXPERIENCE

MAY 16 – JUNE 3, 2011

THE PENNSYLVANIA STATE UNIVERSITY

Table of Contents

The Penn State Hydrogeophysics Field Experience

Welcome to Penn State! You will participate in 3 weeks of a summer camp to learn about hydrogeology and environmental geophysics through field work, data analysis, and numerical modeling. Details of the program are provided below.

Duration of the Program

The program will begin on Monday, May 16, 2011, and end on Friday, June 3, 2011. Students should plan to check in the weekend before the start of the program and may check out the Saturday following the program. Participants are expected to participate in all lectures, field data collection, and analysis. You will likely be busy about 40 hours each week. Educational, professional training and fun activities have been planned as part of the summer program. Participants are expected to participate in these activities to fully benefit from the summer experience.

Travel to Penn State

You may arrive at Penn State anyway that is most convenient to you. If you are driving and will need a parking pass, please let me know so we can arrange parking near your housing. If you are flying, SCE is the closest airport and is here in State College. You may either arrange your flight independently and be reimbursed, or book it through Penn State Travel.

Orientation

The first day of the program will be devoted to a general orientation which will include 1) a tour of campus, with information about recreational and cultural facilities; and 2) a presentation by the Director on the goals of the program and a discussion of the syllabus. You will also will fill out forms for payroll. Attached in this packet are two forms that must be completed prior to your arrival to ensure there are no glitches in getting your housing and payment organized.

Lectures will be held primarily in the Deike Building on the Penn State Main Campus at University Park, which houses the Department of Geosciences. Lectures will be in 2 Deike, and computational analyses will be completed in 316 Hammond, a computer lab with site licenses to COMSOL. These buildings are circled in the attached campus map. Maps can also be found online at http://www.campusmaps.psu.edu/print/.

Housing Arrangements

Field camp participants will live in the Nittany Apartments on campus with other program participants. **Housing will be available beginning Sunday, May 15 and ending Saturday, June 4.** In addition to housing, you will be provided with a food plan, which includes meals in University dining halls. The apartment location is also labeled on the attached map.

Stipend

The stipend for this period is $500, which will be given to you as a check when you arrive. Your check can be cashed at Citizen's Bank, the closest of which is at 122 W. College Avenue, near the Diner. You will need ID, and believe it or not, they take fingerprints to cash checks for people without accounts there. It is up to you whether you cash it there, or cash it and your home bank when you return (or whether they can do it over the phone, etc.).

Research Contract

During the first day of the program, we will discuss expectations for the field program, and you will fill out a Research Contract. The goal of this contract is to help ensure that we have talked about and agreed upon your expectations for your summer research.

Field Trips and Other Activities

We have planned activities to make the summer undergraduate experience fun and informative. The summer program is a unique opportunity to spend time with folks from different backgrounds and gain new scientific information and perspectives. Therefore, it is important for summer undergraduates to plan on participation in all activities.

Informal seminars are planned and these may focus on both research and personal development topics (e.g., how do you choose a graduate school; what is it like to be a grad student?). There will also be an informational seminar on how to present research and prepare posters. We will conduct field work at the Critical Zone Observatory in Shale Hills Social activities will include paddleboating, volleyball, and a picnic and nearby Whipple Dam, and an optional hike up Mount Nittany.

Research Report and Minisymposium

During the last week of the program, students are expected to give a brief oral presentation at the closing Minisymposium and prepare a poster describing their research.

Health Insurance

It is suggested that students have health insurance. The University Health Services are for enrolled (fee paying) students only; therefore, summer undergrads would not qualify for this service. The local hospital is Mt. Nittany Medical Center.

Additional Information

Additional information regarding housing, directions, roommates, etc. will be provided in future program communications. Questions regarding the summer program should be directed to Dr. Kamini Singha (ksingha@psu.edu).

Directions to Penn State/Nittany Community Center and Apartments

The campus is located within driving distance of many major cities including Harrisburg (1.5 hrs., 90 mi), Pittsburgh (2.5 hrs., 137 mi), Philadelphia (3.5 hrs., 194 mi), Baltimore (3.5 hrs., 155 mi), Washington D.C. (4 hrs., 190 mi), New York City (4.5 hrs., 250 mi) and Toronto (5.5 hrs., 304 mi). See attached campus map for specific information about the location of the apartments.

Driving Directions
From New York City, the suggested route is via the George Washington Bridge to I-80. In Pennsylvania, exit I-80 at exit 161 (Bellefonte) and follow PA Route 220 south to State College. Take exit 74; follow the sign for Penn State University. This will become Park Avenue. Travel Park Avenue to the stop light at Bigler Road. Turn left on Bigler. Near Pollock Road intersection, you will see Nittany Community Center on left.

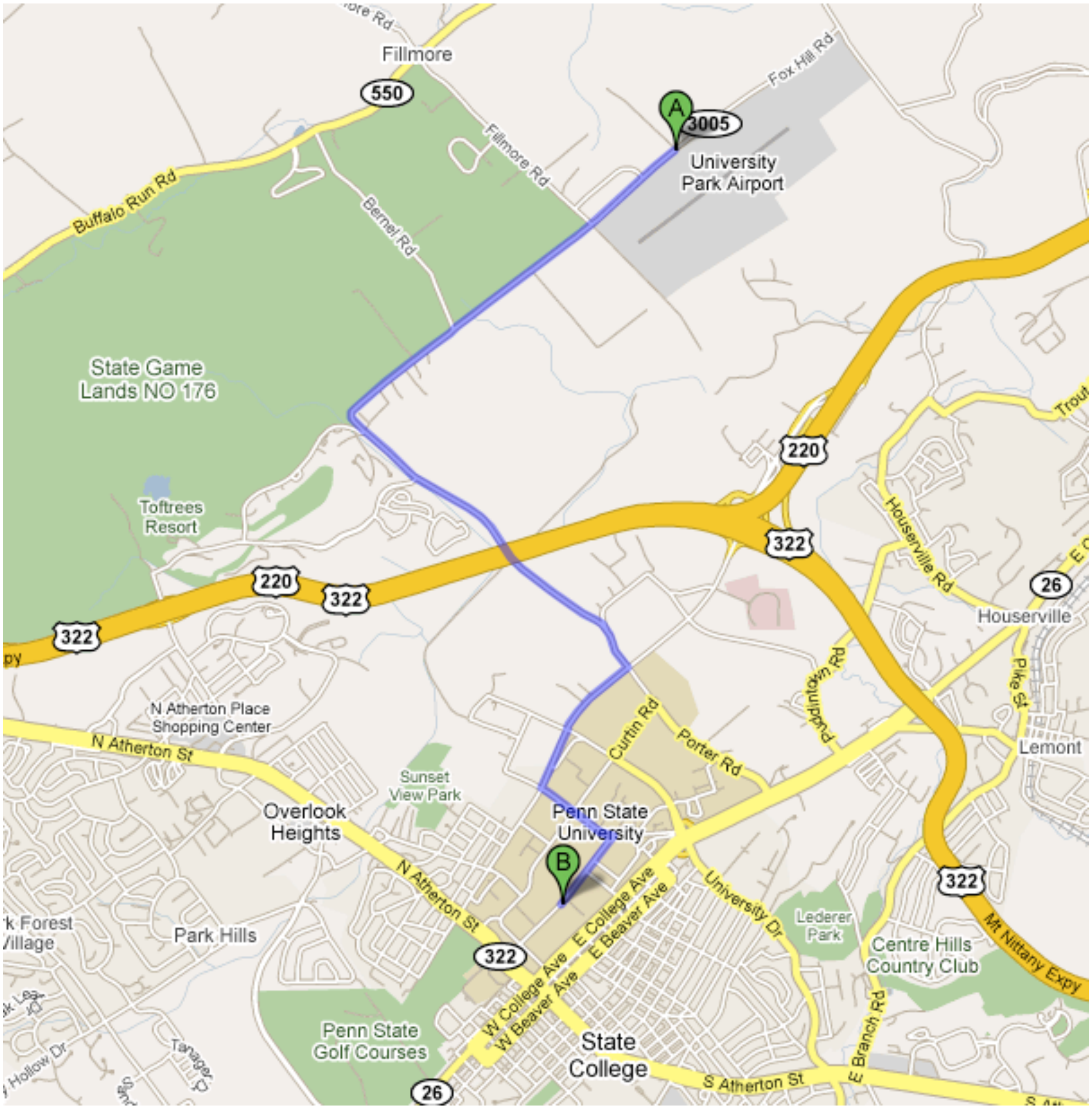
From the Philadelphia area, take Philadelphia Schuylkill Expressway to the Pennsylvania Turnpike, leave the Turnpike at exit 247 (Harrisburg East), and follow I-283 to I-83 and proceed north on I-83 to the I-81 interchange. Then follow I-81 south to Route 322/22 West exit. Proceed west on Route 322 through Lewistown to State College exit #74. Turn right at the stop light and follow Park Avenue. Travel Park Avenue to the stop light at Bigler Road. Turn left on Bigler. Near Pollock Road intersection, you will see Nittany Community Center on left.

From Pittsburgh, follow Route 22 East to Duncansville, I-99/Route 220 North to Route 322 East to Mt. Nittany Expressway/State College. Take exit #73, to Penn State University. Bear right onto Park Avenue. Travel Park Avenue to the stop light at Bigler Road. Turn left on Bigler. Near Pollock Road intersection, you will see Nittany Community Center on left.

From the west, take I-80 to exit 123 (Woodland) just east of Clearfield, then US Route 322 east to State College, or exit I-80 at exit 161 (Bellefonte) and follow PA Route 220 south to State College. Take exit 74; follow the sign for Penn State University. This will become Park Avenue. Travel Park Avenue to the stop light at Bigler Road. Turn left on Bigler. Near Pollock Road intersection, you will see Nittany Community Center on left.

From Washington, D.C., take Route 270 to Frederick then Route 70 to Breezewood - PA turnpike (exit 12) - and go one exit West to Bedford (exit 11); Take I-99 north to Route 220 to Route 322 East to State College. Take exit #73, to Penn State University. Bear right onto Park Avenue. Travel Park Avenue to the stop light at Bigler Road. Turn left on Bigler. Near Pollock Road intersection, you will see Nittany Community Center on left.

Airport Information
The closest airport to the Penn State campus (5.5 miles, approximately 15 minutes) is the University Park Airport (code SCE). To get from the airport to campus, you can arrange a cab at the airport (or contact me in advance and we'll organize shuttle service). To get to campus, you'll head south on Fox Hollow Rd, turn right at E. Park Ave. Travel Park Avenue to the stop light at Bigler Road. Turn left on Bigler. Near Pollock Road intersection, you will see Nittany Community Center on left.



Map from State College Airport (SCE) to Nittany Apartments. Drive distance is approximately 5.5 miles, and will take about 15 minutes.

Housing at Nittany Apartments

Check-in will be conducted at the Pollock Commons Desk, which is open 24/7 for the duration of the summer. Participants should bring their own belongings including bed linens, towels. Even though you have use of a kitchen, **they are not furnished with utensils, pots, pans, or dishes and glassware**. In addition, a full-size refrigerator and stove and oven are provided, but a microwave is not.

There are three student resident Community Assistants (CAs) living in the Nittany Apartments. Their photos, names and telephone numbers are posted in the Community Center above the lobby phone and in the outside bulletin board near Building 21. CAs act as University representatives and student advocates within the residence hall areas.

The University reserves the right to change the assignment of a student in specific locations in the event that (1) the location is needed for other programs or purposes, and/or (2) the student's room is specially equipped to provide for a medical need and such need arises, and/or (3) conditions in a specific location require such reassignment to ensure a proper educational environment or the health and safety of individuals. The student will be given area assignment preference after reassignments are completed.

MAINTENANCE and FACILITIES

If you have a maintenance request, a question about your apartment, housing policies, etc., call the Nittany Community Center Desk at 863-2577. For emergencies after the Community Center is closed, call the Community Assistant on duty @ 814-883-7270.

TELEPHONE SERVICE

You'll have a phone jack in your room, but **no phone**, so bring your own if you want. From an on-campus phone, you will be able to dial on-campus and local numbers by dialing 8 before the seven-digit number. To make long distance calls, prepaid phone cards may be purchased on the web from the PSU Computer Store (http://moc.cac.psu.edu/) or local vendors. If you suspect a telephone line problem check first by borrowing and testing another phone to make sure it is not a problem with your phone. If it is not the phone, then report the problem to TNS at 814-865-4662.

TRASH REMOVAL

Regularly remove household trash to the dumpster that is located closest to your apartment. Trash should not be stored inside or outside your apartment. Trash, bicycles, or furniture may not be stored on front or rear porches at any time. A charge can be assessed for trash that Housing must remove that is not placed in the dumpsters. Residents are required to keep apartments in a sanitary and orderly condition.

RECYCLE!

It's everyone's earth, and everyone's responsibility. Check the bulletin board in Community Center for recycling information.

LAUNDRY
The Nittany Apartments and Suites Laundry is located inside the Community Center. The laundry is for the use of residents only. Please read the posted operating instructions carefully before using the machines. The machines are activated by the PSU ID+ card. Lioncash may be added to your card at any Commons Desk. The fee for the use of the laundry facilities is $1.50 per load to wash and $.50 per load to dry for 50 minutes of use. **See information on the PSU ID+ Card below.**

REPLACEMENT APARTMENT KEYS
If you lose or misplace your apartment key, a replacement key is available at the Pollock Commons Desk. The replacement key must be returned within 2 hours or the key core(s) will be changed and you will be charged a fee. As many as four cores may have to be changed if a resident loses a key and the fee is based on the number of cores changed. PHOTO ID MUST BE SHOWN TO SIGN OUT REPLACEMENT KEY. Remember: the replacement key must be returned within 2 hours to avoid a fee to re-core the lock(s).

MAIL INFORMATION
Mailbox Keys: *Pick up your mailbox key at the Campus Post Office, located in the McAllister Building (in alley beside the HUB).*

Mailing Address:
Your new residence mailing address is:
Your name
600 E. Pollock Road
Nittany Apt. No. ___
State College, PA 16801

Mailbox Locations:
Your mailbox is located at the cluster boxes near the Community Center for those in the 1000, 2000, 4000 and 5000 series of apartments. For those living in the 3000 series, your mailbox is located near Building 31 near the parking lot.

There is one mailbox per apartment, two keys per mailbox. These keys may be duplicated. The bank of mailboxes near the Community Center has "outgoing mail" collection slots. This is where you mail your outgoing mail.

A branch of the U.S. Postal Service is located in the basement level of McAllister Building. The U.S. Post Office for State College is located at 237 South Fraser Street.

PACKAGE DELIVERIES
Only U.S. Postal Service packages are delivered to the community center. UPS and FedEx packages are delivered directly to your apartment. UPS or FedEx packages delivered to the community center will not be accepted.

QUIET POLICY
One of the goals of Housing and Residence Life is to provide an atmosphere that is conducive to study and rest. In order to meet this goal, all students must understand that the right of students to

study and sleep takes precedence over the right to make noise that disturbs others. Quiet hours are Sunday through Thursday nights from 8:00 p.m. to 8:00 a.m., and Friday and Saturday nights from 2:00 a.m. to 10:00 a.m.

DESK SERVICE HOURS

Services such as issuing vacuum cleaners, cleaning supplies, etc., are available at the Community Center Desk Monday through Friday from 8:00 a.m. to 11 p.m., and on Saturday and Sunday from 8 a.m. to Noon, 1 to 4 p.m., and 6 to 11 p.m. Photo ID must be shown to sign out items. *Summer and holiday hours differ.* Check postings in Community Center.

- A fax machine (814-865-0706) is located in the Center. There is a charge to send or receive faxes.
- Vacuums, moving carts, bicycle pump, jumper cables, various tools, an assortment of cleaning supplies, and an iron (for use in laundry only) may be signed out for a two-hour limit at the Nittany Community Center Desk. Items borrowed MUST BE RETURNED TO A EMPLOYEE WHEN THE DESK IS OPEN.

FURNITURE

University provided furniture and furnishings may not be removed from the apartment.

- Mattresses are to be used on the bed frames provided and not on the floor. Additional furniture is restricted.
- Candles, halogen lamps, electric space heaters, kerosene heaters and are not permitted in University housing because of the fire hazards they pose.
- Only University-owned refrigerators and stoves may be used in the apartment.
- Weight-lifting equipment is not permitted in apartments because of noise and potential damage to floors.
- Liquid-filled beds and other liquid-filled furniture are not permitted due to excessive weight and potential for damage
- **Charcoal grills, lighter fluid and charcoal briquettes are not permitted**.
- Small propane grills may be used outside the apartments.
- Microwave ovens are not provided.

SAFETY CONCERNS

Alcoholic Beverages

State laws prohibit the purchase, use, or possession of alcoholic beverages by individuals under 21 years of age. University regulations restrict the use and possession of all alcoholic beverages to the apartments of persons 21 years or older.

Illegal Drugs

Illegally possessing, using, distributing, manufacturing, or selling illegal drugs in Nittany Apartments is forbidden. Simply being present in a residence hall room where an illegal drug, including marijuana, is present is a violation of the Housing Contract.

Meningococcal Disease Vaccination
All residents must either have had a meningococcal vaccination or sign a waiver stating they choose not to get the vaccination at the time they move in. If the student is under age 18, his/her parent must sign the waiver. Vaccinations are available from the student's local health care provider or at University Health Services. More information is available at www.hfs.psu.edu/vaccine and www.cdc.gov/ncidod/dbmd/diseaseinfo/meningococcal_g.htm.

Smoking
Penn State has developed a policy that prohibits smoking in all buildings, thus creating a smoke-free environment. This policy is enforced in all University facilities, including Nittany Apartments, residence halls and dining commons.

Firearms and Fireworks
The possession, storing, carrying or use of any weapon, ammunition or explosive by any person, except authorized law officers and other persons specifically authorized by the University, is prohibited in University apartments and residence halls, University owned or controlled property and at any University sponsored or supervised event or activity. Weapons, ammunition and or explosives are defined as any firearm (including but not limited to pistols, rifles, shotguns, BB guns, paintball guns, flare gun, tranquilizer gun, stun gun, zip gun, spear gun, dart gun, sling gun, air gun or spring gun) that propels a pellet of any kind with a force that can be reasonably expected to cause bodily harm; bows and arrows, handbillies, dirk knives, razors, switch blades or other dangerous knives; any striking instruments (including but not limited to, clubs, truncheons, blackjacks, sandbags or metal knuckes; any weapon used in martial arts; smoke grenades and explosives (including fireworks); and dangerous chemicals (including but not limited to lighter fluid).

Resident Responsibility for Security
Residents are responsible for helping ensure that adequate security is maintained in Nittany Apartments. Residents must refrain from behavior that compromises building security, such as leaving room doors unlocked or propping open apartment doors. Students should report unauthorized persons to proper authorities, and be constantly aware of the importance of maintaining security.

PETS
Pets, other than fish in a small tank, are not permitted in Nittany Apartments and Suites to reside or to visit.

MEALS
The id+ card (with sufficient point balance) serves as the meal access card and will give the student access to the dining commons and food service cash operations. Students must present their id+ cards in order to pay for meals using their A-La Board accounts. The cashier cannot make exceptions.

The meal plan provided will be adequate for meals at the dining commons, but please be aware that the price for meals is higher per meal at non-dining-common places, so I can't guarantee that the card balance will last your entire stay. I'll find out more information for you on this.

Removing Food or Unauthorized Entry into the Dining Commons
Carryout food is limited to one piece of hand fruit (i.e., apple, orange, banana, peach) and one ice cream cone only. Removing additional food or beverages from the dining hall or entering the dining commons without paying for the meal will be considered theft.

Special Diets
It is not possible to provide specific menus for special diets in the dining commons under any circumstances. A student with special requirements (religious, medical, personal dietary preference, etc.) that cannot be fulfilled by individual selection from the multiple-choice menu offered should not submit a contract. Students with questions about special diets should contact the Assignment Office, 201 Johnston Commons, before signing the contract.

Penn State ID+ Card

You will be issued a Penn State non-photo ID card, which has multiple uses and should be carried by you at all times. It may provide building security and/or spending privileges; therefore, it is important that participants do not lend it to anyone else.

The non-photo ID may be used for:

- Door access to respective residence hall
- Access to meal plans
- Use of on-campus laundry facilities
- Use of select on-campus vending and copier machines
- Use of library services and borrowing library materials
- Use of fitness facilities and memberships

To use the laundry facilities in the residence halls, participants must first deposit funds into the LionCash+ spending account associated with their non-photo ID card.

LionCash+ funds may also be used in select copier and vending machines located around campus. LionCash+ funds on non-photo ID cards may be accepted at participating off-campus locations (www.idcard.psu.edu/students/locations.shtml) at the discretion of the merchant. Presentation of a photo ID, such as driver's license or passport, may be required.

Deposits to a LionCash+ account may be made in one of the following ways:

- Online at www.idonline.psu.edu with a Visa or MasterCard credit/debit card – transactions are processed in real time so funds are available immediately
- In person with cash, check, Visa, or MasterCard in one of the following locations:
    - The Commons Desk in the your residence hall
    - The id+ Office, 103 HUB-Robeson Center
- With cash at one of the following Value Transfer Stations (VTS), one of which can be found in the Deike Library

NOTE: Unspent LionCash+ funds are non refundable.

Lost or stolen cards should be reported immediately to prevent unauthorized use of the non-photo ID. During regular business hours contact the id+ Office at 814-865-7590 or visit them in person at 103 HUB-Robeson Center. After hours, contact Police Services at 814-863-1111. Students who lose their id+ cards should report the card lost at www.idcard.psu.edu. This service is available 24 hours a day, seven days a week. Reporting lost or stolen cards will deactivate door access, meal access, and LionCash+ funds. After hours, you can visit the local Commons Desk who can issue temporary cards good for a period of seven days for a fee of $3. LionCash+ balances remaining on the ID will be transferred to the temporary or replacement ID. It your responsibility to appear in person at the id+ Office to obtain the replacement non-photo ID card. The replacement fee for a lost or stolen card is $15.

<u>List of Items to Bring to Campus</u>

<u>University Park Housing at Nittany Apartments</u>

Nittany Apartments (Four bedroom Garden Apartment) accommodates four single students of the same gender (each student will have one's own bedroom). Area residents are within a block or two of the ice-skating rink, swimming pools, tennis courts, the varsity track and field facility, Indoor Sports Complex, Eisenhower Auditorium, and the HUB-Robeson Center (student union). It is within 10-15 minutes walk to most of the university units.

Located right in the complex is the Nittany Community Center. Situated on the corner of Bigler and Pollock Roads, the center has an information desk, administrative office, multi-purpose room, TV room, and University laundry facilities. Washers and dryers are provided for residents only.

Each bedroom includes a chest of drawers, desk with light, desk chair, bookshelf, bed with mattress, bulletin board, TV cable, and individual door lock.

What to Pack for the Apartment

- Alarm Clock
- Answering machine (if wanted)
- **Bedsheets (single, extra-long)**
- **Bedspread, blanket, pillow**
- Bike
- Computer
- Fan
- Games (cards, etc.)
- Laundry bag & detergent
- Music (CD player, radio, MP3 player, etc.)
- Padlock (for desk, laptop, bike)
- Phone card
- Toilet paper
- **Towels**
- Trash bag
- **Utensils, plate, mug, any cooking pots wanted**

What to Leave Behind

- Appliances
- Ashtrays (no smoking in residence halls)
- Blinds
- Candles/incense
- Ceiling fans
- Firearms
- Charcoal grills (small gas grills OK)
- Halogen lamps
- Heaters
- Pets
- Waterbed

Living/Dining Room

The Living/Dining room includes a table and four chairs, two-seater couch, easy chairs (2), end tables (2), table lamps (2), floor lamp, coffee table, TV cable.

Kitchen

Kitchens include a stove with oven, refrigerator, garbage disposal. **(Note: utensils, plates and cups are not provided.)**

Please note that if you want phone service in your room, you will need to bring your own phone.

Other Items
If you are bringing a car, you will need: a parking permit, vehicle registration, and your Driver's License.

Items for the Field
You should bring outdoor gear for field trips, including sturdy shoes or sneakers—there will be no open-toed shoes allowed in the field. Make sure you bring clothes that can get dirty. Sunscreen, bug repellent, and rainy day gear are all suggested. Bring a water bottle, pens, and a highlighter. Most of the time you will either be in the field or in the classroom/computer lab, but one nice set of clothes is suggested for the poster presentations at the end of the field course. We will also have a field trip on the first weekend out to an area with swimming and canoeing, so bring a swimsuit just in case you decide to get in the water.

You will not need a computer, as you will have a Penn State computer account and will be able to access computers in the labs on campus. You are welcome to bring one if you choose. Please also bring a calculator that you can use while in the field.

The apartments are in walking distance of downtown, so you will be able to pick up necessities without having a car. There is also good public transportation; buses run out to the mall, Wal-Mart and grocery stores (see attached bus map). There are movie theatres within walking distance.

Fitness Information

There are a number of facilities on campus for exercise and fitness. For more information on facilities, check http://www.athletics.psu.edu/psustrength/index_rec.html. You can purchase a semester long membership (April-September) when you get here at the Sales Area in the White Building for $85 if you plan to go frequently (or stay at PSU for other activities post-field course), or pay $5 per time. You will need your PSU ID+ card and a photo ID to get into the facilities. You should be able to purchase a membership at the desk when you arrive; if there are any problems, please let me know. I give a tour when you get here – you can check out the centers then. Pick up volleyball, basketball, and racquetball at the Intramural Building is free.

The McCoy Natatorium is close to the Nittany Apartments and contains a few pools, so bring a swimsuit if you are interested in using them. The fee for the outdoor pool is $5 per visit or a book of 15 passes can be purchased for a slight discount on that price. The indoor pool is, unfortunately, not accessible to summer visitors.

The area abounds in hiking opportunities and there are quite a few state parks in the vicinity. You will have Sundays to explore the area around State College.

There are bike racks around campus and bike paths in town. Bicycles are an easy way to get around town, should you like to bring one up or rent one in town. Make sure to bring a helmet if you plan to bike around!

Special Accommodations

Penn State encourages persons with disabilities to participate in its programs and activities. If you anticipate needing any type of accommodation or have questions about the physical access provided, please contact me in advance of your participation or visit.

Getting Around: Parking, Bus Service, and Bicycle Registration

Registration, parking information and permits may be obtained by visiting Parking Services at 1 Eisenhower Parking Deck, 814-865-1436 or www.transportation.psu.edu. Anyone utilizing University parking facilities must purchase a parking permit. This permit must be displayed from the rearview mirror facing forward while the vehicle is parked on campus.

The parking office has not yet set its Summer 2010 parking rates, but they will likely be very close to the Spring 2010 rates. The best parking options for participants living in Nittany Apartments is Lot 42 (Nittany Silver), which is $20/week. You can see this lot at http://www.transportation.psu.edu/forms/StudentParkingMap.pdf .

Payment may be made via cash, check or money order made payable to the Pennsylvania State University. Permits can be issued one of two ways, either at the Parking Office or issued by the event's coordinator upon the participant's arrival.

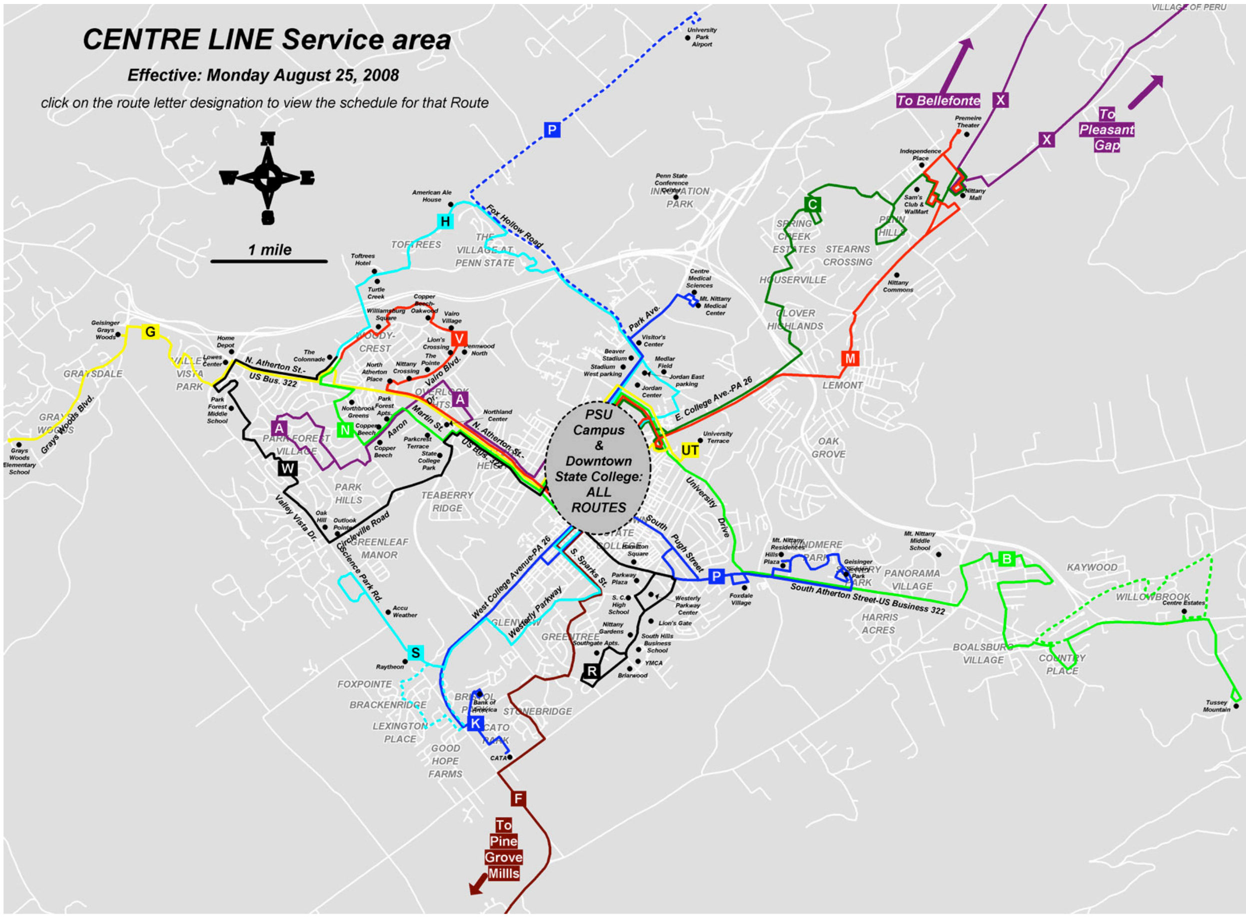
Guidelines for picking permit up at the Parking Office: If arrival is on the weekend, the participant needs to first park their vehicle in the Eisenhower Parking Deck. Their permit can be purchased the following Monday morning at our office between 7:30 am and 8:30 am. They must then move their vehicle to their assigned lot.

Guidelines for issuing on arrival: Permits will be issued on consignment to the coordinator. Permits will then be purchased upon their arrival and they must then move their vehicle to their assigned lot. All payments and unused permits need to be returned to the parking office within two (2) business days after the start of the program. Receipts will be written upon request.

Bicycles must be registered at any visitor booth or at Police Services in the Eisenhower Parking Deck. Registration is free. Bicycles must be placed in designated bike racks, not chained to posts or stored on apartment porches.

Nittany community walkways are for pedestrian traffic – vehicles are not permitted on these walkways. Only authorized vehicles are permitted inside the complex.

Bus service around campus is easy and efficient. CATABUS is available to get you around campus as well as to most parts of State College (see map below; a larger version as well as other information about bus service can be found at http://www.catabus.com/). On-campus travel is free, rides off-campus are $1.25 per trip.



Map of bus service in State College Area. More information is available at at http://www.catabus.com/.

Internet on Campus

You will have access to the internet through the computer labs, although unfortunately there are no Ethernet connections in the Nittany Apartments for non-PSU students. Should you decide to bring a computer, you can also get wireless internet many places on campus; more information can be found at http://its.psu.edu/wireless/ . This site has instructions, links and information on campus buildings that have wireless. You will not need a computer, however; we will provide access to labs here.

What you need to use PSU Wireless
Hardware: An 802.11 wireless capable laptop, such as those that are wireless-ready or that have a PCMCIA card slot with a wireless adapter card. Note: Some Linksys wireless cards are incompatible with the Cisco VPN client required to use the Penn State VPN service, specifically the WPC11 version 4 PC card, although other Linksys cards may also be incompatible.

Software: Download and configure the Virtual Private Network (VPN) software which enables you to have a secure network connection between your laptop and Penn State's VPN server and to access Penn State networking resources. VPN software clients for Linux, Windows, and Mac OS X are available for download as well as documentation and installation instructions for each client: https://www.work.psu.edu/access/vpn/

From here, all you need to do is:
- Power up your laptop.
- Launch your VPN client software, and select the Penn State University Park Campus location.
- Use the wireless network for your tasks.
- Disconnect the VPN client when you are done.

<u>Health Information and Emergency Services</u>

Note: When dialing from a campus phone, you do not need to dial the "86" before the phone number

<u>EMERGENCY CONTACT NUMBERS</u>

MEDICAL EMERGENCIES
911 or **814-863-1111** (UNIVERSITY POLICE)

POLICE EMERGENCIES
911 or **814-863-1111** (UNIVERSITY POLICE)

CAMPUS ESCORT SERVICE (Provides an escort if you need to walk around campus after dark) **814-865-9255 (865-WALK)**

<u>HEALTH INFORMATION</u>

Below is information on health services. Please note that you are not considered students for the summer since you are not taking classes, so *<u>in the event of illness or injury requiring treatment, hospitalization, or surgery, family medical insurance must be used</u>*. (University Health Services does not have contracts with any health insurance companies and does not send bills to insurance companies. Patients will receive an itemized bill at the end of a visit.). **The University urges that participants be covered by some form of personal medical insurance.**

You first choice in a medical emergency should be Mt. Nittany Medical Center. It is close by and can be reached by leaving the Apartment complex via Hastings Road, and turning left on University Drive. From University, turn right onto Park Avenue. Proceed down Park—you will see Hospital signs on right. Turn right on Hospital Drive.

Mt. Nittany Medical Center
1800 E. Park Avenue
State College
(814) 231-7000

University Health Services
216 Ritenour Building
(814) 865-6556
University Health Services is for registered Penn State students (previous or current semester) and emergency situations, if you are unable to get to Mt. Nittany Medical Center. For others seeking non-emergency or routine care, please make appointments with your regular physician or contact your health insurance for a recommendation.

Your health and safety are important to us! Please practice safe research during your time here at Penn State.

Things to Take Care of BEFORE You Arrive if You Are Not A PSU Student

The following forms need to be returned PRIOR to arriving on campus. This includes the pre-arrival information form, your Penn State VISIT form (which allows you to receive your stipend as well as reimbursement for your travel) and an Access Account Application so you will have computer access.

On the VISIT form, please fill out sections I and II (and III and IV if you are not an American citizen) on page 1, and on page 2 fill in the following:

Host's Name: Kamini Singha
Address: 311 Deike Building
Phone Number: 814.863.6649
Fax Number: 814.863.7823
Internet Address: ksingha@psu.edu

For the Penn State Access Account Application, please fill out the information ABOVE "Penn State Status" on page 1 and sign page 2. You do not need to include your PSU ID on page 1 (I will add this) or fill out the status information at the bottom. Use the following:
Campus Address: 311 Deike Building
Phone Number: 814.863.6649
Campus: University Park
Department: Geosciences

You will also need to get a Friends of Penn State (FPS) account to use Penn State's Course Management System, ANGEL:

1. Log on to https://fps.psu.edu and create a Friends of Penn State account.

2. Send me your FPS "Digital IDs."

3. Once I have received your Digital ID, I will add you to your course so that you will be able to log on to ANGEL (https://cms.psu.edu/frames.aspx). If you attempt to log on prior to receiving an email telling you that you can logon, you will get a login failed message that explains that you are not yet enrolled in the course.

4. Upon the first login, you will be prompted to enter your personal information. Please do that at this time so your name shows up in the main computer.

PRE-ARRIVAL INFORMATION SHEET

Name of Participant

Please let me know which of the following apply to you by checking the appropriate boxes:

☐ I will be arriving via car.
  ☐ I will need a parking pass on campus (PSU students must pay for parking).
☐ I will be arriving via plane.
  ☐ I plan to pay for my plane ticket in advance and be reimbursed.
  ☐ I would like to work with you to purchase my plane ticket through Penn State.
☐ I will need housing on campus (optional only for PSU students WITH permission).
☐ I would like to participate in the on campus meal plan during my visit (optional only for PSU students).

Please let me know if there are other needs you have, or concerns that should be addressed prior to your arrival at Penn State:

Please submit this form (with the needed forms below attached) by March 22 to Dr. Kamini Singha at 311 Deike Building, University Park, PA, 16802, or scan and email to ksingha@psu.edu.

☐ I have attached the VISIT form (non-PSU students).
☐ I have attached the Access Account Application form (non-PSU students).
☐ I have attached the medical form.
☐ I have attached a copy of my medical insurance information.
☐ I have signed up as a "Friend of Penn State" (non-PSU students). My Digital ID is:

MEDICAL FORM

Name of Participant:

Dietary Restrictions:

Known Allergies:

Are you on any medications (prescription or non-prescription)? Yes No (If Yes, please provide details. Please be sure to clearly print proper spelling for medications and provide clear dosage and condition details):

Medication Name_________________________ Dosage_______Condition_____________________

Medication Name_________________________ Dosage_______Condition_____________________

Medication Name_________________________ Dosage_______Condition_____________________

Have you been under a doctor's care in the last 12 months? Yes No

If yes, give details:

*Chronic Disability or Illness (Please list appropriate: high blood pressure, heart condition, epilepsy, diabetes, headaches, nosebleeds, fainting, asthma, emphysema, or other):

*History of joint injury (Tendonitis, Bursitis, Sprain, Dislocation or other) Please describe and specify which joints:

Do you have any physical limitations?

Do you feel that you have any psychological limitations? (fear of water, fear of heights, etc.)

Please explain:

***I understand that if I have answered yes to above questions marked with * that I am responsible to consult my doctor about my ability to participate in this field work and may require a letter from my doctor. Please contact us if you have any questions.**

____

Signature of Student Printed Name Date

Visitor's Information Sheet for Income and Travel

The Pennsylvania State University

I. General Information

Please Provide All Information Requested — Important Information On The Reverse Side

This information will be used to prepare any forms needed **prior to your visit** to the Pennsylvania State University.

IMPORTANT NOTE: You must have a U.S. Social Security Number (or tax identification number) in order to receive any payment other than an expense reimbursement.

Last or Family Name / First or Given Name / Middle Initial		Country of Residence	U.S. Social Security Number
Street Address		Telephone Number	Fax Number
City	State or Province	Zip or Postal Code	Country

II. Residency Status – Please check the appropriate box (1, 2, 3, or 4) below to indicate your residency status for tax purposes only.

1 ☐ **I AM A UNITED STATES CITIZEN** I hereby certify that I am a citizen of the United States of America.

2 ☐ **I AM A PERMANENT RESIDENT** I hereby certify that I have been given the privilege, according to U.S. Immigration Laws, of residing permanently in the United States as an immigrant, and that this status has not been revoked, and has not been administratively or judicially determined to have been abandoned. **A completed W-9 form must be attached (www.irs.gov/pub/irs-pdf/fw9.pdf**).

3 ☐ **I AM A RESIDENT FOR TAX PURPOSES** I hereby certify that I am a resident of the United States of America, for tax purposes, because I have met the Substantial Presence Test for residency. **ATTACH A COMPLETED W-9 FORM (www.irs.gov/pub/irs-pdf/fw9.pdf) AND SUBMIT A COPY OF YOUR I-94 CARD TO YOUR HOST UPON ARRIVAL TO PENN STATE.**

4 ☐ **I AM A NON-RESIDENT FOR TAX PURPOSES** I DO NOT meet the requirements for residency in the United States of America. **SUBMIT A COPY OF YOUR I-94 CARD TO YOUR HOST UPON ARRIVAL TO PENN STATE.**

III. Visa Type – Please indicate the Immigration designation you intend to enter the United States with on this trip.

If you checked either box 1 or box 2 in the residency section above, do not complete this section.

☐ B-1 or WB (visa waiver business classification)	*Entering the U.S. on this visa type will prohibit Penn State from making any payments to you other than the reimbursement of actual travel expenses, unless each requirement in Part IV is satisfied.*
☐ B-2 or WT (visa waiver tourist classification)	*Entering the U.S. on this visa type will prohibit Penn State from making any payments or expense reimbursements to you, unless each requirement in Part IV is satisfied.*
☐ F-1	*Must maintain full-time enrollment as defined by the academic institution; part-time study only with approval of DSO in accordance with INS guidelines* **EXPENSES:** *You must provide Penn State with I-94 or I-20 forms and* ***if you are receiving an honorarium you must also submit an 8233 form.***
☐ H1B1	**EXPENSES:** *You will need to provide Penn State with copies of your visa and your I-94.* ***No honorarium is allowed.***
☐ J-1 Exchange Visitor	*Entering the U.S. on this visa type will allow Penn State to make payments to you according to form DS-2019.* **EXPENSES:** *You must provide Penn State with form DS-2019 and a letter from your host institution authorizing payment.* ***If you received an honorarium you must also submit form 8233.***
☐ Other – please specify:____	

IV. Payments To B1/B2 Visa Holders – Acknowledgements of individuals on a B-1, B-2, WB, WT visa status or those who are exempt from visa requirements. *Check those that apply:*

- ☐ The honorarium payment and/or expense reimbursement will relate to an academic activity.
- ☐ In the last six months, I have not accepted an honorarium or expense reimbursement from more than four institutions of higher education and/or research institutions within the United States of America.
- ☐ My activity at The Pennsylvania State University will be for 9 days or less.

Treaty Usage: In order to claim treaty exemption from U.S. Federal Income Tax, you must submit a completed IRS Form 8233 (Exemption from Withholding for Compensation of Independent Personal Services of a Non Resident Individual). These forms (8233 and VISIT forms) must be completed EACH time you wish to claim exemption, even within the same tax year.

I hereby certify, under penalties of perjury, that all of the above information is true and correct:

Signature: Date:

Visitor's **I**nformation **S**heet for **I**ncome and **T**ravel

Purpose: The purpose of this document is to allow The Pennsylvania State University to collect the necessary information to smoothly and efficiently handle the details of your upcoming visit to our institution. Please return completed form to your host as soon as possible.

I. General Information Personal data requested in the first section of this document (name, address, etc) will be used in the preparation of various university forms as they pertain to your visit. In most cases, any eligible payments to be made to you will be based on this information.

Please note that there are two fields requesting country. The block labeled as "Country" is for your mailing address. The block labeled "Country of Residence" is the country which is your tax home. If you have a U.S. Social Security Number, please enter in the appropriate block. Penn State's Accounting systems differentiate between individuals by this unique number. In addition, one is required by our federal government to have a Social Security Number in order to receive any payment other than the reimbursement of actual travel expenses.

II. Residency Status This section is used by the University to establish (by your declaration), the determination of your tax residency. An alien will not be considered a United States Resident for Tax Purposes unless the individual is:

A. a lawful permanent resident of the United States at any time during the calendar year, OR

B. *able to meet the Substantial Presence Test as specified by the Internal Revenue Service regulations.*

Only those individuals who can claim to be a Non-Resident for tax purposes can claim treaty benefits for exemption from U.S. federal income taxes. If you wish to find out whether you qualify for treaty benefits, have your host contact Accounting Operations at Penn State University.

III. Visa Type This section is to notify Penn State as to which type of Visa you intend to use in order to enter the United States. For those visitors who are from countries that participate in the Visa Waiver Program, please note that Penn State can only reimburse actual expenses for those that enter under the "business" classification, unless you satisfy the federal law requirements listed in Part IV of this form. Business classification is noted as a "WB" on a card placed in your passport upon entry to the United States, known as an I-94 card. If you are unsure as to the type of Visa classification you should attempt to attain, contact your host as The Pennsylvania State University.

IV. Payments To B1/B2 Visa Holders The American Competitiveness Workforce Act allows payment of honoraria or incidental expenses to B-1, B-2, WB, and WT visa holders for "usual academic activity," if paid by a United States institution of higher education, nonprofit, or a governmental research organization. Under the Act, an academic activity may not exceed nine days at a single institution. In addition, such visa holders cannot accept honoraria and/or incidental expenses from more than five institutions or organizations in the previous six month period. **Instead of B1/B2 status (not eligible to obtain US Social Security number), Short-term Scholar status should be used by all visitors expecting payment (other than expenses) if the visitor does not have a Social Security or Tax Payer Identification Number.**

Affirmation: Your signature on this document represents that the information you have provided is both true and accurate. It also signifies that you understand it is your responsibility to enter the U.S. on this trip with the appropriate Visa, so that Penn State can honor the commitments made to you by your host.

If you have any questions regarding this document, contact your host as soon as possible in order to expedite the preparations needed for your upcoming visit.

Host's Name:	
Address:	
Phone Number	
Fax Number:	
Internet Address:	

PENNSTATE

1 8 5 5

Information Technology Services
its@PennState

ITS Accounts Services Office
204 Wagner Building
University Park, PA 16802
Phone: 814-865-4772
Fax: 814-865-9289
accounts@psu.edu

Penn State Access Account Application for Faculty and Staff, page 1

Please complete all required fields carefully and clearly!

Last Name	First Name	Middle Initial	Suffix	PSU ID

This form is for Penn State faculty and staff to request a Penn State Access Account from Information Technology Services (ITS). Enter your name **carefully and clearly**, because your initials (when available) can affect the assignment of your Penn State Access Account userid, which cannot be changed once created. The userid and password assigned to you will enable you to use a variety of Internet services, including electronic mail and the ITS Student Computing Labs. Return the completed form to the ITS Accounts Services via surface mail or fax per the contact information noted above.

To obtain your userid and password, please allow three business days for this form to be processed. Visit an ITS Signature Station and follow the instructions there. Signature Station locations are found at http://aset.its.psu.edu/accounts/sigstations.html. Make note of your userid and password once they display on the screen. Once obtained, the account will be fully functional within one business day. If you experience problems with using a Signature Station, please bring a photo ID to either the ITS Accounts Services Office or to one of the Help Desk locations at University Park, or to a consulting location at a Penn State campus.

To obtain assistance and free Internet access software, please contact the ITS Help Desk staff/consultants at your local campus. ITS Help Desks are located at 2 Willard Building and 215 Computer Building. Inquiries may be send via e-mail at **helpdesk@psu.edu** or by calling 814-863-1035 or 1-888-774-4010 (toll free within Pennsylvania). For hours, locations, and additional information, please visit **http://css.its.psu.edu/consulting/consult.html**.

Campus Address		Phone Number	
Campus	**Department**	**Birthdate**	
Home address	**Home City and State**	**Zip Code**	**Country**
Penn State Status			
Accounts that will not expire by a specific date: ❑ Faculty ❑ Full-time staff ❑ Hershey Medical Center	Accounts that will expire by a specific date: ❑ Wage Payroll* ❑ Sponsored Accounts* ❑ Other*______________________ ❑ Expiration Date______________________		
Employee start date (if new or returning employee)			

SPECIAL NOTES: As an Access Account holder, you are responsible for reading and signing the reverse side of this form. Applicants who have a status marked with an asterisk (*) must get the signature and userid of his/her supervisor to verify that this account is required for the performance of assigned duties.

07/16/2007

Penn State Access Account Application for Faculty and Staff, page 2
Agreement

I agree to abide by the conditions set forth in University Policy AD20 and the EDUCOM statement on using software in my use of all computer and network resources. I understand that access to the network and other information services is a privilege and not a right. I also understand that this account is for my sole use and will be terminated when I leave the University unless I retire with full benefits. If I am retired, I understand it will be terminated when I no longer receive benefits. Violation of policy or law may result in suspension of network access or other information service privileges, disciplinary action, and legal proceedings. Relevant policies can be referenced on the World Wide Web at http://its.psu.edu/policies/ and in the administrative offices of colleges and departments.

Some computer programs and computer networks have made possession of copyrighted material such as computer programs, music files and videos easier than ever. In many cases, this is in violation of state and federal laws, and University policy. The University takes such violations very seriously.

If I own a personal computer, I will remove and keep off all material that I do not have the right to possess while it is connected to the University's networks. If I use a University owned computer of any kind, I will not place such material on it at any time. This includes storing such material on Personal Web spaces, and in the form of programs or files that I maintain on any University-owned Computer Resources. I understand that the University may disconnect my machine and suspend other access (e.g., Personal Web Space, Access Account) while determining whether I possess such material.

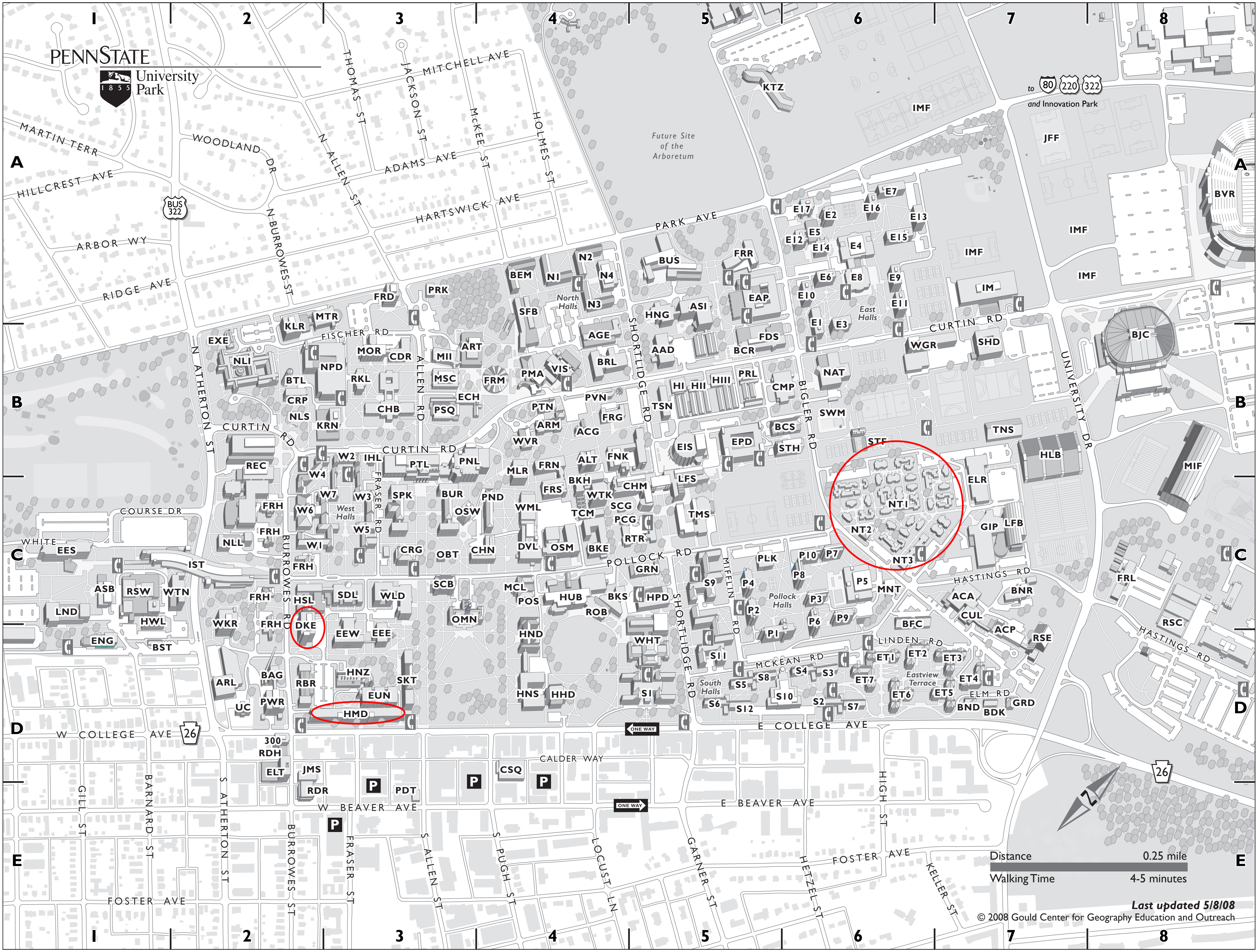
If the University believes that I have infringing materials on my computer that is connected (e.g., Residence Hall Connection, Dialup Service) to the Penn State network, the University reserves the right to suspend services immediately until such time that it is determined that such materials are no longer on the computer. I understand that my Access account and/or Residence Hall connection will be restored only upon certification to the University that all infringing materials have been permanently removed. Additionally, I am aware that copyright infringement is against University Policy and can result in serious penalties including dismissal. I also understand that there are serious legal ramifications to copyright infringement that can include large financial penalties, potential confiscation of my computer, and in some case imprisonment.

In addition, I will not use the Penn State network or computers to engage in unauthorized copying, transmission, distribution and/or downloading of such works in violation of federal and state civil or criminal law. I understand that my ultimate responsibility is to ensure that the copyright holder has granted permission to make or distribute the copy in question.

I understand that penalties for possession of copyrighted material that I am not entitled to include discontinuance of network access, expulsion from the University for students and termination of employment for employees. In addition, I understand that I may also be charged with offenses under state and federal law that includes penalties of up to 10 years imprisonment and significant fines if found guilty.

Applicant's signature Date

*Supervisor's signature Access Account userid Date
Must be a full-time Penn State Employee



PENNSTATE
1855
University Park
MITCHELL AVE
THOMAS ST
JACKSON ST
McKEE ST
HOLMES ST
MARTIN TERR
WOODLAND DR
N ALLEN ST
ADAMS AVE
HILLCREST AVE
BUS 322
HARTSWICK AVE
ARBOR WY
N BURROWES ST
RIDGE AVE
PARK AVE
Future Site of the Arboretum
KTZ
IMF
to 80 220 322 and Innovation Park
JFF
BVR
E7
E16
E17
E2
E13
E5
E12
E14
E4
E15
BUS
FRR
N2
BEM
N1
N4
E6
E8
E9
E10
E11
North Halls
N3
SFB
PRK
FRD
EAP
HNG
ASI
East Halls
IM
KLR
MTR
FISCHER RD
E1
E3
CURTIN RD
BJC
SHD
WGR
EXE
NLI
MOR
CDR
ALLEN RD
MII
ART
AGE
AAD
FDS
BCR
SHORTLIDGE RD
UNIVERSITY DR
NPD
BRL
BTL
RKL
MSC
FRM
PMA
VIS
PRL
NAT
HI
HII
HIII
CMP
CRP
ECH
PVN
TSN
NLS
CHB
PSQ
PTN
SWM
N ATHERTON ST
CURTIN RD
KRN
ARM
FRG
BCS
TNS
ACG
WVR
EPD
STF
EIS
STH
REC
W2
IHL
CURTIN RD
PNL
PTL
FNK
ALT
HLB
MIF
W4
MLR
FRN
ELR
BKH
CHM
LFS
W7
W3
SPK
BUR
PND
FRS
WTK
NT1
FRH
W6
West Halls
FRASER RD
OSW
WML
SCG
TMS
COURSE DR
TCM
PCG
W5
NT2
GIP
LFB
FRH
RTR
WHITE
EES
NLL
W1
DVL
OSM
BKE
CRG
OBT
CHN
P10
P7
NT3
FRH
IST
POLLOCK RD
PLK
GRN
ASB
RSW
WTN
MCL
SCB
S9
P4
P8
P5
HASTINGS RD
FRL
BNR
FRH
SDL
HSL
WLD
POS
HUB
BKS
HPD
MNT
LND
ROB
Pollock Halls
P3
ACA
MIFFLIN RD
P2
OMN
CUL
BURROWES RD
HWL
WKR
FRH
DKE
P6
P9
RSC
EEW
EEE
BFC
ACP
ENG
HND
WHT
P1
RSE
BST
LINDEN RD
HASTINGS RD
ET1
ET2
ET3
S11
BAG
HNZ
MCKEAN RD
ARL
SKT
Eastview Terrace
RBR
S4
S3
ET7
ET4
S8
EUN
HNS
HHD
South Halls
S5
S1
ET6
ET5
ELM RD
PWR
S10
S2
S7
UC
S6
S12
BND
GRD
HMD
BDK
ONE WAY
E COLLEGE AVE
W COLLEGE AVE
26
300 RDH
CALDER WAY
ELT
JMS
CSQ
P
RDR
PDT
GILL ST
BARNARD ST
S ATHERTON ST
W BEAVER AVE
E BEAVER AVE
ONE WAY
HIGH ST
BURROWES ST
FRASER ST
S ALLEN ST
S PUGH ST
LOCUST LN
GARNER ST
HETZEL ST
FOSTER AVE
KELLER ST
FOSTER AVE
Distance 0.25 mile
Walking Time 4-5 minutes
Last updated 5/8/08
© 2008 Gould Center for Geography Education and Outreach
1
2
3
4
5
6
7
8
A
B
C
D
E

PENNSTATE
University Park

300 300 Building, The **D2**
ACA Academic Activities **C7**
ACP Academic Projects **D7**
AAD Agricultural Administration **B5**
AGE Agricultural Engineering **B4**
ASI Ag. Science & Industries **A5**
ALT Althouse Lab **B4**
ARL Applied Research Lab (ARL) **D2**
ASB Applied Science **C1**
ARM Armsby **B4**
ART Arts (Playhouse Theatre) **B3**
ACG Arts Cottage **B4**
BAG Bag House **D2**
BCS Bank of America Career Services **B6**
BEM Beam **A4**
BVR Beaver Stadium **A8**
BDK Beecher-Dock House **D7**
BND Benedict House **D7**
BFC Bennett Family Center **C6**
BCR Berkey Creamery **B5**
BTL Biomechanics Teaching Lab **B2**
BKS Bookstore **C4**
BRL Borland **B4**
BKE Boucke **C4**
BNR Breazeale Nuclear Reactor **C7**
BJC Bryce Jordan Center **B8**
BKH Buckhout Lab **C4**
BUR Burrowes **C3**
BST Bus Station **D1**
BUS Business **A5**
CSQ Calder Square II **D4**
CRG Carnegie **C3**
CRP Carpenter **B2**
CDR CEDAR **B3**
CHB Chambers **B3**
CHN Chandlee Lab **C4**
CHM Chemistry **C4**
CUL Coal Utilization Lab **C7**
CMP Computer Building **B6**
DVL Davey Lab **C4**
DKE Deike **C2**
EES Earth-Engineering Sciences **C1**
ELR East Area Locker Room **B7**
EAP East Parking Deck **A5**
EIS Eisenhower Auditorium **B5**
ECH Eisenhower Chapel **B3**
EPD Eisenhower Parking Deck **B5**
EEE Electrical Eng. East **D3**
EEW Electrical Eng. West **D3**
ELT Elliott **D2**
ENG Engineering Services **D1**
EUN Engineering Units (A-C) **D3**
EXE Executive Education **B2**
FNK Fenske Lab **B4**
FRG Ferguson **B4**
FDS Food Science **A5**
FRD Ford **A3**
FRL Forest Resource Lab **C8**
FRR Forest Resources **A5**
FRM Forum **B4**
FRH Fraternity House **C2**
FRN Frear North **C4**
FRS Frear South **B4**
GRD Gardner House **D7**
GRN Grange **C5**
GIP Greenberg (Ice Pavillion) **C7**
HWL Hallowell **C1**
HMD Hammond **D3**
HI Headhouse I **B5**
HII Headhouse II **B5**
HIII Headhouse III **B5**
HHD Health & Human Dev. **D4**
HND Henderson **D4**
HNS Henderson South **D4**
HNG Henning **A5**
HUB Hetzel Union (HUB) **C4**
HNZ Hintz Family Alumni Center **D3**
HLB Holuba Hall **B7**
HSL Hosler **C2**
HPD HUB Parking Deck **C5**
IHL Ihlseng **B3**
IST Information Sciences & Technology **C2**
IM Intramural **A7**
IMF Intramural Fields **A6, A7, A8**
JMS James **D2**
JFF Jeffrey Field **A7**
KTZ Katz **A5** (complete January '09)
KLR Keller **A2**
KRN Kern **B3**
LFB Lasch Football Building **C7**
LND Leonhard **C1**
LFS Life Sciences **B5**
MNT Maintenance I (Pollock) **C6**
MTR Mateer **A3**
MCL McAllister **C4**
NAT McCoy Natatorium **B6**
MOR Moore **B3**
MLR Mueller Lab **B4**
MIF Multi-Sport Indoor Facility **B8**
MSC Music **B3**
MII Music II **B3**
NLI Nittany Lion Inn **B2**
NLS Nittany Lion Shrine **B2**
NPD Nittany Parking Deck **B3**
NLL Noll Lab **C2**
OBT Old Botany **C3**
OMN Old Main **C3**
OSM Osmond Lab **C4**
OSW Oswald Tower **C3**
PMA Palmer Museum of Art **B4**
PRK Park Avenue Building **A3**
PSQ Pasquerilla Spiritual Center **B3**
PRL Pasture Research Lab **B5**
PNL Paterno Library **B3**
PTL Pattee Library **B3**
PTN Patterson **B4**
PVN Pavilion Theatre **B4**
PDT Penn State Downtown Theatre Center **E5**
PCG Pine Cottage **C4**
PLK Pollock **C5**
PND Pond Lab **C4**
PWR Power Plant **D2**
RKL Rackley **B3**
RBR Reber **D2**
REC Recreation (Rec Hall) **B2**
RSC Research Center **C8**
RSE Research East **D7**
RSW Research West **C1**
RDH Rider House **D2**
RDR Rider **E2**
RTR Ritenour **C5**
ROB Robeson Cultural Center **C4**
SKT Sackett **D3**
STF Sarni Tennis Facility **B6**
SCB Schwab Auditorium **C3**
SHD Shields **B7**
SPK Sparks **C3**
SCG Spruce Cottage **C4**
SDL Steidle **C3**
SFB Stuckeman Family Building **A4**
STH Student Health Center **B6**
SWM Swimming Pool (outdoor) **B6**
TCM Telecommunications **C4**
TNS Tennis **B7**
TMS Thomas **C5**
TSN Tyson **B5**
UC University Club **D2**
VIS Visual Arts **B4**
WGR Wagner **B6**
WKR Walker **C2**
WTK Wartik Lab **C4**
WTN Water Tunnel (G. Thomas) **C2**
WVR Weaver **B4**
WHT White **D5**
WML Whitmore Lab **C4**
WLD Willard **C3**

East Residence Halls

E1 Bigler Hall **A6**
E2 Brumbaugh Hall **A6**
E3 Curtin Hall **A6**
E4 Findlay Commons **A6**
E5 Fisher Hall **A6**
E6 Geary Hall **A6**
E7 Hastings Hall **A6**
E8 Johnston Commons **A6**
E9 McKean Hall **A6**
E10 Packer Hall **A6**
E11 Pennypacker Hall **A6**
E12 Pinchot Hall **A6**
E13 Snyder Hall **A6**
E14 Sproul Hall **A6**
E15 Stone Hall **A6**
E16 Stuart Hall **A6**
E17 Tener Hall **A6**

Eastview Terrace

ET1 Brill Hall **D6**
ET2 Curry Hall **D6**
ET3 Harris Hall **D7**
ET4 Miller Hall **D7**
ET5 Nelson Hall **D7**
ET6 Panofsky Hall **D6**
ET7 Young Hall **D6**

Nittany Residence Area

NT1 Nittany Apartments **C6**
NT2 Nittany Community Center **C6**
NT3 Nittany Hall **C6**

North Residence Halls

N1 Holmes Hall **A4**
N2 Leete Hall **A4**
N3 Runkle Hall **A4**
N4 Warnock Commons **A4**

Pollock Residence Halls

P1 Beaver Hall **D5**
P2 Hartranft Hall **C5**
P3 Hiester Hall **C6**
P4 Mifflin Hall **C5**
P5 Pollock Commons **C6**
P6 Porter Hall **C6**
P7 Ritner Hall **C6**
P8 Shulze Hall **C6**
P9 Shunk Hall **C6**
P10 Wolf Hall **C6**

South Residence Halls

S1 Atherton Hall **D5**
S2 Cooper Hall **D6**
S3 Cross Hall **D6**
S4 Ewing Hall **D6**
S5 Haller Hall **D5**
S6 Hibbs Hall **D5**
S7 Hoyt Hall **D6**
S8 Lyons Hall **D5**
S9 McElwain Hall **C5**
S10 Redifer Commons **D6**
S11 Simmons Hall **D5**
S12 Stephens Hall **D5**

West Residence Halls

W1 Hamilton Hall **C2**
W2 Irvin Hall **B3**
W3 Jordan Hall **C3**
W4 McKee Hall **B2**
W5 Thompson Hall **C3**
W6 Waring Commons **C2**
W7 Watts Hall **C3**

PENNSTATE

1855

EMERGENCY CONTACT INFORMATION

Name of Participant

Please provide us with the names of two individuals who could be notified in an emergency.

Contact Name	Relationship
Address	Home Phone
Work Phone	Cell Phone

Contact Name	Relationship
Address	Home Phone
Work Phone	Cell Phone

THE PENNSYLVANIA STATE UNIVERSITY

MEMORANDUM OF UNDERSTANDING / WAIVER AND RELEASE/RESEARCH CONTRACT
FOR REVIEW AND EXECUTION FOR THE
PENN STATE HYDROGEOPHYSICS FIELD EXPERIENCE

Name: _______________________________

Permanent address: ____

____

Email Address: ___________________________________

Telephone Number: ___________________________

This course has been developed as an integrated environment to link your classroom education with field campaigns through a three-week experience. During this time, you will work with one another in groups to explore to hydrologic questions regarding fluid flow and solute transport. Graduates from this program will be able to: (1) apply their knowledge of mathematics, science, and engineering to real field problems, (2) conduct experiments, and analyze and interpret data, (3) function in multidisciplinary teams, and (4) communicate their scientific data and analyses effectively. The skills you gain here will serve you well in many careers, including future academics, environmental consulting, oil and gas exploration, and environmental law.

1. PARTICIPATION IN THE PROGRAM: I voluntarily desire to participate in the following embedded short-term faculty-led field program ("the Program") offered by The Pennsylvania State University ("Penn State"):

GEOSC 397 The Hydrogeophysics Field Experience, University Park, PA, May 19-June 4, 2010
(Program title, location, program start and end dates)

I agree to comply with the terms of this Memorandum of Understanding / Waiver and Release form. I have been informed by Penn State of the scope and focus of the Program, eligibility requirements, costs, registration procedures, travel, itinerary, logistics, academic credit and content. By signing this Memorandum of Understanding /Waiver and Release form, I acknowledge that I have fully educated myself as to the details of this Program and agree to abide by its terms.

2. ASSUMPTION OF RISK: I understand and acknowledge that my participation in the Program is wholly voluntary. I further understand and acknowledge that I have voluntarily chosen this particular Program (identified below) and I am aware that other options exist for studying abroad. I am fully aware that there are risks and hazards connected with participation in the Program for which I am accepting this offer of participation. These risks include, but are not limited to, those associated with ground, air or water transportation, adverse weather conditions, communicable disease, medical care, substandard building construction or maintenance, civil unrest, terrorism, war, and negligent or criminal acts of third parties. I understand that Penn State is not responsible for my safety. I hereby elect to voluntarily participate in this Program, and voluntarily assume full responsibility for any risks of loss, property damage or personal injury, including death, that may be sustained by me (my son, daughter) as a result of participating in this Program.

3. RELEASE FROM LIABILITY: In consideration for Penn State's sponsorship of this program and for allowing me to participate, I do hereby agree that Penn State, its officers, employees, agents and representatives shall not be liable for any claims, demands or causes of action based upon or arising out of any illness or injury, including death, property loss or damage, deviation, delay or curtailment, however caused, which I (my son, daughter) may suffer in connection with my enrollment in this Program.

4. INDEMNIFICATION: I hereby agree to indemnify and hold harmless Penn State, its officers, employees, agents and representatives, from any and all claims, demands or causes of action and all expenses incidental thereto (including reasonable attorney's fees), based upon or arising out of any personal injury (including death) or property damage or loss caused by or resulting from my (my son's, daughter's) acts or omissions during enrollment in this Program.

5. MEDICAL TREATMENT: I understand that Penn State cannot be held responsible for my health, safety, or well-being during participation in the Program. I further understand that on rare occasions an emergency may develop which necessitates the administration of medical care, hospitalization or surgery. Therefore, in the event of injury or illness to myself necessitating emergency medical care, I hereby authorize Penn State, by and through its authorized representative(s) or agent(s), to authorize and secure any necessary treatment, including hospital admission and the administration of an anesthesia and surgery. It is understood that such treatment shall be solely at my expense and I agree to reimburse the University for any expenses which it might suffer on account of said injury or illness or treatment thereof. I understand that Penn State makes no representation with respect to the quality or accessibility of medical services and facilities abroad. Appropriate treatment may not be as readily available abroad as in the United States. I voluntarily assume any and all risks associated with medical treatment while a participant in the Program. I acknowledge that it is my responsibility to make any arrangements necessary for continuation of medical treatments, such as prescription medications or special diet.

6. PROGRAM CANCELLATION AND WITHDRAWAL: I understand that Penn State reserves the right to decline any application or to cancel any program without notice, in which event all monies paid will be refunded in full. Penn State reserves the right to require withdrawal from the program of any participant whose continuation would be detrimental to himself, to others, or to the University. Return passage and any other expenses due to such involuntary withdrawal are the responsibility of the student. I understand that if I voluntarily leave the Program for any reason, including illness, I will be responsible for any and all costs associated with my return home and that I will receive a refund of tuition or fees only to the extent allowed pursuant to applicable Penn State policies.

7. CHANGES TO ITINERARY: I understand that circumstances may require Penn State to make changes to the program itinerary, possibly without notice, and I agree that Penn State shall not be liable for any loss whatsoever to me by reason of any such cancellation or change. I understand that Penn State is not responsible for penalties assessed by air carriers that may result due to operation and/or itinerary changes. Any additional expense resulting from a change to the Program itinerary will be paid by me. Penn State reserves the right to substitute hotels or accommodations or housing of a similar category at any time. I understand that Penn State assumes no responsibility or liability for any cost or inconvenience associated with delays or changes to departure or arrival times, fare changes, problems with hotel, airline or vehicle rental reservations, missed carrier connections, or similar problems related to travel.

8. LEGAL PROBLEMS: I understand and acknowledge that should I experience any sort of legal problems with any foreign nationals or with any government while participating in the Program, I will attend to the matter myself and with my own personal funds. While Penn State will endeavor to provide reasonable assistance under such circumstances, Penn State is not responsible or obligated to do so.

9. GOVERNING LAW: I agree that this Memorandum of Understanding / Waiver and Release shall be construed in accordance with the laws of the State of Pennsylvania and that Centre County, Pennsylvania, shall be the forum for any disputes or lawsuits filed under or incident to this document and/or the Program. The terms and provisions of this Memorandum of Understanding / Waiver and Release shall be severable, such that if a court of competent jurisdiction holds any term to be illegal, unenforceable, or in conflict with any relevant law, the validity of the remaining portions shall not be affected thereby.

10. PERSONAL CONDUCT: I will adhere to the Penn State Principles and Code of Conduct (http://www.psu.edu/ur/principles.html; http://www.sa.psu.edu/ja/conduct.shtml) that include the following:
1. I will respect the dignity of all individuals within the Penn State community.
2. I will practice academic integrity.
3. I will demonstrate social and personal responsibility.
4. I will be responsible for my own academic progress and agree to comply with all University policies.

11. HOUSING: I will adhere to all university housing policies (see attached). I will be held responsible for the condition of the room and furnishings and for any damages or losses that may occur during occupancy. Individuals identified as responsible for damage, theft, or losses in the Community Center will be billed for the cost of repair or replacement. Amounts billed are additional charges under the Housing and Food Service Contract. I may be held collectively responsible for damages, theft, or losses in common areas of the building that may occur during occupancy when the individual(s) responsible cannot be identified. For the purpose of damage, theft, or loss assessment, occupancy shall be inclusive from the date of check-in to the date I check out of the room.

12. MEAL PLAN: I will adhere to all meal plan policies (see attached). I understand that my meal plan is limited to dining halls and on-campus food courts. I cannot use meal plans at on-campus or off-campus convenience stores.

13. TEXTBOOKS/COURSE MATERIALS: I understand that I am responsible for the proper use and handling of course textbooks and materials. I understand that I cannot sell textbooks or course materials; furthermore, I will return all textbooks and materials in the condition I received them.

14. PHOTOGRAPHY RELEASE: I authorize The Pennsylvania State University to photograph, videotape, and/or audiotape me in promotion of the summer research program.

15. COMMUNICATION WITH INSTRUCTOR: I understand that it's expected to exercise proactive communication skills.

16. OBJECTIVES OF FIELD COURSE:
My objectives for this field course:

Instructor's objectives for this field course:

17. OUTCOMES: Anticipated project outcomes include an abstract of summer research and a poster presenting results of work. The timeline for completion of these objectives is the field course end date listed above.

With the intent to be legally bound, I acknowledge and represent that I have read this Memorandum of Understanding / Waiver and Release/Research Contract, that I understand same, and that I voluntarily sign below in order to evince my agreement with the terms set forth herein, with full knowledge of the educational benefits and possible risks associated with my participation in the Program. I further acknowledge that by signing this document, I give Penn State permission to share this and other application information with external institutions that work closely in the administration in the Program.

____

Signature of Student Printed Name Date

____

Signature of Instructor Printed Name Date

THE CODE OF CONDUCT

The Code of Conduct describes behaviors that are inconsistent with the essential values of the University community. Intentionally attempting or assisting in these behaviors may be considered as serious as engaging in the behavior. A person commits an attempt when, with intent to commit a specific violation of the Code of Conduct, he/she performs any act that constitutes a substantial step toward the commission of that violation. Many Code items are supported by University Policy Statements. The Code of Conduct Charge Codes can be found within the Judicial Affairs Reference and Training Manual at http://www.sa.psu.edu/ja. The Code of Conduct behaviors include, but are not limited to:

1. ABUSE/ENDANGERMENT/HAZING OF A PERSON: Physically harming or threatening to harm any person, intentionally or recklessly causing harm to any person or reasonable apprehension of such harm or creating a condition that endangers the health and safety of self or others, including through the facilitation of or participation in any mental or physical hazing activity (also see Policy Statement 8).

2. SEXUAL MISCONDUCT OR ABUSE: The University does not tolerate sexual misconduct or abuse, such as sexual assault, rape (including acquaintance rape) or other forms of nonconsensual sexual activity. Sexual misconduct and abuse can occur between acquaintances or parties unknown to each other. Sexual abuse is attempted or actual unwanted sexual activity, such as sexual touching and fondling. This includes the touching of an unwilling person's intimate parts (defined as genitalia, groin, breast or buttock, or clothing covering them), or forcing an unwilling person to touch another's intimate parts. Sexual misconduct includes, but is not limited to, sexual assault, rape, forcible sodomy or sexual penetration with an inanimate object, intercourse without consent, under conditions of force, threat of force, fear or when a person is unable to give consent because of substance abuse, captivity, sleep or disability (also see Policy AD-12).

3. HARASSMENT CREATING HOSTILE ENVIRONMENT AND HARASSMENT, OR STALKING OF ANY PERSON: Harassment creating a hostile environment is a violation of University policy. Such harassment is a form of discrimination consisting of physical or verbal conduct that (a) is directed at an individual because of the individual's age, ancestry, color, disability or handicap, national origin, race, religious creed, sex, sexual orientation, gender identity or veteran status; and (b) is sufficiently severe or pervasive so as to substantially interfere with the individual's employment, education or access to University programs, activities and opportunities.

To constitute harassment creating a hostile environment, the conduct must be such that it detrimentally affects the individual in question and would also detrimentally affect a reasonable person under the same circumstances. This harassment may include, but is not limited to, verbal or physical attacks, threats, slurs, or derogatory comments or threats of such conduct, that meet the definition set forth above. Whether the alleged conduct constitutes prohibited harassment depends on the totality of the particular circumstances, including the nature, frequency and duration of the conduct in question, the location and context in which it occurs and the status of the individuals involved.

General harassment, stalking of any person is a violation of University policy. A person violates this section when, with intent to harass or alarm another, the person (a) subjects the other person or group of persons to unwanted physical contact or the threat of such contact; or (b) engages in a course of conduct, including following the person without proper authority, under circumstances which demonstrate intent to place the other person in reasonable fear of bodily injury or to cause the other person substantial emotional distress (also see Policy Statement 7, and Policies AD-41 and AD-42).

4. WEAPONS, FIREARMS, AND PAINTBALL DEVICES: The possession, storing, carrying, or use of any weapon, ammunition, or explosive by any person is prohibited on all University property except by authorized law enforcement officers and other persons specifically authorized by the University. No person shall possess, carry, or use any fireworks on University property, except for those persons authorized by University and local governments to discharge such fireworks as part of a public display. Paintball guns and paintball markers may only be used on the property of the University in connection with authorized University activities and only at approved locations.

5. FIRE SAFETY VIOLATIONS: Tampering with fire or other safety equipment or setting unauthorized fires.

6. ALCOHOL AND/OR DRUGS: Illegally possessing, using, distributing, manufacturing, selling or being under the influence of alcohol or other drugs. Use, possession or distribution of beverages containing alcohol on University property shall comply with the laws of the Commonwealth of PA and University Policies and Rules. Note: Anyone, including those under 21, serving alcohol to persons under 21 is in violation of both University regulations and state law. Also, simply being present in a residence hall room where a quantity of alcoholic beverages is present and/or being served implies possession. Public drunkenness occurs when a person appears in public when intoxicated to the degree that the person may endanger himself or other persons or property, or annoy persons in the vicinity. (also see Policies AD-18 and AD-33 and "Policy Statement on Beverages Containing Alcohol" in Policies and Rules).

7. FALSE INFORMATION: Intentionally providing false or inaccurate information or records to University officials or employees. Providing a false report of an emergency or University rule or Code violation. Knowingly providing false statements or testimony during a University investigation or proceeding.

8. THEFT AND OTHER PROPERTY OFFENSES: Stealing, vandalizing, damaging, destroying, or defacing University property or the property of others.

9. DISRUPTION OF OPERATIONS: Obstruction or disruption of classes, research projects, or other activities or programs of the University; or obstructing access to University facilities, property, or programs. Disruption is defined as an action or combination of actions by one or more individuals that unreasonably interferes with, hinders, obstructs, or prevents the operation of the University or infringes on the rights of others to freely participate in its programs and services (also see Policy Statement 1).

10. ACADEMIC DISHONESTY: Academic integrity is the pursuit of scholarly activity in an open, honest and responsible manner. Academic integrity is a basic guiding principle for all academic activity at The Pennsylvania State University, and all members of the University community are expected to act in accordance with this principle. Consistent with this expectation, students should act with personal integrity, respect other students' dignity, rights and property, and help create and maintain an environment in which all can succeed through the fruits of their efforts. Academic integrity includes a commitment not to engage in or tolerate acts of falsification, misrepresentation or deception. Such acts of dishonesty violate the fundamental ethical principles of the University community and compromise the worth of work completed by others.

Academic dishonesty includes, but is not limited to, cheating, plagiarism, fabrication of information or citations, facilitation of acts of academic dishonesty by others, unauthorized possession of examinations, submitting work of another person or work previously used without informing the instructor, and tampering with the academic work of other students (also see Faculty Senate Policy 49-20 and G-9 Procedures).

11. FAILURE TO COMPLY: Failing to comply with reasonable directives from University officials when directed to do so. Failure to provide identification or to report to an administrative office or, when reasonable cause exists, failing to leave University-controlled premises or dangerous situations when directed to do so by properly authorized persons, including police and/or other University staff. This charge may be added to other charges, e.g., when a student fails to leave a residence hall during a fire drill and refuses to leave when directed to do so by a University official.

12. FORGERY/ALTERATION: Making, using or possessing any falsified University document or record; altering or forging any University document or record, including identification, meal or access cards. This includes but is not limited to; forging (signing another's name and/or ID number) or mis-signing key request forms, manufacturing IDs or tickets, altering permits, misuse of forms (letterhead stationery, University forms), and keys to mislead.

13. UNAUTHORIZED ENTRY OR USE: Unauthorized entry into or use of property facilities or University facilities including residence halls, classrooms, offices, and other restricted facilities. Unauthorized entry or use of facilities is referred to in University policy regarding the rights of individuals and the rights of the institution. Specifically, policy refers to an "obligation not to infringe upon the rights of all members of the campus to privacy in offices, laboratories and residence hall rooms, and in the keeping of personal papers, confidential records and effects, subject only to the general law and University regulations." The University also has the right to control use and entry into facilities for reasons of security, safety or protection of property. This includes closing facilities at specified times. It should also be recognized that an open or unlocked door is not an invitation to enter and use facilities. The same concept applies to computer entry or misuse.

14. DISORDERLY CONDUCT: Engaging in disorderly, disruptive, lewd or indecent conduct. The item includes but is not limited to: inciting or participating in a riot or group disruption; failing to leave the scene of a riot or group disruption when instructed by officials; disruption of programs, classroom activities or functions and processes of the University; creating unreasonable noise; or creating a physically hazardous or physically offensive condition.

15. VIOLATIONS OF UNIVERSITY REGULATIONS: Violating written University policy or regulations contained in any official publications or administrative announcements, including University Computer policies. University policies and regulations are contained in official publications, administrative announcements, contracts and postings (also see Policy AD-20 and Policy Statement 4).

16. VIOLATION OF LAW: Students are members of the campus, local and state communities. As citizens, students are responsible to the community of which they are a part, and the University neither substitutes for, nor interferes with the regular legal or criminal process. Students are also responsible for offenses against the academic community and in some instances student conduct that violates federal, state, or local law may affect a Substantial University Interest on the University community. Because the University expects students to conduct themselves in accordance with the law, student misconduct that occurs on or off the premises of the University that violates any local, state, or federal law will be reviewed by the University. Criminal or civil decision is not a necessary prerequisite for a disciplinary decision nor is it necessary that criminal or civil charges be lodged against the student either before or after a University decision. Therefore, action taken in a civil or criminal court does not free the student of responsibility for the same conduct in a University proceeding.

Department of Geosciences Pennsylvania State University Acceptable Use Policy

This document outlines acceptable uses of the Department of Geosciences (Department) computer equipment and the Pennsylvania State University (University) computer network. Access to the equipment and network is restricted to account holders for authorized uses only. Authorized uses are research, teaching/class work, and University administration tasks.

This account provides access to electronic mail, a limited amount of storage for worldwide web pages and working files, and access to certain licensed software.

You are responsible for the proper use of all software installed on the machines including compliance with the terms of all software licensing agreements. Software installed on Department machines is licensed by the Department and may not be used on any unauthorized machine. Use of Department equipment to illegally duplicate copyrighted material (as per the United States Copyright Law Title 17) is strictly prohibited. This includes the unauthorized duplicating of copyrighted printed material and copyrighted digital media.

All account holders must choose a new password upon receipt of the login credentials. Passwords must be changed annually. Sharing of passwords is prohibited. You are responsible for all activity attributed to your account – protect your password!

Passwords must meet the following criteria:

1. It must be at least 8 characters in length and have at least one numeric and one non-alphanumeric character.
2. It must not be a word found in any dictionary.
3. It should not consist of personal information about the user. This includes social security numbers, driver's license numbers, phone numbers, birthdays, names, addresses, etc.
4. It must not match your username.
5. It must not include your initials.
6. It must not include your given, middle, or surname.

Computer abuse and network security are of great concern to the University. You are expected to exercise responsible, ethical behavior when using the Department and University computers, information, software, networks, and other resources. You are responsible for compliance with all applicable University and Department policies, local, state and federal laws, and copyright and licensing agreements.

University policies are available on the web at http://guru.psu.edu. Please become familiar with policies AD-20 (Computer and Network Security), University Policy AD-23 (Use of Institutional Data), and University Administrative Guideline 2 (Computer Facility Security Guidelines).

Department policies are available on the web at http://www.geosc.psu.edu/computing .

Violations of all or part of these policies may result in (but not be limited to):

1. A limitation to a user's access to some or all University systems
2. The initiation of legal action by the University
3. The requirement of the violator to provide restitution for any improper use of service
4. Disciplinary sanction, which may include dismissal from the University

This document is available on the web at http://www.geosc.psu.edu/computing/?q=455 . Alternative media available upon request.

By signing below you agree to abide by the preceeding statements, referenced policies and guidelines.

_________________________ _________________________

Signature Date

_________________________ 602068 ___________________

Printed Name PSU ID serial number*

_________________________ UGRAD | GRAD | FACULTY | STAFF | POSTDOC | VISITOR

PSU ITS user name (xyz123) Circle One

____

Office

A wireless network is available throughout the building.
If your computer requires a wired network connection please provide the following information.

_________________________ _________________________

Port Number Name for computer

_________________________ _________________________

Operating System Brand and version of anti-virus software installed***

*The serial number is the 16-digit number listed on the front of your University-issued ID card. Please copy carefully, as this number is used to grant you access to the computer labs.

** The PSU ITS user name is your University issued computer lab account ID and can be obtained by taking your student ID card to Room 3 in the Willard Building or by visiting an ITS signature station.

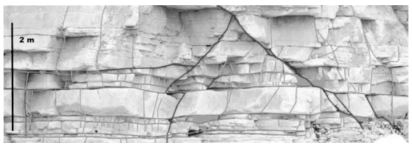
*** Before your port is activated, one of the systems administrators must verify that you have anti-virus software installed and that the virus definition auto-update feature is enabled. The University provides Symantec Norton Anti-virus at no charge. See https://downloads.its.psu.edu .

____

Assigned username

Geosc 397: The Hydrogeophysics Research Experience

- Instructor: Dr. Kamini Singha

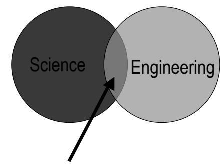


What is Hydrogeology?

Hydrology: The geoscience that seeks to describe and predict

- The spatial and temporal variations of water in the terrestrial, oceanic, and atmospheric compartments of the global water system.
- The movement of water on and under the earth's surface, and the physical, chemical, and biological processes that affect that movement.

Hydrogeology: The science of groundwater—its quantity, quality, movement, and interactions with geologic materials.

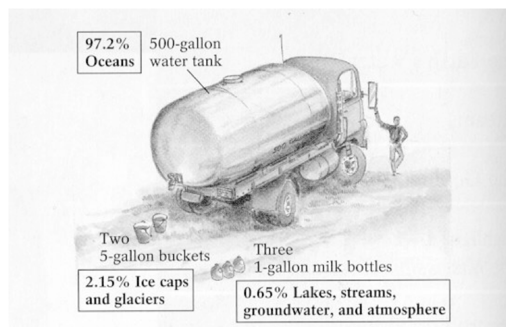


Why is Hydrogeology Important?

Hydrogeology is important for a variety of problems in basic and applied science, including:

- **Water supply and water quality**
- **Waste management**
- **Environmental remediation**
- **Mining**
- **Fluids in geologic processes**

Hydrogeology is also an important field of employment for geologists and engineers.



Distribution of Earth's water by relative volume

Water Use

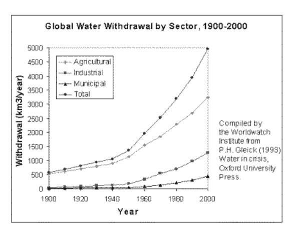
Personal water use per capita (in gallons per day):

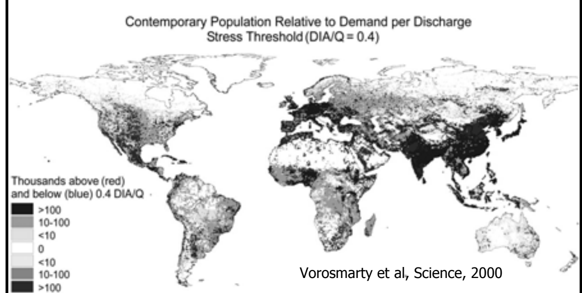
- **Subsistence conditions 3 to 5**
- **Urban use 260**
- **U.S. fresh water use 1280**

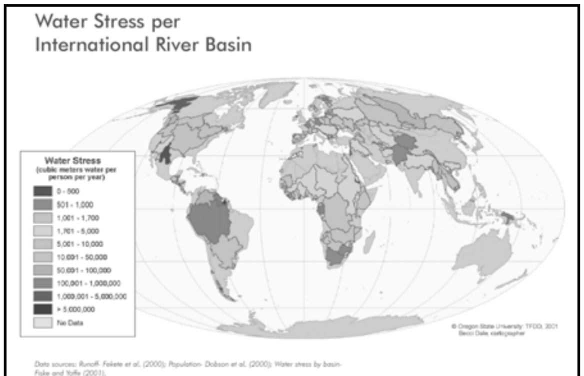
What's all that water used for?

To make things, to clean things…

Item	gallons
A flushing toilet	5
10-min shower	25-50
1 load of laundry	60
1 kilowatt of electricity	80
1 pound of rubber	100
1 pound of steel	25
1 pound of grain-fed beef	800
1 car	100,000







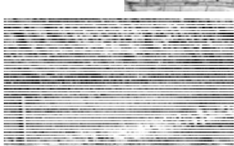
A need for characterization

- 300,000-400,000 contaminated sites in the US
- Total cost to clean: $500 billion to $1 trillion

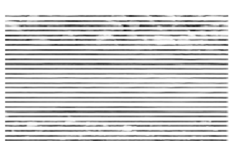
Motivation

The subsurface looks like this this:

Hartman et al, *JCH*, 2007



British Geological Survey, 2004

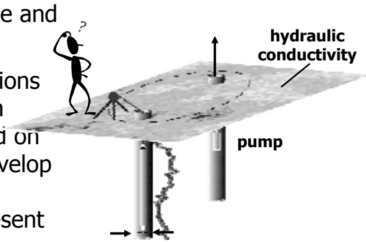


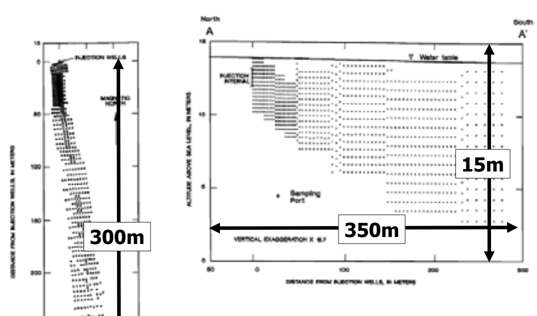
British Geological Survey, 2004

What we have to work with

Motivation

- Subsurface data are frequently sparse and costly
- Reliable predictions of future system behavior depend on our ability to develop models that accurately represent field conditions



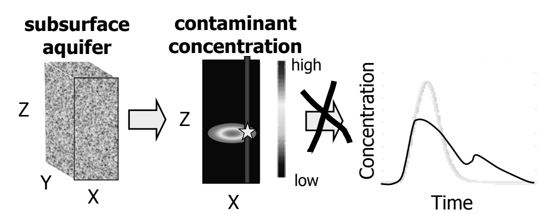


Cape Cod tracer test borehole sampling array. (from LeBlanc et al., *WRR*, 1991)

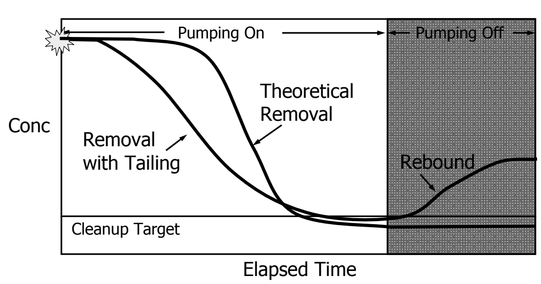
Motivation

Need to understand flow and transport processes

- to assess risk
- create schemes for contaminant cleanup

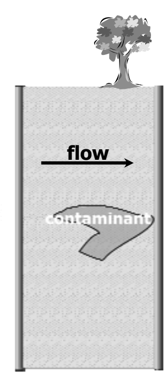


A Common Problem in Pump-and-Treat Remediation



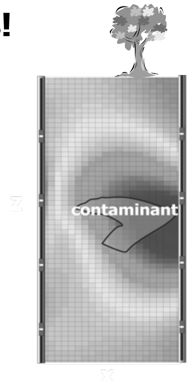
Now what?

- Hydrologic data are frequently sparse or volume averaged, and costly



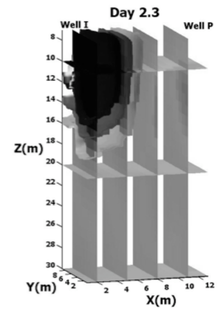
Geophysics!

- Able to collect spatially exhaustive data



Applications

- Electrical methods have been used to monitor changes in salinity, moisture content; image flow barriers and pathways



GEOSC 397: objectives & approach

-
  - Information
  - Intuition about hydrologic processes
  - Creative problem solving skills
-
  - Lecture & in-class activities
  - Field work
  - Data analysis + modeling
  - One-minute papers
  - Final presentation

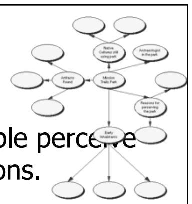
"Learn your instrument, learn the music, then forget both"

We Test Our Hypotheses with Data and Models…

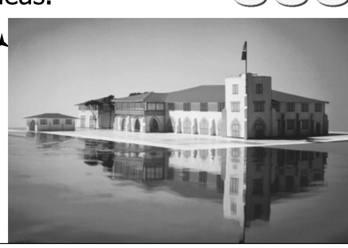
- **What's a model?**

Model Types

- Physical models: Miniature versions of large systems that are made to test out designs and ideas.
- Graphic models compile and display data in meaningful network.
- Conceptual models help people perceive the world and build connections.

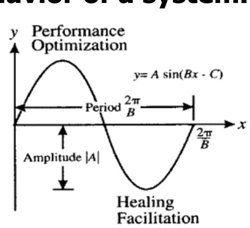


-



Mathematical Model

- **Consists of one or more mathematical equations to describe the behavior of a system.**



Sand Tank Aquifer Experiment

Today you'll explore this sand tank aquifer, and get a sense for what happens in the subsurface. Take the time to talk about what's going on so everyone understands. If you're not sure about something—make sure you ask your classmates, who might not understand what's happening either.

When you complete this exercise, you will be able to:

1. identify the following:
    - a. confined aquifer
    - b. unconfined aquifer
    - c. water table
    - d. potentiometric surface
    - e. hydraulic gradient
2. describe the nature and significance of each of the terms in #1 (above).
3. calculate the hydraulic gradient in an aquifer.
4. describe how groundwater and surface water are interconnected.

Equipment:

1. sand tank
2. nalgene water bottles with lids
3. syringe
4. funnel
5. ruler
6. calculator
7. pencils
8. buckets
9. towels
10. gallons of water

Start by filling the tank. Close all on/off vales and add water as uniformly as possible across the top of the model. Once full, fill the two plastic recharge bottles with water, secure the rubber stopper assemblies, and insert into the two wells on each side of the demonstration (see Figure 1). This will maintain a constant water level just below the two outlet drains at the top of the demonstration. The several empty containers and bucket included with the model can be used to catch any overflow.

1. While filling the sand tank (aquifer recharge), observe the sand as it becomes saturated. Does the sand around the stream get saturated before water enters the stream?

2. Which fills first, the lake or the lagoon? Why?

3. Draw the sediment layers on the sand tank diagram provided.

4. Sketch the water table on the sand tank diagram and label it.

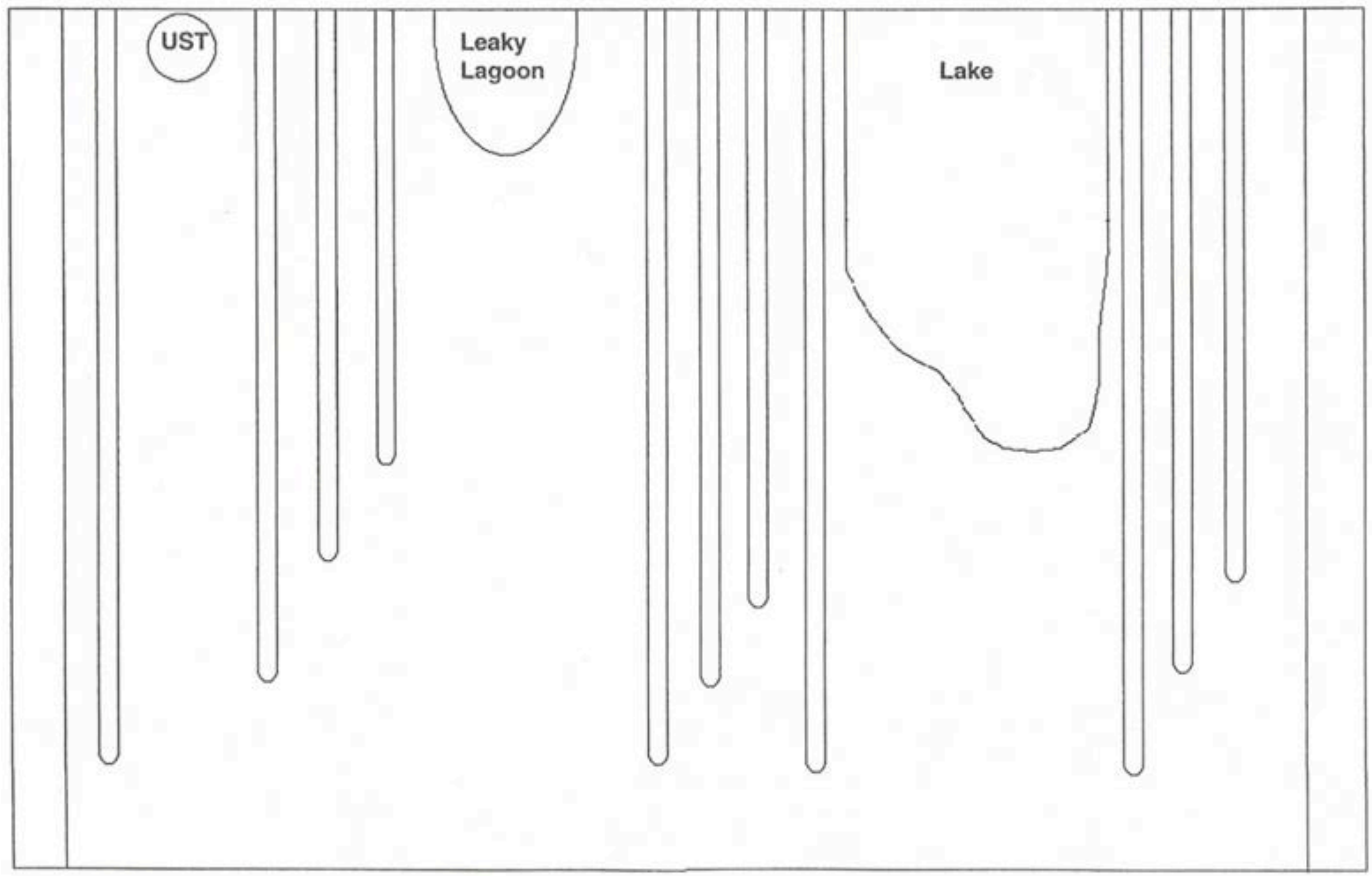
5. Calculate the hydraulic gradient in the unconfined aquifer.

6. Open the lake/river outlet, and wait a few minutes for the flow in the unconfined aquifer to stabilize. With water flowing, measure the water level of the water table at two wells (also known in hydrology as "piezometers" if only open at the bottom) sampling at the same depth in the upper aquifer. What is the new gradient between these wells?

7. Why does the gradient differ?

8. Comparing the sand aquifer and the gravel aquifer, (without reference to whether or not they are confined or unconfined), consider the following question: if the hydraulic gradient were the same in each aquifer, in which would the water flow faster? Why?

9. Using a syringe, pump water out of one of the confined wells. For a good seal (particularly when withdrawing water), gently twist the syringe into the well opening. Observe what happens to the water levels in the rest of the wells (both unconfined and confined). Why the different responses? Which piezometer(s) were affected most by pumping?

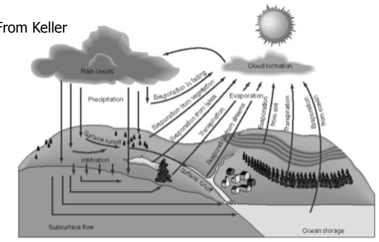


Amy Hobbs, 2001
Department of Geological Science:
University of Texas at Austin

Introduction to Hydrogeology

- **Outline:**
  - **Permeability, hydraulic head. Darcy's law.**

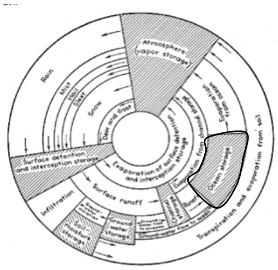
The Hydrologic Cycle



Key Features:

- Driven by the sun
- Conservative (over a long period): ***Storage = Input - Output***
- Water compartments are not equal in terms of storage or residence time

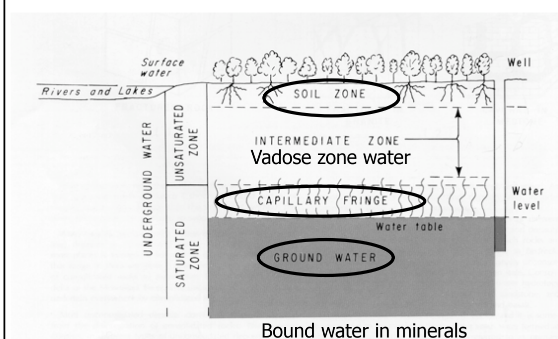
Water Budget for the Earth



- **On every circumference, storage = input – output**
- **An increase in storage is considered a POSITIVE change**

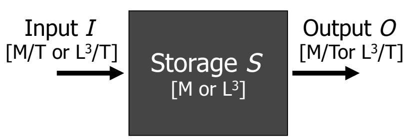
Why might this diagram mislead you in calculating the ocean budget?

Reservoirs



Like banking, but without the money

- For a balance to be meaningful, all inputs, outputs, and changes in storage must be quantified
- Just like finances!



So what exactly is groundwater, anyway?

Pressure in the subsurface

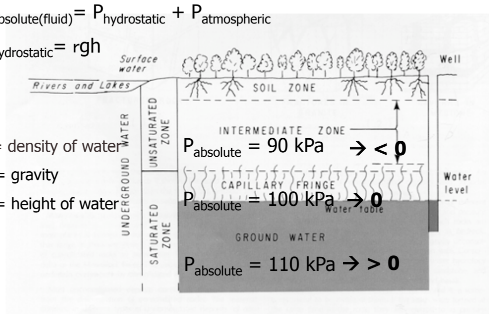
$P_{absolute(fluid)} = P_{hydrostatic} + P_{atmospheric}$

$P_{hydrostatic} = rgh$

r = density of water

g = gravity

h = height of water



$P_{absolute}$ = 90 kPa → < 0

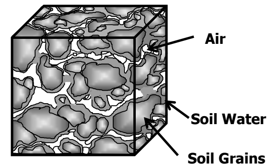
$P_{absolute}$ = 100 kPa → 0

$P_{absolute}$ = 110 kPa → > 0

Porosity

- total material:

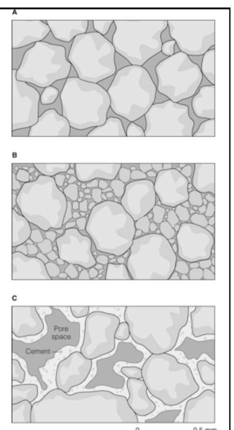
$$n = \frac{V_{pore}}{V_{total}}$$



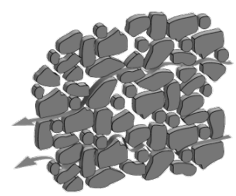
- Total volume of rock
- n is dimensionless

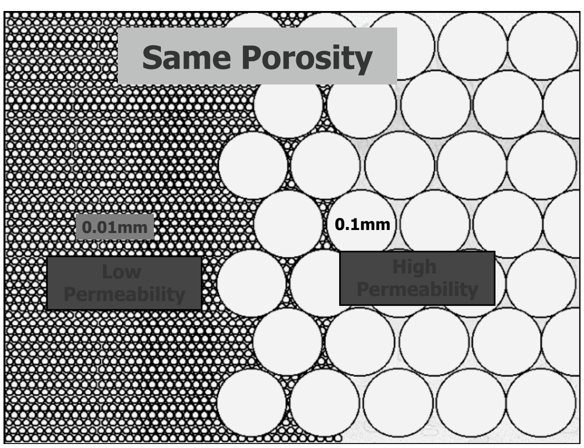
Permeability (k)

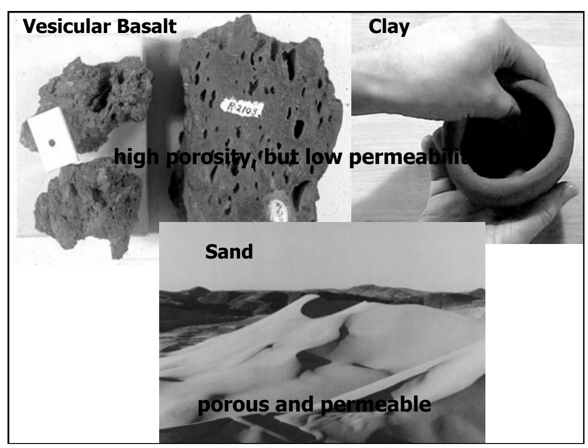
- The ease with which water can flow through rock
- Depends on:
  - the size of the pores
  - the degree to which the pores are interconnected



Is porosity an indicator of permeability?







Flow Properties

Permeability (k), with dimensions of area [L²], depends only on the properties of the porous medium: k a d²

Hydraulic Conductivity (K), with dimensions of velocity [LT⁻¹] depends on the properties of both the porous medium and water:

$$K = \frac{k\rho g}{\mu}$$

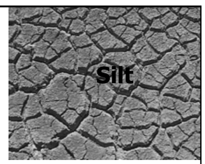
where

k	is intrinsic permeability [L²]
r	is density of the fluid [M/L³]
g	is acceleration of gravity [L/T²]
m	is dynamic viscosity [M/LT]

K/k controls

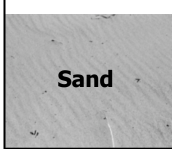
$$K = \frac{k\rho g}{\mu}$$

Property	k	K
↑ m	-	decrease
↑ g	-	increase
↑ r	-	increase
↑ grain size	increase	increase
↑ sorting	increase	increase
↑ temp	-	↑ (due to ↓r&↓m)



Sediments have wide range of values for K (m/s)

Clay	**$10^{-11} – 10^{-8}$**
Silt	**$10^{-8} – 10^{-6}$**
Silty Sand	**$10^{-7} – 10^{-5}$**
Sands	**$10^{-5} – 10^{-3}$**
Gravel	**$10^{0} – 10^{3}$**



How do we estimate K or k?

1.
2.
3. measurement
4. Tracer tests

Often knowing K to an order of magnitude is satisfactory and may be all that is obtainable within temporal and financial constraints

Take 5

⅄ ’

constant-head permeameter (a Darcy apparatus). What measurements do you need?

Be Aware of Your Units

⅄ F = ma ...... m = F/a = W/g

SI

⅄ Basic units: L M T length mass time
m kg s meter kilogram second

⅄ Derived unit: F - force, N Newton

⅄ 2

English

⅄ Basic units L F T length force time
ft lb s foot pound second

⅄ Derived unit: M - mass, S slug

⅄ 2
of 1 lb is applied to it (S= W/g)

Significant Figures

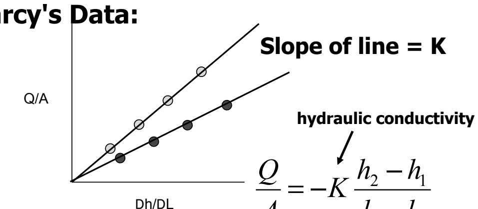
- Adding/subtracting: no more significant digits than the least significant placeholder.
  - Example: 1.05 + 21 = 22.05 → 22
- Multiplying/dividing: no more significant digits than the number of digits in the number with the fewest digits.
  - Example: 3.1 x 6 = 18.6 → 2 x 10^1.
- However, remember that exact numbers (often integers) have infinite significance.
  - Example: diameter of a circle = 2 x radius.
  - If radius = 3.47 m, then diameter = 2 x 3.47 = 6.94 m
- Carry all digits through calculations and round at the end

Take 3 minutes…

- **With a partner: convert**
  - **3.6 ft to inches?**
  - **3.6 m^3/s to liters per minute?**
  - **806 acre-ft/yr into gpm (gallons per minute).**

Time to experiment…

Darcy's Data:



$$\frac{Q}{A} = -K\frac{h_2 - h_1}{l_2 - l_1}$$

Darcy showed that Q is:

- In direction of decreasing water level
- Proportional to Dh, given L fixed
- Inversely proportional to L, given Dh fixed

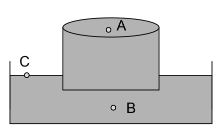
Independent of porosity!!!

How to we determine the driving force that makes water move?

What is the driving force? Pressure?

No, but some petroleum engineers in the 1930's thought so (big mistakes…)

Pressure at A = atmospheric
Pressure at B > atmospheric
Pressure at C = atmospheric



Flow is from A to B to C, so it's not going "down pressure gradient". Must be something else…

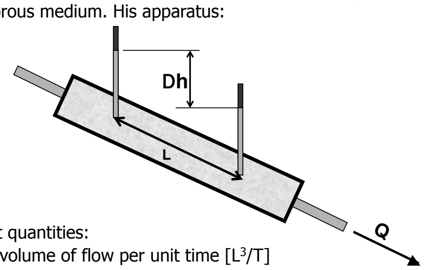
What controls flow velocity?

-
  develop a water purification system for Dijon, France
- Filtered the water supply through sand beds

Henri Darcy
(1803-1858)

What makes groundwater flow?

In Dijon, France, in 1856, Henri Darcy conducted an experiment in flow in porous medium. His apparatus:



Important quantities:

Q	is volume of flow per unit time [L^3/T]
A	is cross-sectional are [L^2]
Dh	is the difference in the height of water [L]
q	is Q/A, the specific discharge [L/T]

Energy!

In 1940, M. K. Hubbert clarified that groundwater flow is driven by differences in fluid potential.

Examples of potential:

- Heat conduction: from high temp to low temp
- Electricity: from high voltage to low voltage

Fluid potential (F) has three components:

- Potential (position) energy
- Pressure (elastic) energy
- Kinetic (velocity) energy

Fluid potential (F) has three components:

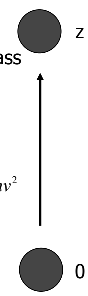
- Potential (position) energy
- Kinetic (velocity) energy
- Pressure (elastic) energy

Fluid potential is the energy required to move unit mass

The three components:

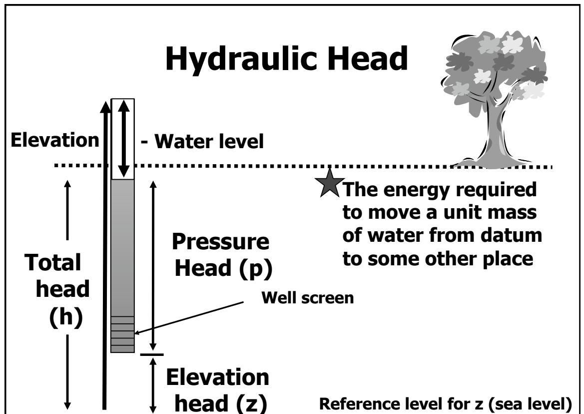
1) Energy to lift the mass (where z = 0): $E_p = mgz$
2) Energy to accelerate fluid from v=0 to v: $E_K = \frac{1}{2}mv^2$
3) Energy to raise fluid pressure from P=0 to P:

$$E_{pres} = \int_0^P VdP = \frac{m}{\rho}\int_0^P dP$$

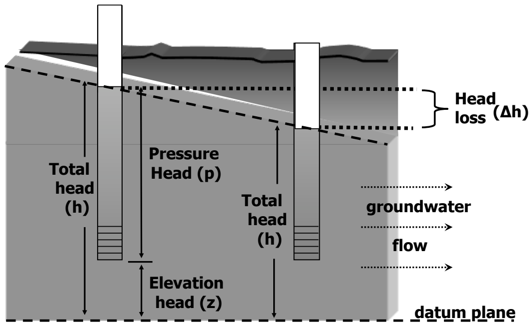


To the board!!!

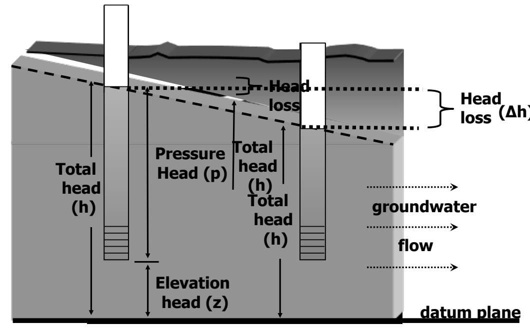
Hydraulic Head



Subsurface Fluid Flow

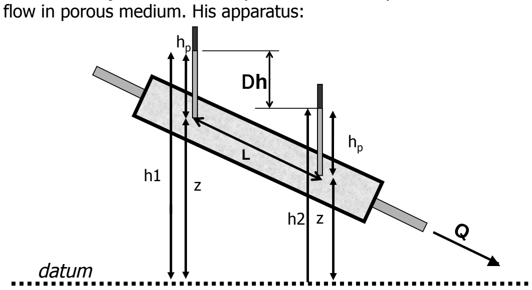


So Why Doesn't the Datum Matter?

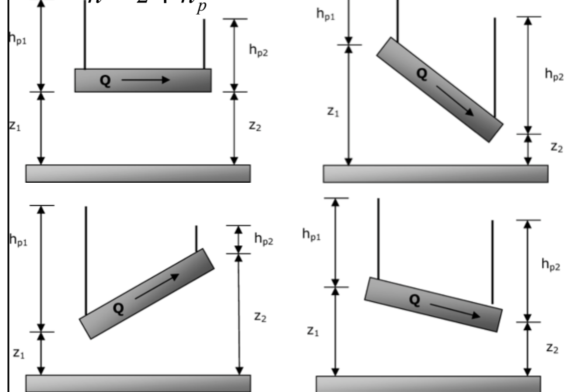


Henri Darcy's experiment:

In 1856, in Dijon, France, Darcy conducted an experiment about flow in porous medium. His apparatus:

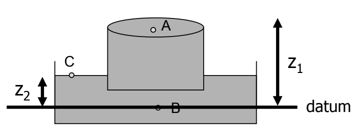


$$h = z + h_p$$



What is the driving force? Hydraulic head!

Head at A = atmospheric + elevation z_1
Head at B > atmospheric
Head at C = atmospheric + elevation z_2
$h_a > h_b > h_c$



Flow is from A to B to C, so it's going "down head gradient"

Darcy's Law

$$Q = -KA\frac{h_2 - h_1}{l_2 - l_1}$$

Things to note:

D
the medium, and caused by frictional energy loss

•Why the negative sign????

Take Home Messages

- Storage = Input – Output
- Permeability is dependent only on the medium, whereas hydraulic conductivity is also dependent on the fluid; both control flow
- Fluid moves along the potential or hydraulic head gradient, not according to pressure
- Darcy's law defines the volume flux or flow rate expected for a given head gradient and hydraulic conductivity

Darcy Lab Activity

This experiment is designed to investigate the relationships between flow rate, aquifer material, fluid properties, head gradient, and flow area. These relationships are described formally by Darcy's Law, which you will use to quantify the hydraulic conductivity of each material type.

Experimental Equipment:

Darcy Column (bottle filled with porous medium)
1 graduated cylinder
Bottle filled with water
Funnel
Ruler
Stopwatch

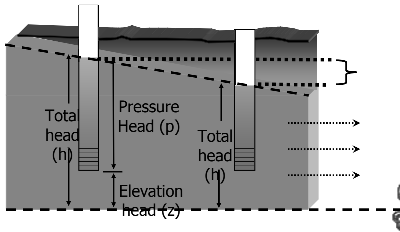
Instructions:

1. Divide into groups of 2-3 people each.
2. Begin with one of the Darcy Tubes. Find the cross sectional area of the tube and record it on the attached table.
3. Measure the height of the material in the column and record it in the table. This is the path length, *dl*.
4. Note the "fill line" on your Darcy Tube. This is the water level that you will maintain during your experiment. Measure the head difference from that mark to the bottom of the porous material, and record it in the table. The top and bottom of the bottle must be your two measurements of water height, so that we can compare measurements between groups.
5. Remove the cap from the bottle and insert the funnel into the top of the bottle.
6. Measure the flow rate of water through the column as follows:
    a. Hold the column over the graduated cylinder. Pour water from the jugs into the bottle through the funnel, trying to **maintain a constant water level** (or head) at the marked line. Start the stopwatch.
    b. Measure the amount of time needed for a fixed amount of water (e.g., 50 cc's) to flow through the column in to the cylinder. The larger volume you use, the smaller your experimental error will be. Alternatively, mark the volume every X seconds.
7. Repeat step #6 twice, and determine the average flow rate from your trials. Record it in the table.
8. Repeat steps #2-7 using an additional bottle.
9. Pool the full dataset for the class.
10. Using your data, calculate the following for each tube. Be sure to include proper units as part of your answers.
    a. Hydraulic conductivity (K)
    b. Permeability (k)
11. For each tube, make a single plot of Q/A vs. dh/dl. Discuss, briefly, the meaning of these graphs.
12. Assuming a water viscosity of 10^{-3} Pa-s, calculate the viscosity of the orange juice.
13. Discuss possible sources of error in the experiment. Based on those sources of error, how many significant digits do you feel comfortable reporting for questions #9 or #12?

Column #	Material	Cross Sectional Area (cm^2)	Height of material (cm) (*dl*)	Head difference (cm) (*dh*)	Flow Rate (cm^3/s)	K	Notes

Potentiometric Surfaces

- **Outline:**
  - **Measuring head in the field**



Darcy's Law

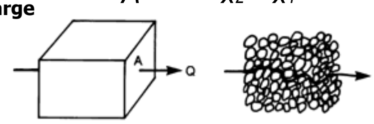
$$Q = -KA\frac{\Delta h}{\Delta l} \quad \text{or} \quad q = -K\frac{\Delta h}{\Delta l}$$

Things to note: not valid for

- Flow through individual pores
- High velocities (turbulent flow)
- Situations where pressure and elevation are not only driving forces
- A discontinuum or variable properties
- Compressible fluids

Specific discharge (aka Darcy velocity or volume flux)

specific discharge →
$$q = \frac{Q}{A} = -K\frac{h_2 - h_1}{x_2 - x_1}$$

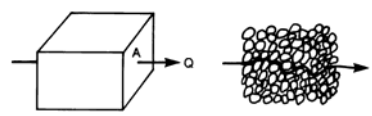


"apparent velocity" –velocity water would move through an aquifer if it were an open conduit

Not a true velocity as part of the column is filled with sediment

Average Linear Velocity (aka Seepage Velocity)

$$v = \frac{Q}{nA} = -\frac{K}{n}\frac{h_2 - h_1}{x_2 - x_1}$$



Only account for area through which flow is occurring

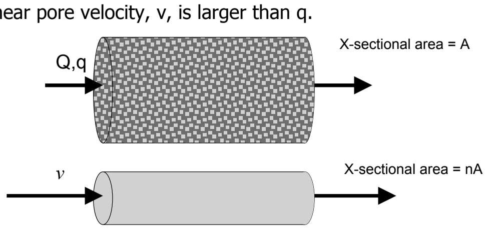
Water can only flow through the pores

Flow area = porosity x area

So how fast is groundwater actually moving?

$$v = -\frac{K}{n}\frac{\Delta h}{\Delta x} = \frac{Q}{An} = \frac{q}{n}$$

Groundwater is only moving through the pores contributing to the effective porosity, so the average linear pore velocity, v, is larger than q.

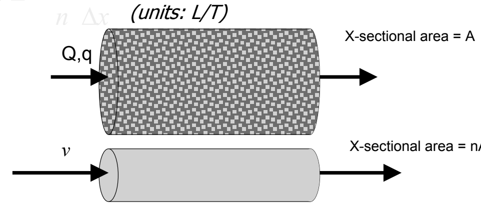


In short: Q, q, and v

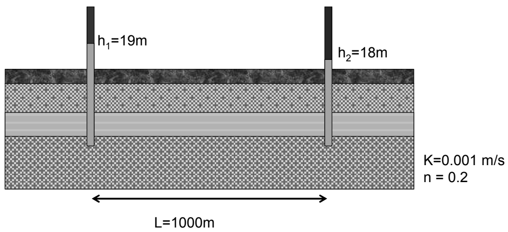
$$Q = -KA\frac{\Delta h}{\Delta x}$$ *Flow rate (units: L^3/T)*

$$q = -K\frac{\Delta h}{\Delta x}$$ *Specific discharge (units: L/T)*

$$v = -\frac{K}{n}\frac{\Delta h}{\Delta x}$$ *Average linear velocity (units: L/T)*



Example using Darcy's Law in a confined aquifer



Determining direction and rate of groundwater flow?

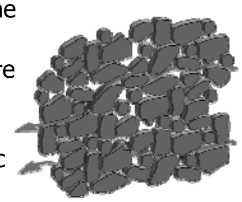
Flow is to the right

q = - (0.001 m/s) x (18 m – 19 m) / (1000 m) = 1 x 10^{-6} m/s

v = (1 x 10^{-3} m/s) / (0.2) = 5 x 10^{-6} m/s

Groundwater Velocity

- Controlled by:
  - size of the spaces in the soil or rock → porosity
  - how well the spaces are connected → hydraulic conductivity
  - differences in hydraulic head → energy



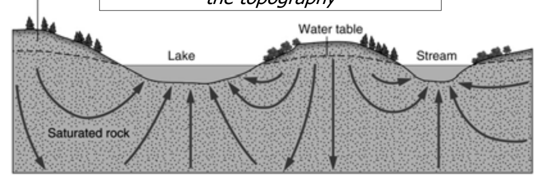
Hydraulic Head Maps

- Hydraulic heads can be contoured on a map
- This contour map is the "topography" of energy of water in the subsurface, and indicates direction of flow
- This is called a potentiometric surface or hydraulic head map.
- If the aquifer is unconfined (not overlain), the surface is a water table map.
- If the aquifer is confined, the potentiometric surface is an imaginary surface defined by the elevations to which water will rise (head) in hypothetical wells tapping a confined aquifer.

Unconfined Aquifers

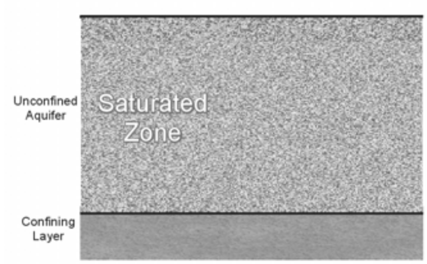
(1) Water table aquifer (Unconfined aquifer): The water is in contact with atmospheric pressure, and the top of the aquifer corresponds to the water table.

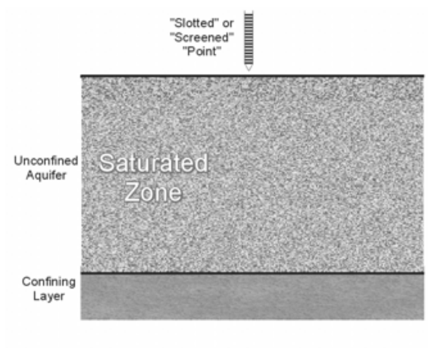
Under most hydrogeologic conditions, the water table is a subdued replica of the topography

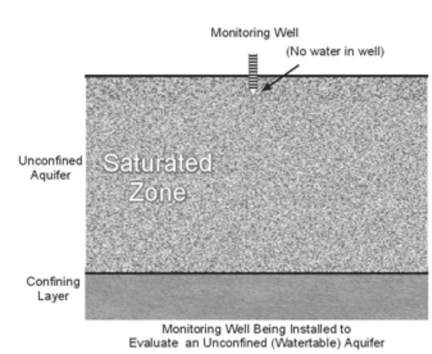


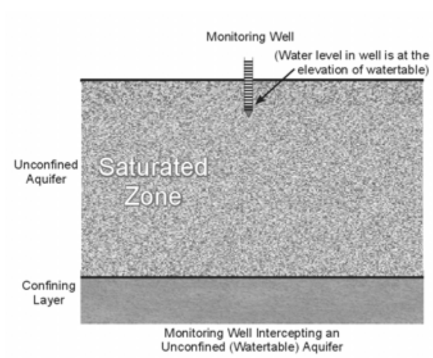
About 30% of the groundwater used for irrigation in the United States is obtained from the High Plains aquifer.

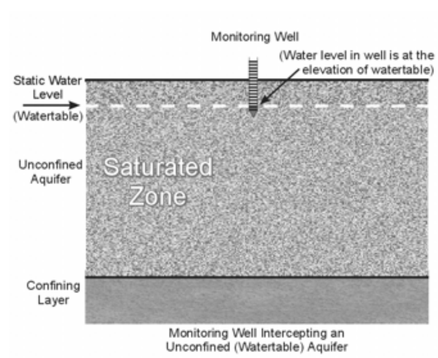
Water levels in unconfined aquifers





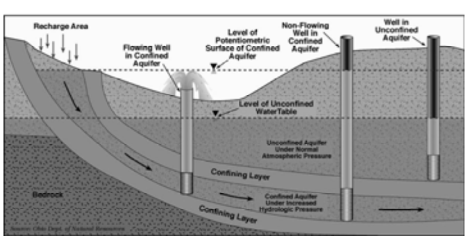




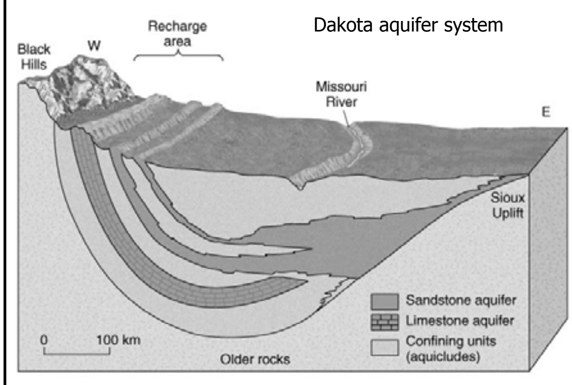


Confined Aquifers

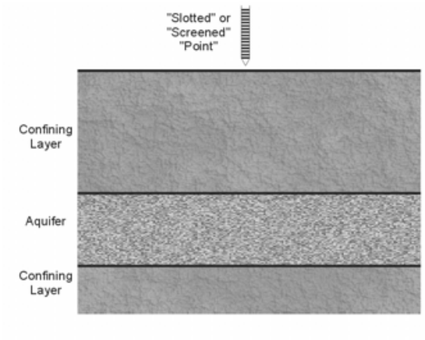
(2) Confined aquifer: Recharge upgradient forces water to flow down and get trapped under an confining unit. Water is under pressure due to the weight of the upgradient water and the confinement between "impermeable" layers.



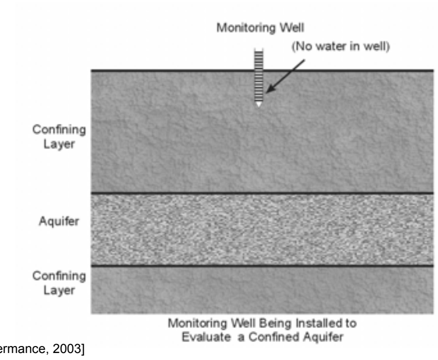
Dakota aquifer system



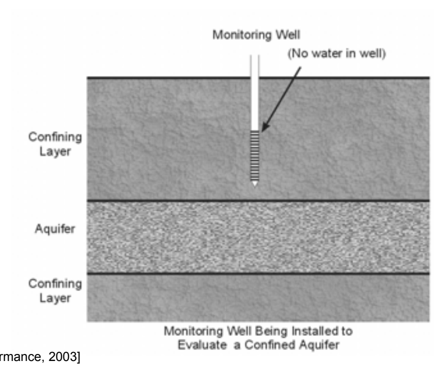
Water levels in confined aquifers



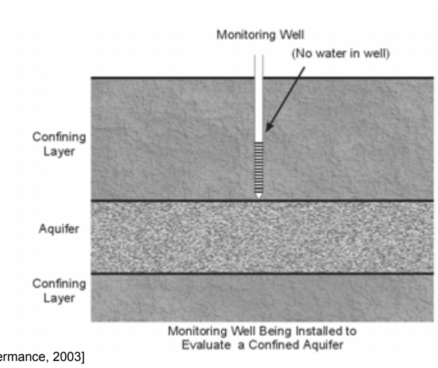
[Hermance, 2003]



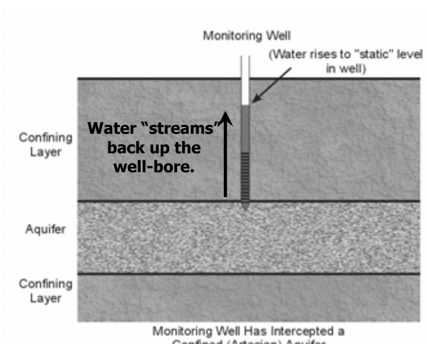
[Hermance, 2003]



[Hermance, 2003]

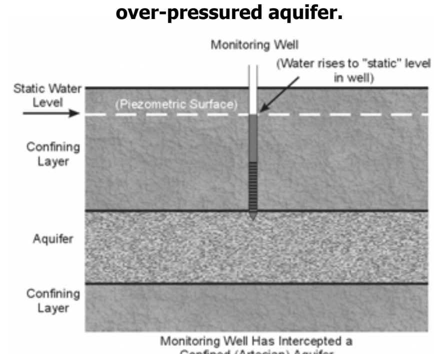


[Hermance, 2003]



[Hermance, 2003]

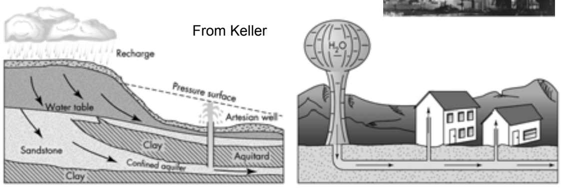
Definitely a confined, artesian or over-pressured aquifer.



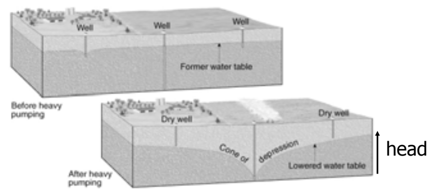
[Hermance, 2003]

Artesian Wells

- If the pressure is great enough, an aquifer may be artesian.



What happens when you pump from an unconfined aquifer?



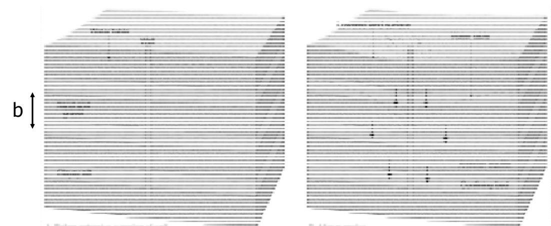
You empty pore space of water, draw down water table around the well

Specific Yield

- We can't recover all water from pore space
- Specific yield: amount of water that will be drained by gravity
- Specific retention: amount of water that will be held

$$n = S_y + S_r$$

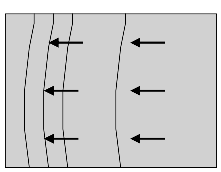
What happens when you pump from a confined aquifer?

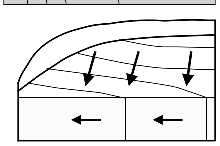


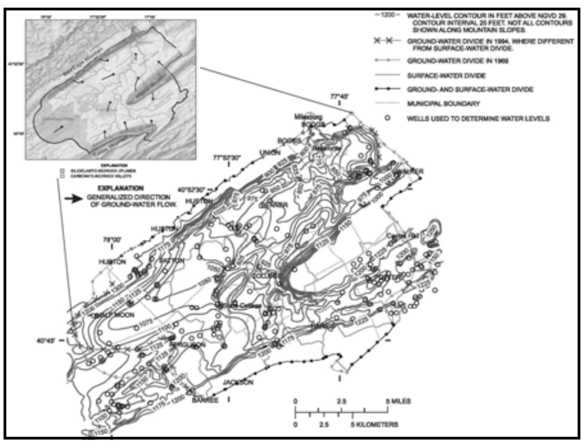
Water pumped from a confined aquifer is coming from expansion of water and compression of aquifer materials→subsidence!!!!

Hydraulic Heads

- Hydraulic heads vary in three spatial directions and time: h(x,y,z,t).
- The time element can be removed if all measurements are made at the same time: h(x,y,z).
- If flow is largely two dimensional: h(x,y). However, the resulting maps must be viewed as 2D projections of a 3D field.







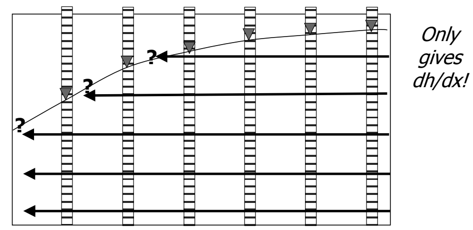
Constructing Potentiometric Maps

To create a head surface map numerous head observations are needed where:

1. Measurements must be made within the same aquifer.
2. There must have enough data points to draw a contour map.
3. Surface bodies of water such as streams, lakes, and springs provide information about the water table in unconfined aquifers.

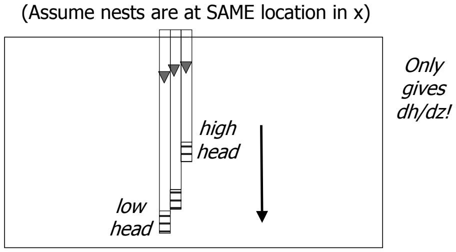
Measuring Head in the Field

Piezometers in an unconfined aquifer



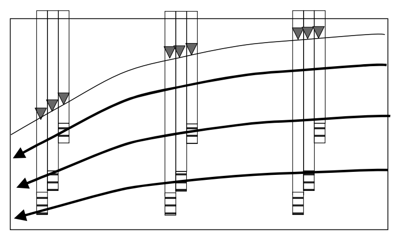
Measuring Head in the Field

Multilevel piezometers in an unconfined aquifer
(Assume nests are at SAME location in x)



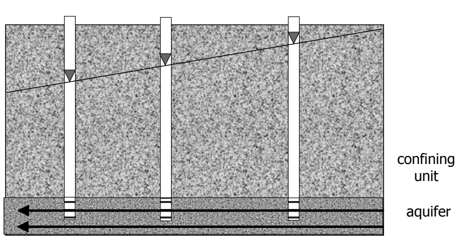
Measuring Head in the Field

Multilevel piezometers in an unconfined aquifer



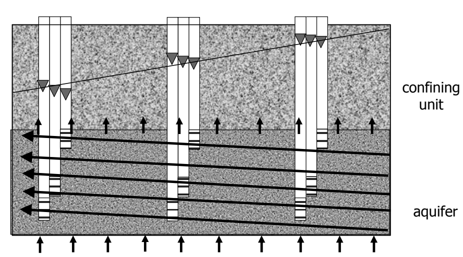
Measuring Head in the Field

Piezometers in a confined aquifer



Measuring Head in the Field

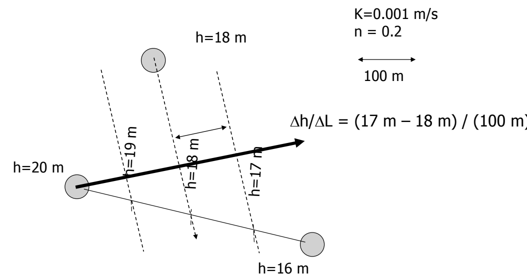
Multilevel piezometers in a confined aquifer



3-point problem

- If you have many piezometers installed over an area, you can map the groundwater potential
- In a material of isotropic K, flow lines are perpendicular to equipotential lines and a flow net can be drawn (more about this later)
- You need at least three points to determine the gradient

Example using Darcy's Law in map view:



$v = -K\,\Delta h/n\Delta L = -(0.001\text{ m/s}) \times (17\text{ m} - 18\text{ m}) / 0.2 \times (100\text{ m}) = 5 \times 10^{-5}\text{ m/s}$

Take 5

- **3-point problem…**

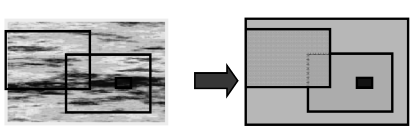
How do we estimate K or k?

1. Grain size analyses: small sample
2. Permeameter: measure in lab, small sample
3. Pumping or slug tests: in situ – larger scale measurement
4. Tracer tests

Often knowing K to an order of magnitude is satisfactory and may be all that is obtainable within temporal and financial constraints

Scale Dependence

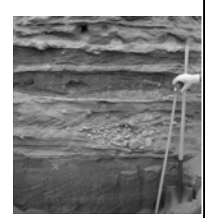
- Additionally: K is volume averaged, so scale dependent
  - Lab (<< 1 m^3)
  - In situ wellbore tests (<10 m^3 - 10^5 m^3)
  - Regional values? (10^2 m^3 - 10^3 km^3)



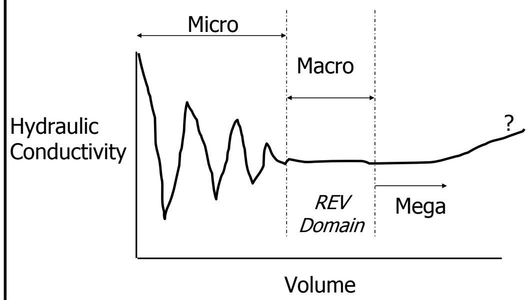
We have two choices…

1) throw up our arms; natural systems are hopelessly complex
2) make some reasonable simplifying assumptions

- For the sake of progress...
  - Assume there is some volume which provides a representative sample of our porous media.
  - This is the Representative Elementary Volume (REV).



Darcy is a macroscopic law

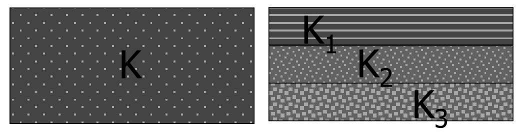


Homogeneous vs Heterogenous

Variation as a function of space

Homogeneity – same properties in all locations

Heterogeneity – hydraulic properties change spatially

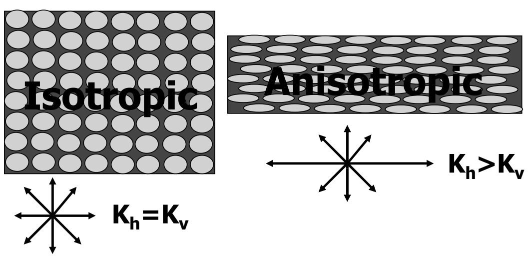


Isotropy vs Anisotropy

Variation as a function of direction

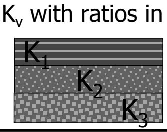
Isotropic: same in direction

Anisotropic: changes with direction

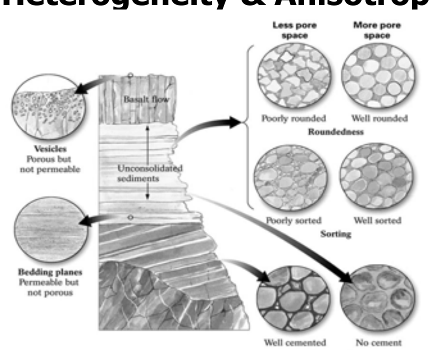


Hydraulic Conductivity is a Tensor

- Most rocks have a directional dependence in their properties as a result of their geologic origins:
  - metamorphic foliation, schistosity and banding
  - sedimentary layering
  - extrusive flow tops and cooling cracks
  - till-weathered tops and desiccation cracks
- Typically K_h > K_v with ratios in the range 2-10



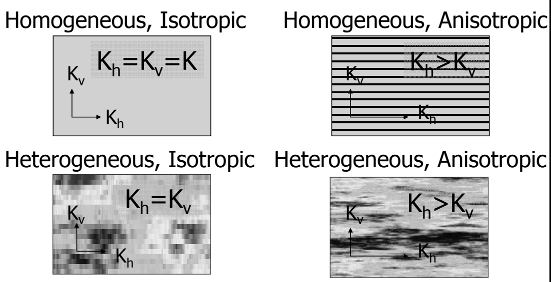
Heterogeneity & Anisotropy



K varies within an aquifer

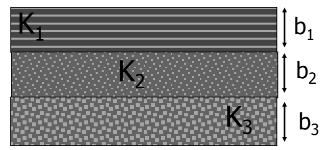
- Definitions:
  - HETEROGENEITY - describes spatial variation
  - HOMOGENEITY - uniform throughout (K independent of position)
  - ANISOTROPY - describes directional variation
  - ISOTROPY- properties do not vary with direction

Four Possible Combinations of Heterogeneity and Anisotropy

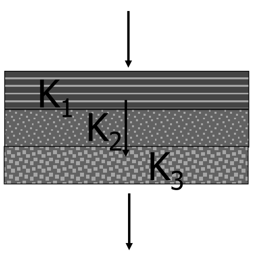


Averaging

- There is a relation between layered heterogeneity and anisotropy
- An equivalent K can be calculated to simplify complex systems thus making it possible to apply Darcy's Law

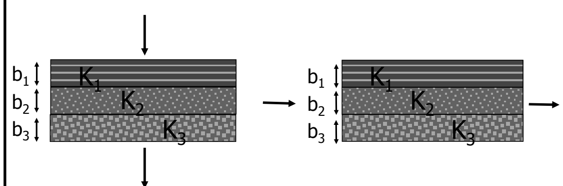


Consider flow perpendicular to layering



To the board!

b?



- b doesn't change direction—it's just the thickness of the layer, and used to define the A for Darcy's Law
- What *does* change direction is Δh and ΔL
- Who cares? If I wanted to know the discharge through this material, you'd need the average K to tell me

Averages

- Arithmetic: largest
  - if all the quantities had the same value, what would that value have to be in order to achieve the same total?
- Geometric: between m_a and m_h
  - if all the quantities had the same value, what would that value have to be in order to achieve the same product?
- Harmonic: smallest
  - tends strongly toward the least elements of the list, minimizes the impact of large values and increases the impact of small ones

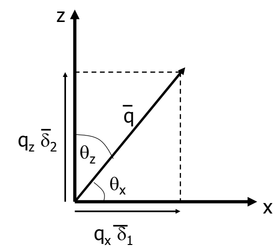
Take 5

- **Calculate equivalent Ks…**

Scalar 1 component	Magnitude	Head, concentration, temperature
Vector 3 components	Magnitude and direction	Specific discharge, (& velocity), mass flux, heat flux
Tensor 9 components	Magnitude, direction and magnitude changing with direction	Hydraulic conductivity, Dispersion coefficient, thermal conductivity

$\bar{q} = Q/A$

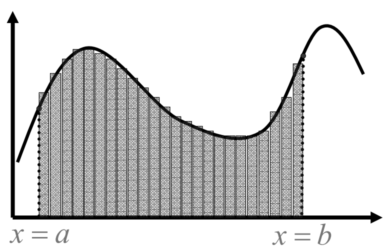
$\bar{q}$ is a vector



In general: $K_z < K_x, K_y$

A Very Brief Review: Integration

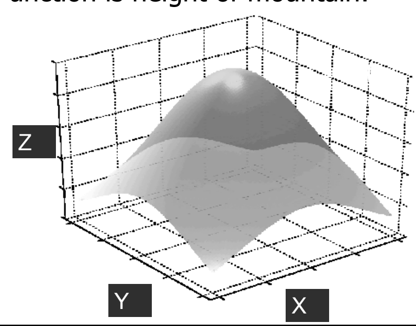
- Sum function while walking along axis



Geometry: Find Area Also: Sum Contributions

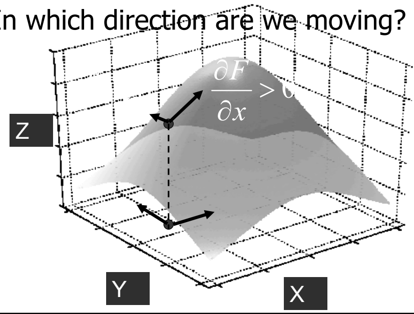
Scalar Functions in 2D

- Function is height of mountain:



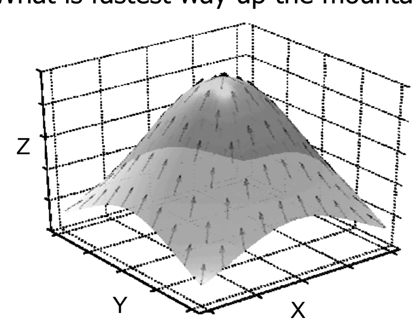
Partial Derivatives

- How does function change with position?
- In which direction are we moving?



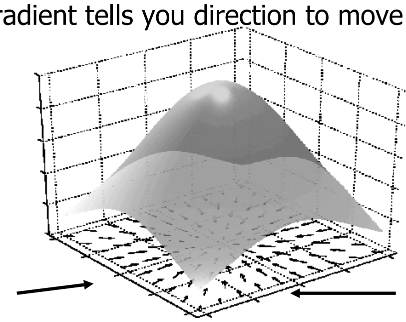
Gradient

- What is fastest way up the mountain?



Gradient

- Gradient tells you direction to move:



Notation

outcome

$$q = -\mathrm{K}\,\nabla h = -\mathrm{K}\,grad(h)$$

$$q = -\mathrm{K}\left(\frac{\partial h}{\partial x} + \frac{\partial h}{\partial y} + \frac{\partial h}{\partial z}\right)$$

"Forcing function"

q is a vector

h is a scalar

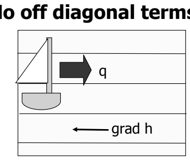
K is a tensor

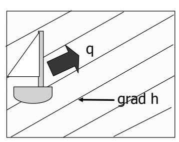
$$q = -\mathrm{K}\,\nabla h$$

$$K = \begin{Bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{Bmatrix}$$

Principal components of **K**

No off diagonal terms

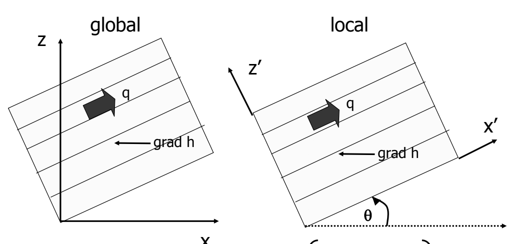




Off-diagonal terms

Consider a diagonal gradient (with and without) tensor notation…

To the board!



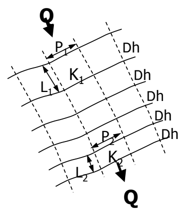
$$\begin{Bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{Bmatrix} \qquad \begin{Bmatrix} K'_x & 0 & 0 \\ 0 & K'_y & 0 \\ 0 & 0 & K'_z \end{Bmatrix}$$

Take Home Messages

- Note difference between specific discharge, average linear velocity, and discharge/flow rate
- Unconfined and confined aquifers behave differently, both in terms of head gradients and where water comes from during pumping
- Measuring head in the field allows us to estimate the average flow direction and gradient over a site

Flownets

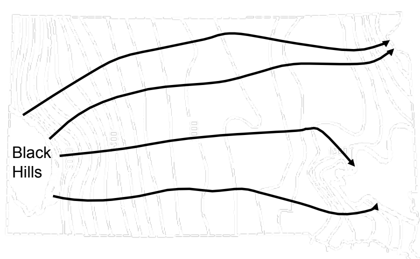
- **Outline:**
  - ,
  - **used for**



So What?

- Flownets are graphical sol' ns to the steady-state GWFE and allow us to estimate head gradients AND flow rates for some reasonably complicated situations
- Flownets are a good stepping stone to numerical modeling

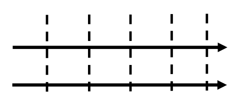
Dakota Sandstone



Darton (1909) was responsible for one of the first potentiometric maps for the Cretaceous Dakota sandstone in South Dakota

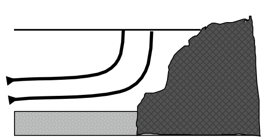
Flow Lines and Flow Nets

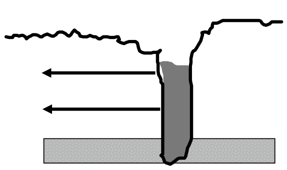
- Flow lines trace groundwater flow paths.
- Flow lines are $\perp$ to equipotential lines in an isotropic medium.
- A set of flow lines and equipotential lines constitute a flow net.



Impact of Boundaries

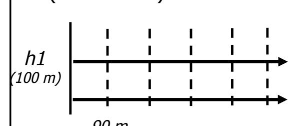
- No aquifer is truly infinite
- Boundaries *(boundary conditions)* define the edges of our domains





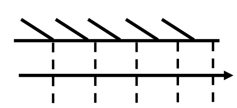
Definitions

- **Constant head boundary**
  (h=constant)



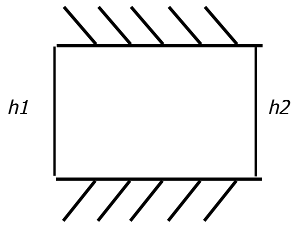
Example: a river

- **No-flow boundary**
  (dh/dx or dh/dy =0)



Example: an impermeable geologic outcrop

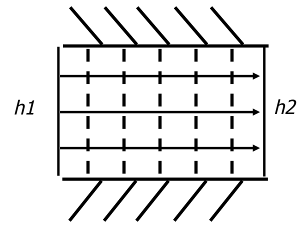
Draw a very simple flow net



$h_1 > h_2$

Draw a very simple flow net

Here is a net with:
- 5 equipotentials
- 6 head drops (n_d)
- 3 flow lines
- 4 flow tubes (n_f)



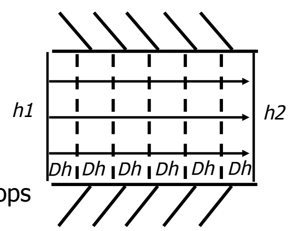
– – Equipotential Line ⟶ Flow Line

Draw a very simple flow net

Total head loss across each drop:

$$\Delta h = \frac{h_1 - h_2}{n_d}$$

where n_d = 6 head drops



– – Equipotential Line ⟶ Flow Line

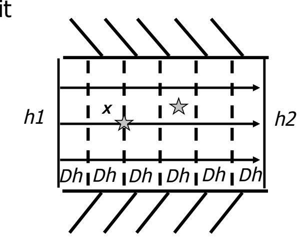
Example

h_1=100; h_2=40 m, unit squares

→h_1-h_2 = 60m, Dh = 10m

→h_{star1} = 80m

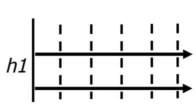
→h_{star2} = 65m

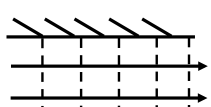


4 flow tubes (n_f)
6 head drops (n_d)

Rules

1. Flow lines are perpendicular to equipotential lines
2. Equipotential lines parallel constant head boundaries
3. Flow lines parallel no-flow boundaries
4. Equipotential lines meet no-flow boundaries at right angles
5. Curvilinear squares (depending on boundaries) should be formed.





Assumptions

- Key assumptions of flow nets:
  - homogeneous
  - isotropic hydraulic conductivity
  - fully saturated
  - Darcy's Law is valid
    - flow is steady, laminar, continuous
    - fluid is constant density
  - Continuity: flow into a zone between 2 flow lines = flow out of the zone

Continuity

Rate of flow through one square:

$Q_x = KA_x i_x$

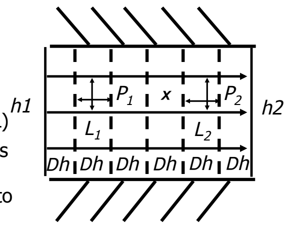
Given a unit thickness into the page:

$Q'_x = KA_x i_x \approx K(1*P)(Dh/L)$

For a flow net flow all tubes carry the same flow and there is no flow normal to flow lines.

This means:

$Q' = K_1 Dh P_1/L_1$
$= K_2 Dh P_2/L_2$



Which means…

Given a unit thickness into the page:

$Q'_x = KA_x i_x \approx K(1*P)(Dh/L)$

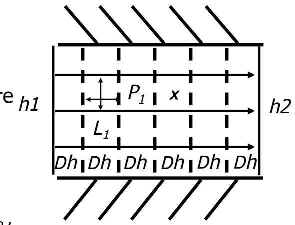
If elements of flow net are squares, L = P, so

$Q'_x = KDh$.

Total Q per width:

$Q' = Q'_x n_f$

where Q'_x (or Q') is in L^3/T *per unit thickness* of section



4 flow tubes (n_f)
6 head drops (n_d)

Example

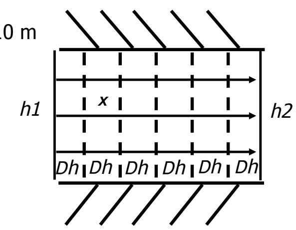
$h_1=100$; $h_2=40$ m, unit squares, K=1 m/d

→ $h_1-h_2 = 60$ m, Dh = 10 m

$Q'_x = KDh$
$= 1\text{m/d}*10\text{ m}$
$= 10\ m^3/d$ per meter of aquifer

Total Q per width:

$Q' = Q_x n_f$
$= 10 m^2/d*4$
$= 40 m^3/\text{day}$ per meter of aquifer



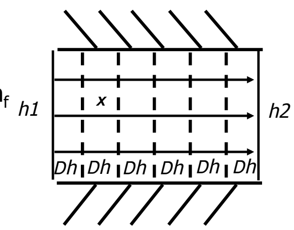
4 flow tubes (n_f)
6 head drops (n_d)

To reiterate…

$Dh = (h_1-h_2)/n_d$

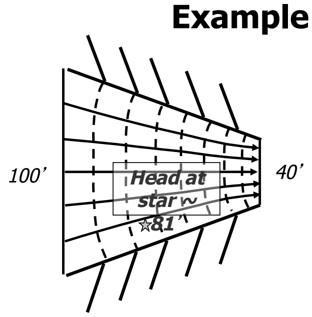
$Q'_x = KDh$

$Q' = KDhn_f = Q'_x n_f$



4 flow tubes (n_f)
6 head drops (n_d)

Example 2



$n_d = 8$
$n_f = 6$

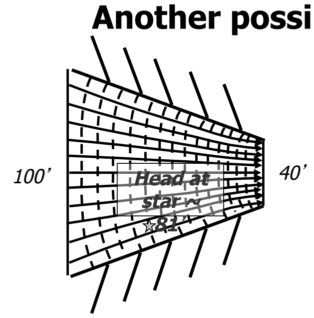
Assume K = 1ft/d

$Dh = (h_1-h_2)/n_d$
$= 60/8 = 7.5'$

$Q'_x = KDh$
$= 1ft/d*7.5'$
$= 7.5\ ft^2/d$

$Q' = Q'_x n_f$
$= 7.5\ ft^2/d*6$
$= 45\ ft^2/\text{day}$

Another possibility…



$n_d = 16$
$n_f = 12$

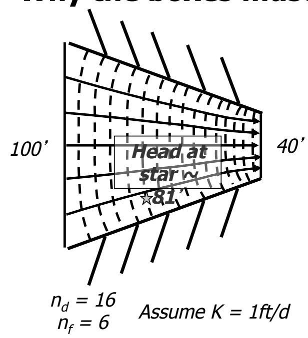
Assume K = 1ft/d

$Dh = (h_1-h_2)/n_d$
$= 60/16 = 3.75'$

$Q'_x = KDh$
$= 1ft/d*3.75'$
$= 3.75\ ft^2/d$

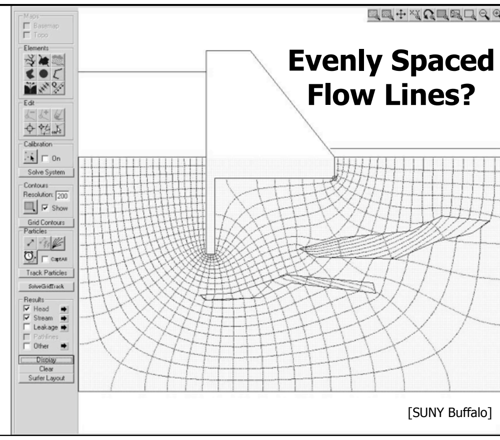
$Q' = Q'_x n_f$
$= 3.75\ ft^2/d*12$
$= 45\ ft^2/\text{day}$

Why the boxes must be square…



$Dh=(h_1-h_2)/n_d$
$= 60/16 = 3.75’$
$Q’_x=KDh$
$=1ft/d*3.75’$
$= 3.75\ ft^2/d$
$Q’ =Q’_x n_f$
$= 3.75\ ft^2/d*6$
$= 22.5\ ft^2/day$

Evenly Spaced Flow Lines?



[SUNY Buffalo]

Take 5

- **Sketch some equipotential lines…**

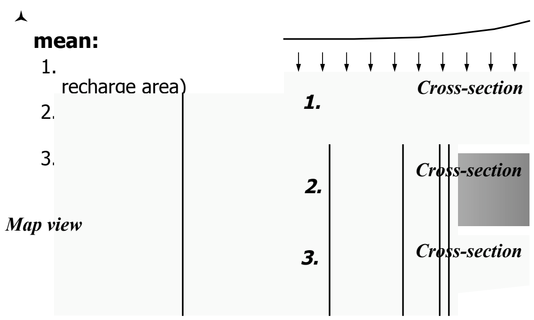
Procrastination is common. It is best to "dive in" and begin drawing. Just keep an eraser handy and do not hesitate to revise!

To summarize:

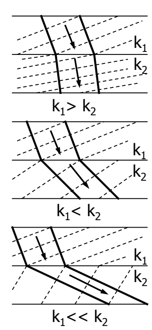
- What is a flow net?
  - A 2D solution to the steady-state groundwater flow equation
  - It’s valid for whatever two dimensions you choose, given appropriate boundary conditions

What do natural “flownets” tell us about processes?

- **mean:**
  1.
  recharge area)
  2.
  3.



Flow Line Refraction

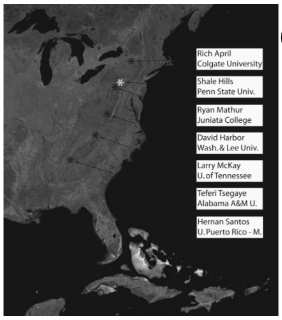


- equipotentials crowd together and flow becomes more vertical
- If k increases with depth, equipotentials spread apart and flow becomes more horizontal
- If k increases significantly with depth, equipotentials become more widely spaced and flow becomes sub-horizontal

Take Home Messages

- Flow nets provide a method for visualizing flow in an area, and quantifying heads & fluxes for steady-state conditions (and in our case, homogeneous and isotropic media)
- Equipotentials and flow lines are perpendicular for isotropic media

The Shale Hills CZO

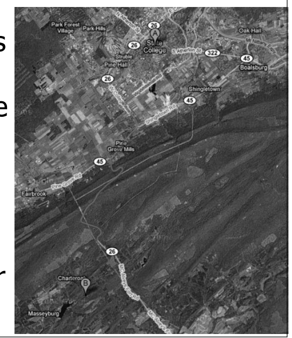


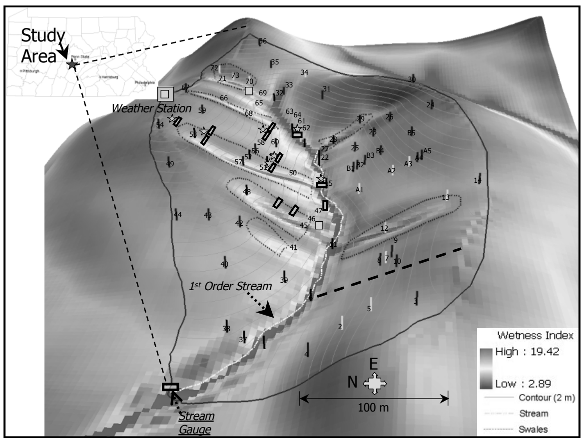
Outline:

- Background information
- Data collected so far
- What we'll be doing

The Shale Hills Critical Zone Observatory

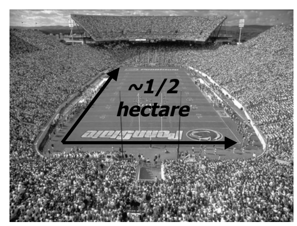
- 12 miles from PSU is an $4.2M NSF-funded "Critical Zone Observatory" (CZO)
- CZOs study the earth from the tops of trees through shallow groundwater



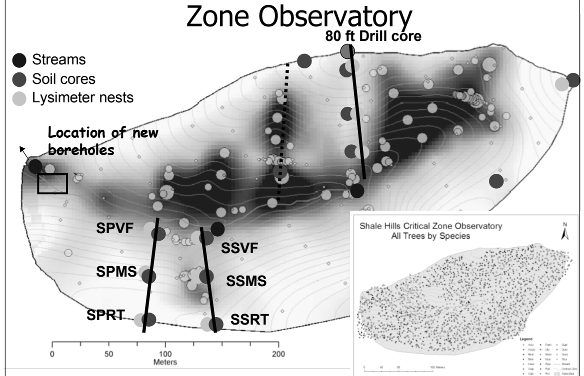


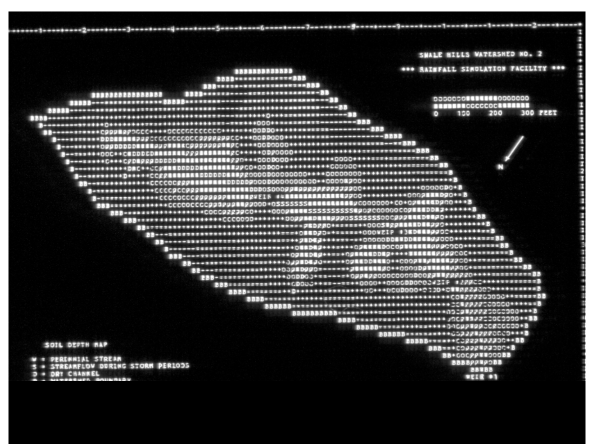
Units

- Hectare = 10,000 m^2 ~ 100,000 ft^2
- Size of a football field = 4500 m^2 ~ acre+



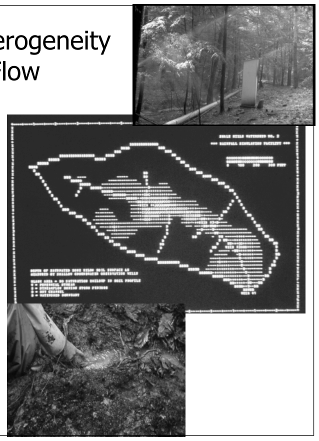
Samples from the Shale Hills Critical Zone Observatory





Understanding Heterogeneity Controls on Flow

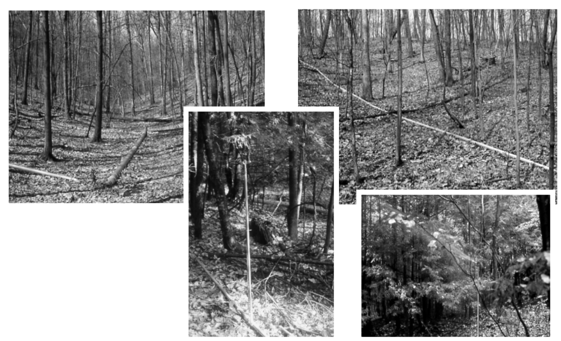
- 1974: Lynch infiltration experiment at SH
- Have to invoke macropores to fit data
- How do we handle them in models?



Irrigation System

8-inch main distribution line leading from the pump house towards the watershed

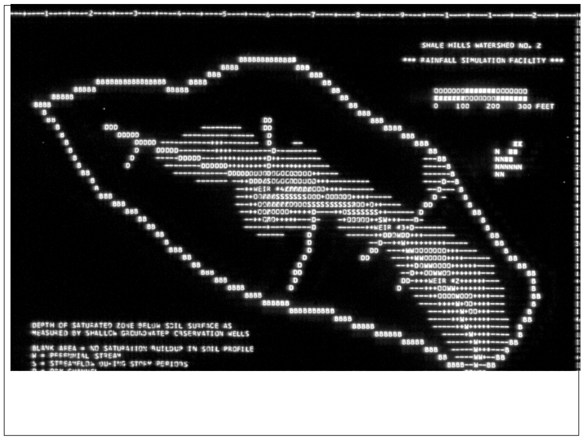
Irrigation System

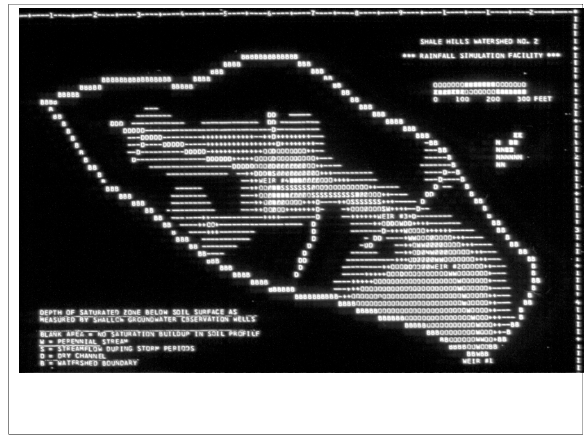


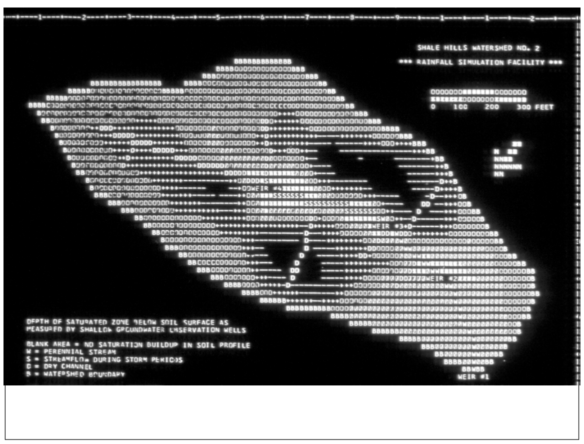
Monitoring Network

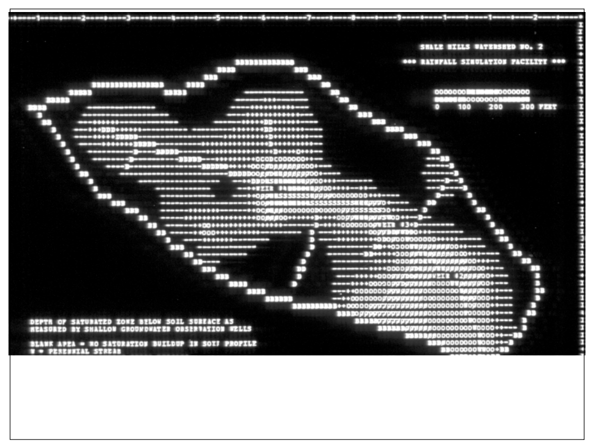
Rain gages

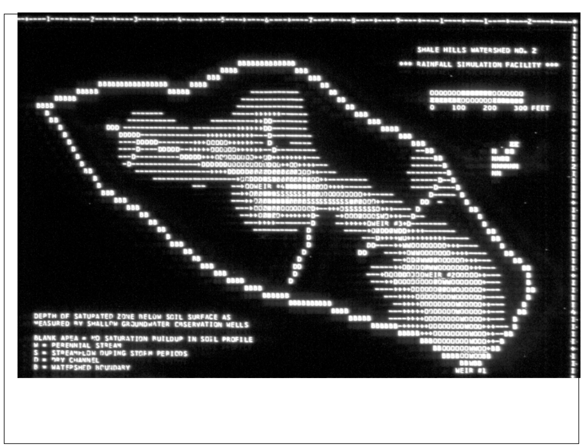
Stem flow monitoring

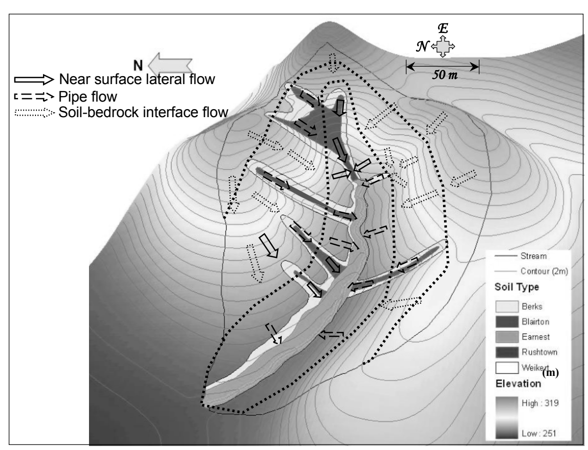

SHALE HILLS WATERSHED NO. 2
*** RAINFALL SIMULATION FACILITY ***
0 100 200 300 FEET
DEPTH OF SATURATED ZONE BELOW SOIL SURFACE AS
MEASURED BY SHALLOW GROUNDWATER OBSERVATION WELLS
BLANK AREA = NO SATURATION BUILDUP IN SOIL PROFILE


SHALE HILLS WATERSHED NO. 2
*** RAINFALL SIMULATION FACILITY ***
0 100 200 300 FEET


SHALE HILLS WATERSHED NO. 2
*** RAINFALL SIMULATION FACILITY ***
0 100 200 300 FEET


SHALE HILLS WATERSHED NO. 2
*** RAINFALL SIMULATION FACILITY ***
0 100 200 300 FEET

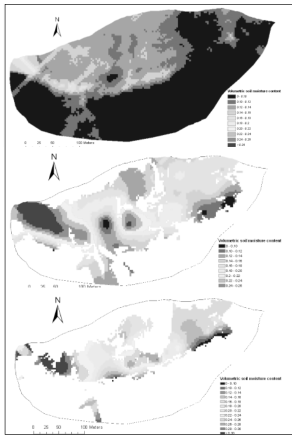

SHALE HILLS WATERSHED NO. 2
*** RAINFALL SIMULATION FACILITY ***
0 100 200 300 FEET


N
Near surface lateral flow
Pipe flow
Soil-bedrock interface flow
E
N
50 m
Stream
Contour (2m)
Soil Type
Berks
Blairton
Ernest
Rushtown
Weikert
Elevation
(m)
High : 319
Low : 251

Results

- Soil moisture controls how easily water gets from ridges to stream!
- How deep are soils?
- What role does heterogeneity play?

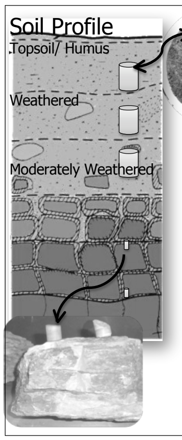
Soil Moisture Content Profile



0.1 m

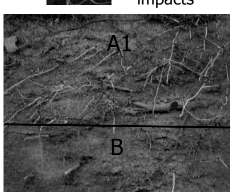
0.4 m

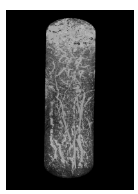
0.8 m



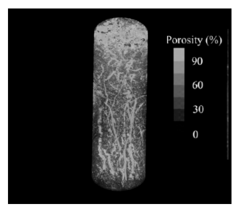
Quantifying heterogeneity

- Exploring the control of preferential pathways on transport with CT scanning, tracer tests
- Are exploring tree root impacts

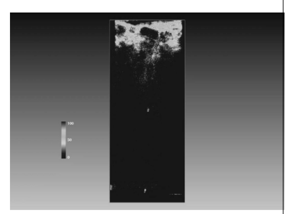




Soil Pore Network



Chemical Movement

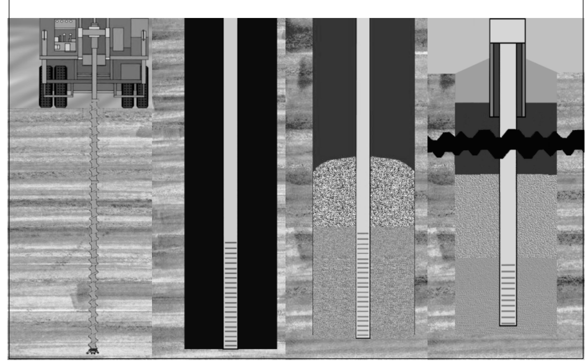


(Luo et al., SSSAJ, 2008)

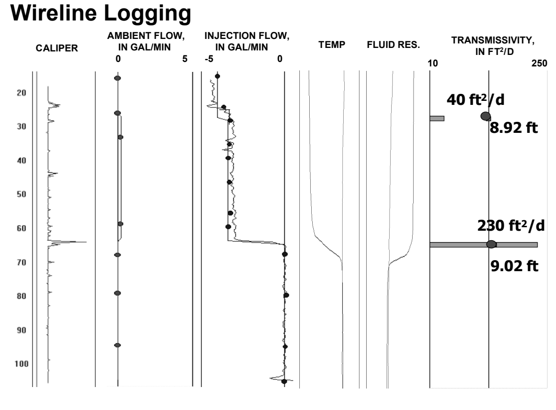
Tomorrow: Borehole Logging

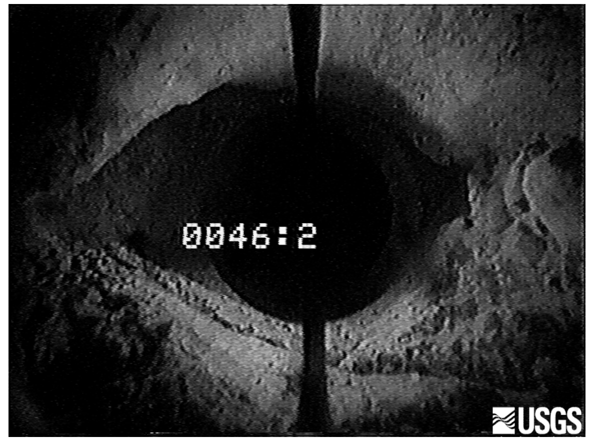
- Caliper
- Gamma
- Fluid resistivity
- Televiewers
- Temperature
- …

Well Drilling



Wireline Logging

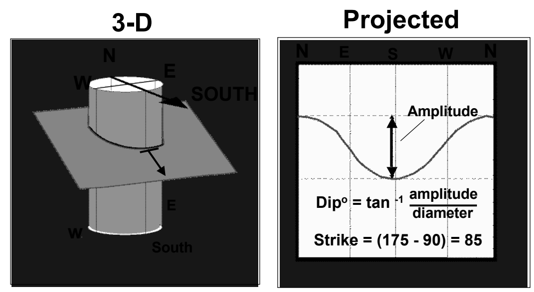




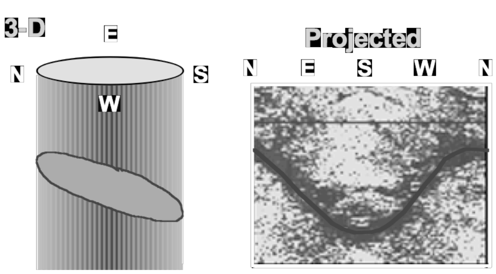
Optical Televiewers

- Oriented video image
- Air- and water- filled holes (clear)
- High resolution (0.1 - .5 mm)
- Fracture and structural orientations
- Borehole deviation
- Speed of logging 0.5 – .9 m/min
- Borehole diameters 66 – 210mm
- Virtual Core

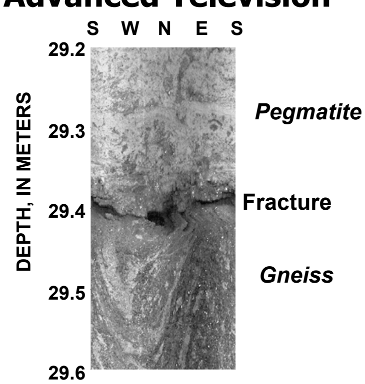
Borehole Imaging



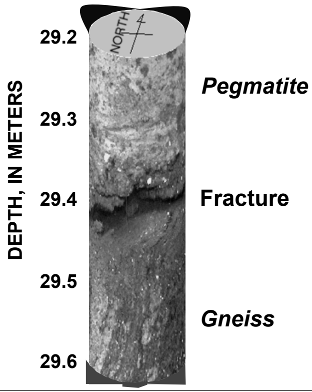
Borehole-Wall Imaging Planar Fracture



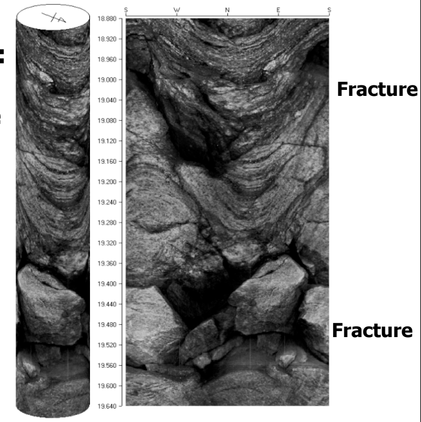
Advanced Television



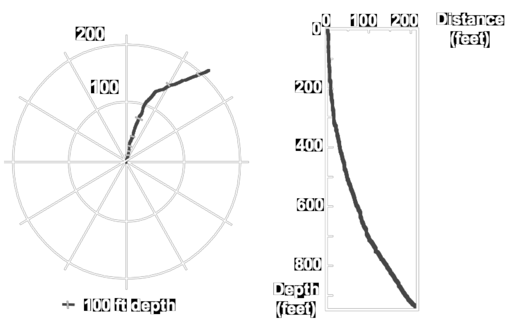
Virtual Core



Optical Televiewer: New Hampshire

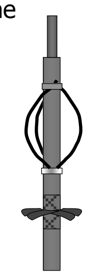


Borehole Deviation

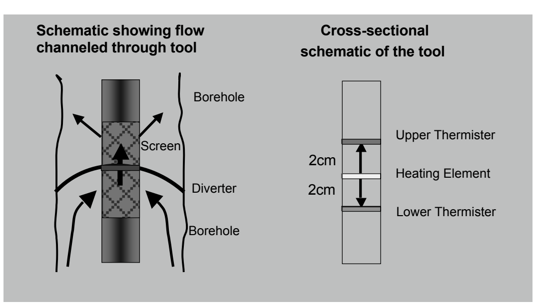


Flowmeters

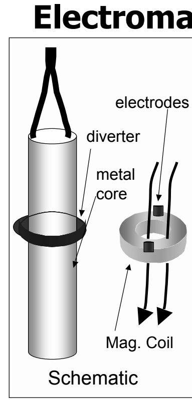
- Used to measure vertical flow in a borehole to characterize hydraulically active zone
- Three common types:
  - Impeller
  - Heat-pulse (0.01-1 gpm)
  - Electromagnetic (0.1-15 gpm)



Heat Pulse Flowmeter

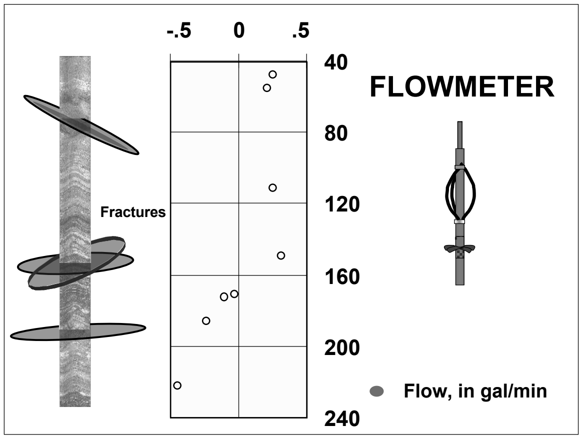


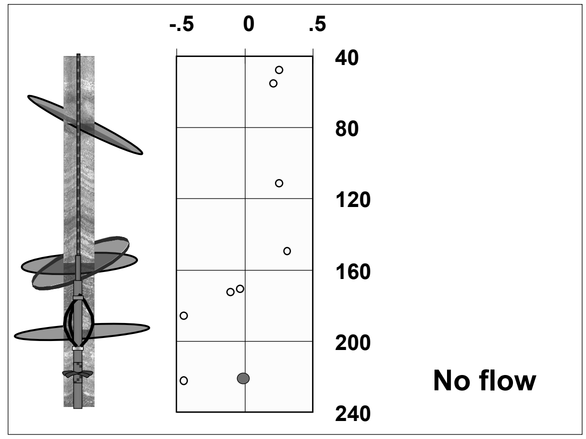
Electromagnetic Flowmeter

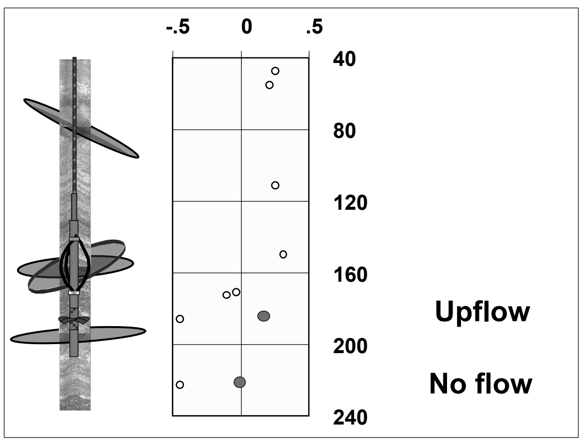


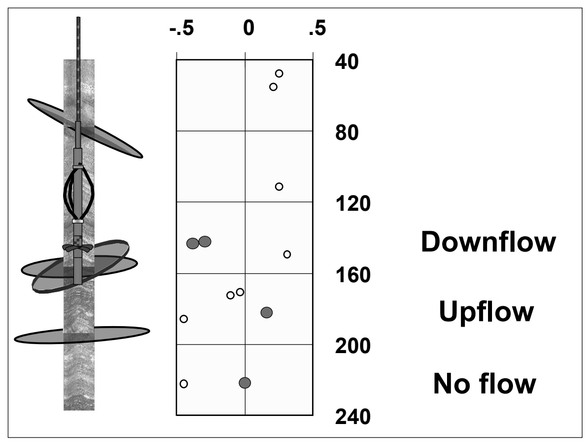
Consists of an electromagnet and 2 electrodes inside the hollow measurement chamber.

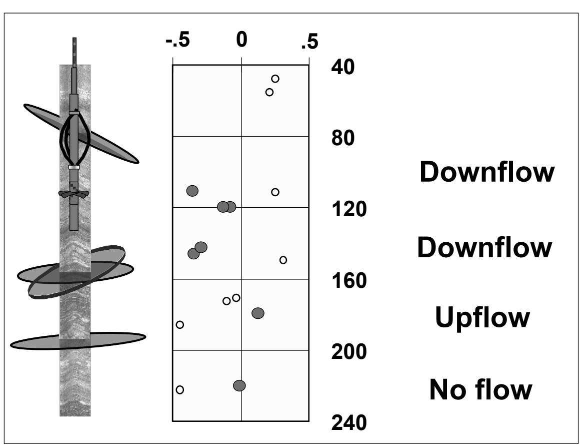
As water moves through the chamber (and the mag field), it induces a voltage proportional to the velocity.

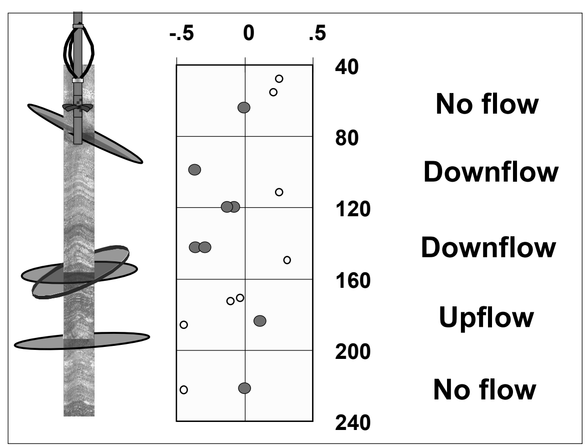

-.5
0
.5
40
80
120
160
200
240
FLOWMETER
Fractures
Flow, in gal/min


-.5
0
.5
40
80
120
160
200
240
No flow


-.5
0
.5
40
80
120
160
200
240
Upflow
No flow


-.5
0
.5
40
80
120
160
200
240
Downflow
Upflow
No flow


-.5
0
.5
40
80
120
160
200
240
Downflow
Downflow
Upflow
No flow

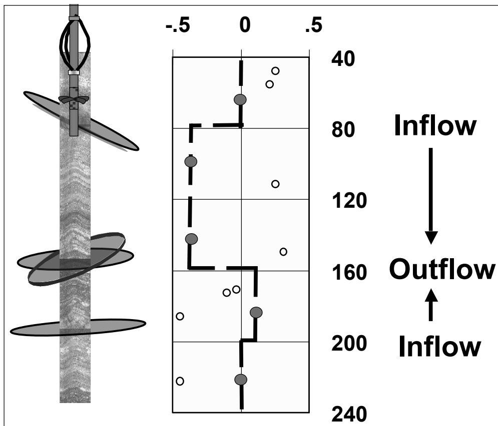

-.5
0
.5
40
80
120
160
200
240
No flow
Downflow
Downflow
Upflow
No flow

INTERPRETATION
of stationary measurement flowmeter data – ideal conditions

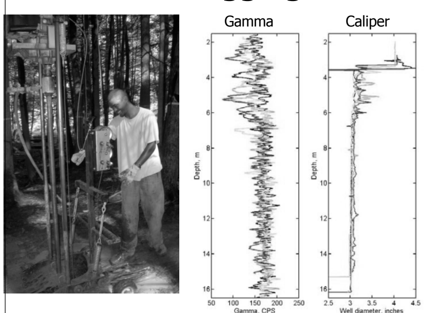
Step 1: Look for and delineate adjacent measurements with similar vertical flow rates

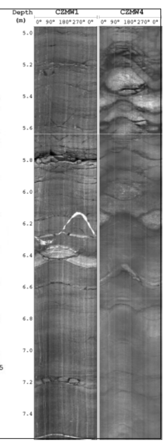
Step 2: Determine regions where there are changes in vertical flow rates – these are zones of inflow or outflow

Step 3: Associate inflow or outflow regions with fractures identified in the borehole



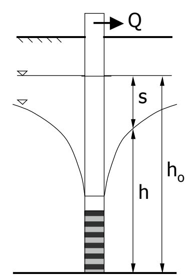
Borehole Logging at CZO



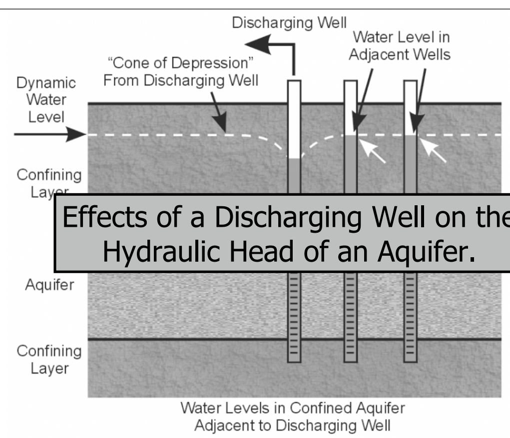


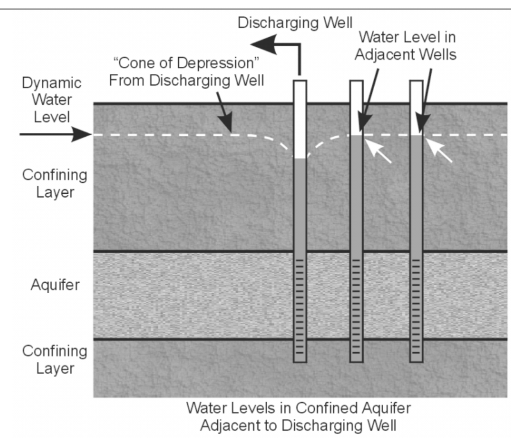
Preliminary wireline logs from the four new groundwater wells.
Segment of optical televiewer wellbore logs on right.

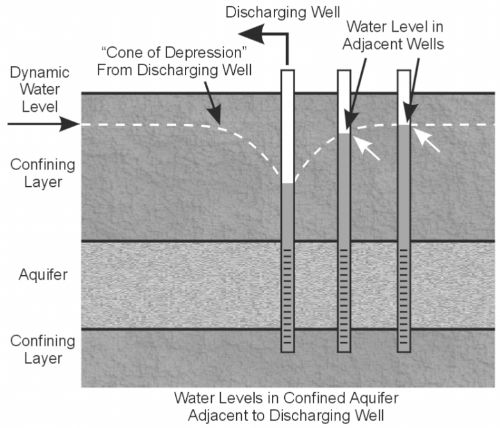
Pumping Well Terminology

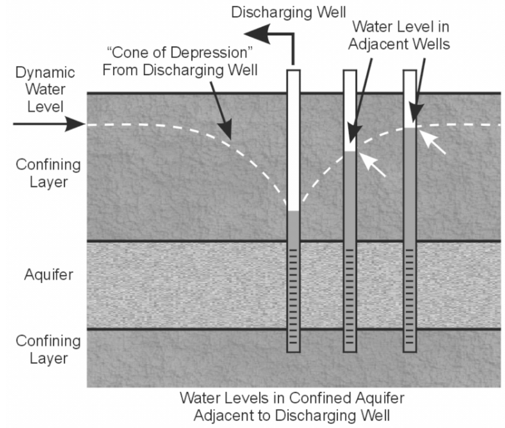


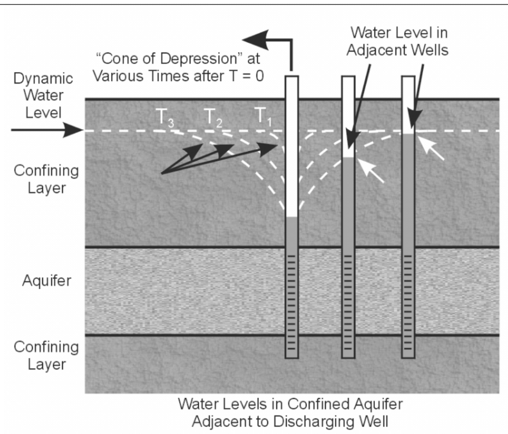
- Static Water Level (h_o) is the equilibrium water level before pumping commences
- Pumping Water Level (h) is the water level during pumping
- Drawdown (s = h_o - h) is the difference between SWL and PWL
- Well Yield (Q) is the volume of water pumped per unit time
- Specific Capacity (Q/s) is the yield per unit drawdown

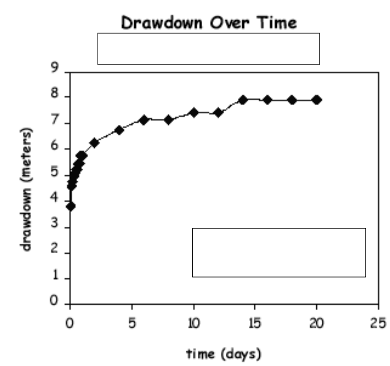




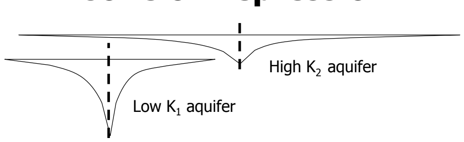








Cone of Depression



- A zone of low pressure is created centered on the pumping well
- Head gradient decreases away from the well and the pattern resembles an inverted cone called the cone of depression
- The cone expands over time until the inflows (from various boundaries) match the well extraction
- The shape of the equilibrium cone controlled by hydraulic conductivity

Potentiometric Surfaces & Surveying

Provided equipment that needs to come back with us:

- Meter tapes (4)
- Depth sounding strings (2)
- Electric water level indicators (4)
- Stadia rod
- Transit
- Compass

During this field trip, we will measure hydraulic heads. The learning goals of this exercise are that you:

1. Discern the difference between water level and hydraulic head, and how the latter must be used to determine direction of flow.
2. Learn to perform error analysis on replicate measurements.

POTENTIOMETRIC SURFACES

A fundamental skill in hydrogeology is accurately measuring and interpreting hydraulic heads in an observation well or piezometer. As you know, water flows from regions of higher potential to regions of lower potential (or high hydraulic head to low hydraulic head). Head is a combination of gravitational potential and pressure potential, and is reported as an equivalent height of a column of water:

$$H = \left(z + \frac{P}{\rho g} \right)$$

where H [L] is the hydraulic head, z [L] is the elevation of the measurement point above some datum, P [M/LT^2] is the pressure at the measurement point, ρ [M/L^3] is the density of water, and g [L/T^2] is the acceleration of gravity. Head is measured by determining the height to which water will rise in a well open to the aquifer; it is common practice to report head in terms of elevation above sea level.

As mentioned in class, we can create potentiometric surface maps for both unconfined and confined aquifers. In an unconfined aquifer, the water table is defined by atmospheric pressure, and denotes the hydraulic head in the aquifer. However, the head in a confined aquifer is at a higher elevation than the top of the aquifer, so the level of head forms an imaginary surface above the aquifer known as the "potentiometric surface" (Figure 1).

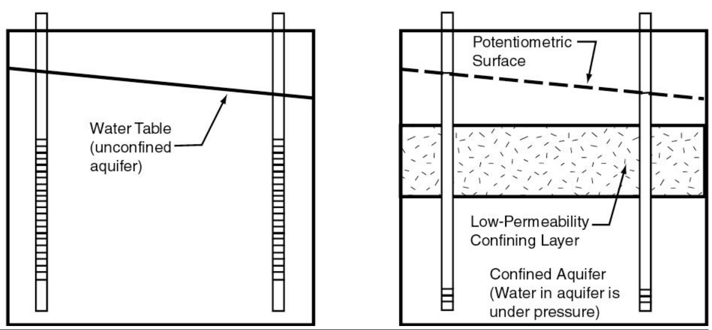


Figure 1: Unconfined and confined aquifers (from Fairley, U Idaho).

When a well has a significant length (or "screened interval") open to the aquifer, the water level in the well is an average of head for the entire screened interval. If the well has only a very limited screened interval (approximating a point) the well is known as a "piezometer", and the water level measured is the head at the open point (see Figure 2). Wells are generally open only at the screen. The bottoms are assumed to be sealed, although this may not be true in practice, particularly in hard rock, where screening may be omitted.

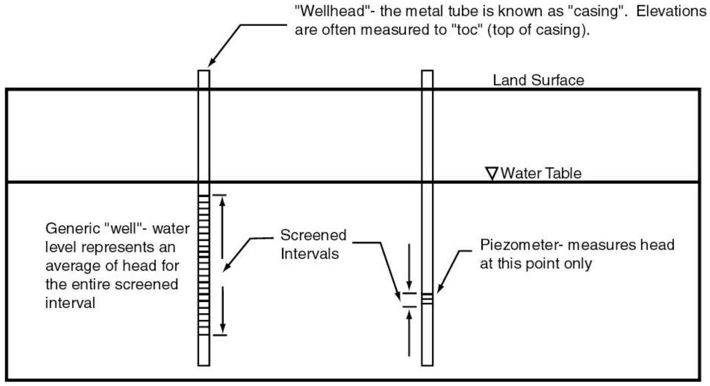


Figure 2: Monitoring wells and piezometers (from Fairley, U Idaho).

The benefit of a piezometer is that if there is a vertical component to the groundwater flow, there will be vertical differences in head, and this component can be measured with nested piezometers screened at different depths. Given the image below: by measuring head in the monitoring wells 1 and 4 (MW-1 and MW-4), shown in Figure 3, we can tell that groundwater is flowing from MW-1 towards MW-4. Also, the difference in head between the two nested piezometers, MW-2 and MW-3 indicates that water in the aquifer is actually flowing upward, as well as left to right.

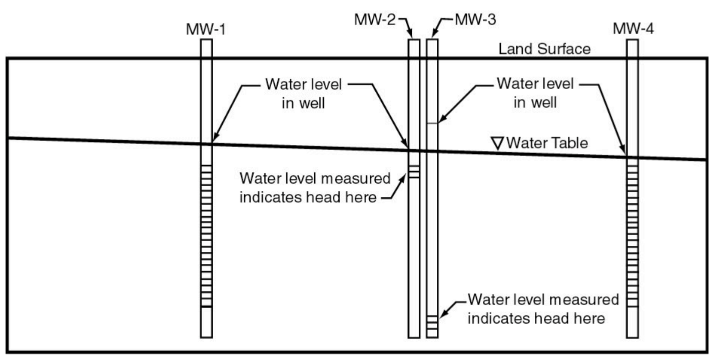


Figure 3: Measuring vertical and horizontal gradients (from Fairley, U Idaho).

Vertical and horizontal gradients often become important when working in multiple aquifer systems, because you may want to know if water is flowing from a deeper aquifer to a shallower aquifer, or the other way around. More importantly, if you measure head in several wells, and the wells are screened in different aquifers, you may not be able to make sense of the data (Figure 4). For this reason, make sure you know what intervals are screened in the wells you are taking measurements in, and understand how the screened intervals relate to the local geology and hydrologic units.

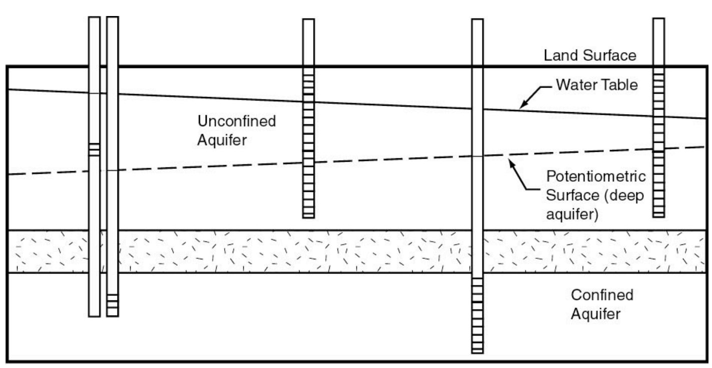


Figure 4: A multi-aquifer system (from Fairley, U Idaho).

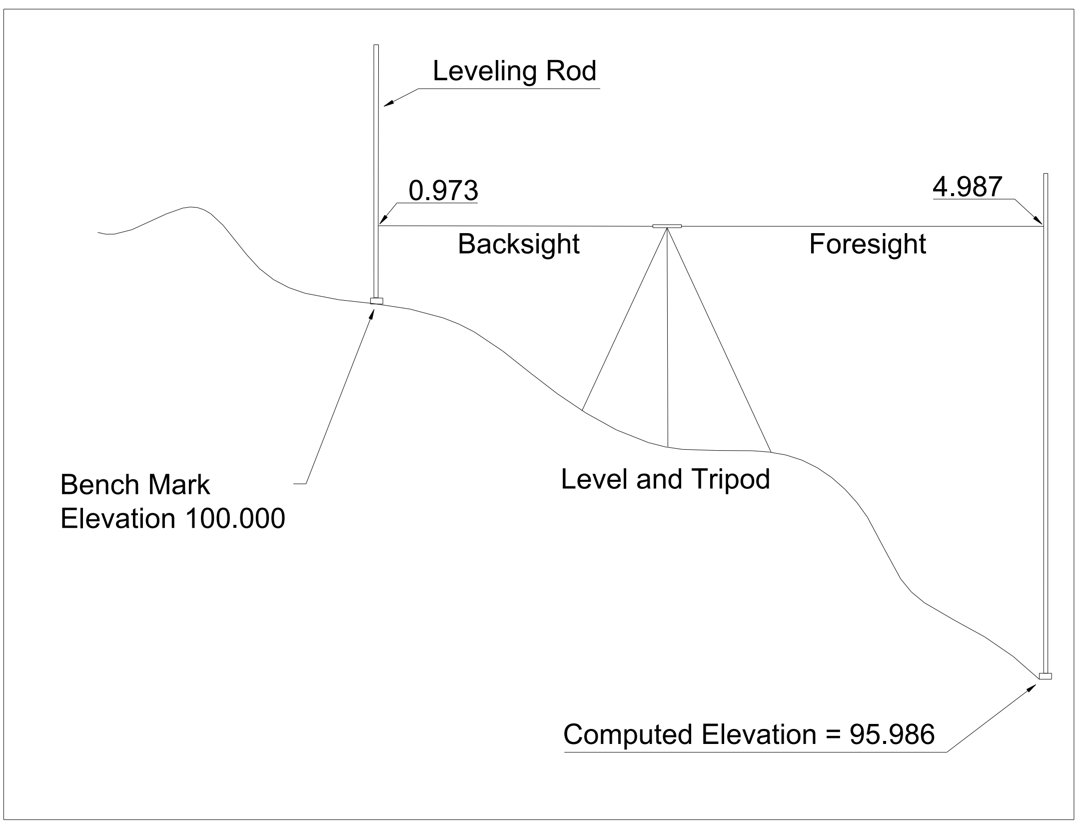
SURVEYING

In the field, you can easily measure the depth to water, but to convert this to hydraulic head, you need to know the relative elevation of the measuring points. To do so, you will need to survey in the wells you are using. We will need to consider three issues to survey wells accurately:

1. horizontal distance
2. difference in elevation
3. direction

Definitions

- Bench Mark (BM): An object that has a known elevation.
- Turning Point (TP): A fixed object used when determining the elevation of other points. Think of turning points as "stepping stones" in your level survey.
- Height of Instrument (HI): The elevation of the line of sight established by the instrument.
- Backsight (BS): The reading on the rod when held on a known or assumed elevation. Backsights are used to establish the height of instrument.
- Foresight (FS): The reading on the rod when held at a location where the elevation is to be determined. Foresights are used to establish the elevation at another location, often a turning point.



Calculations

For our leveling, we need to apply two very simple equations:

Height of Instrument = Known Elevation + Backsight
and
TP Elevation = Height of Instrument – Foresight

For the previous example:

Height of instrument = Known Elevation + Backsight
= 100.000 + 0.973
= 100.973

and

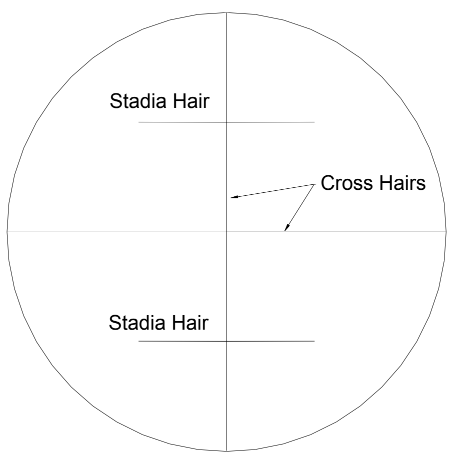
TP Elevation = Height of Instrument – Foresight
= 100.973 – 4.987
= 95.986

Records level surveys using the columns displayed below. The columns are typically labeled as: station, backsight (BS), height of instrument (HI), foresight (FS), and the last column contains the elevation values.

Station	BS (+)	HI	FS (-)	Elevation
BM				100.00
	0.973	100.973		
TP #1			4.987	95.986

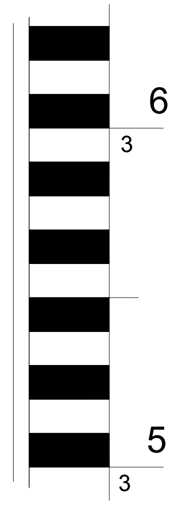
Arrangement of Cross Hairs

When you sight through the telescope, you will see a vertical and a horizontal cross hair and two horizontal stadia hairs.



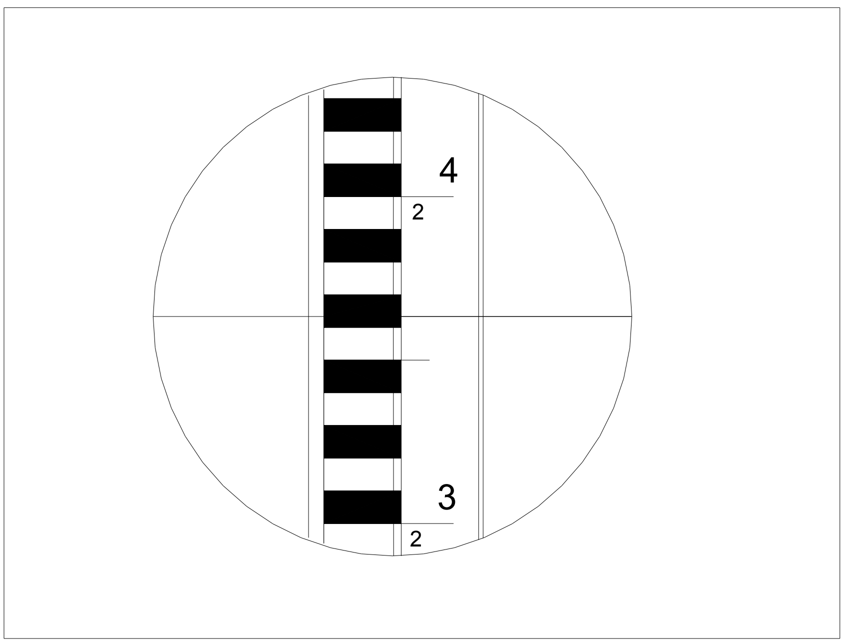
Reading the Rod

- Rod readings are taken using the center cross hairs.
- For now, ignore the presence of the stadia hairs.
- Rod readings are taken to three decimal places (the nearest millimeter).
- Rod readings can be read to two decimal places with certainty.
- Estimate the third decimal place

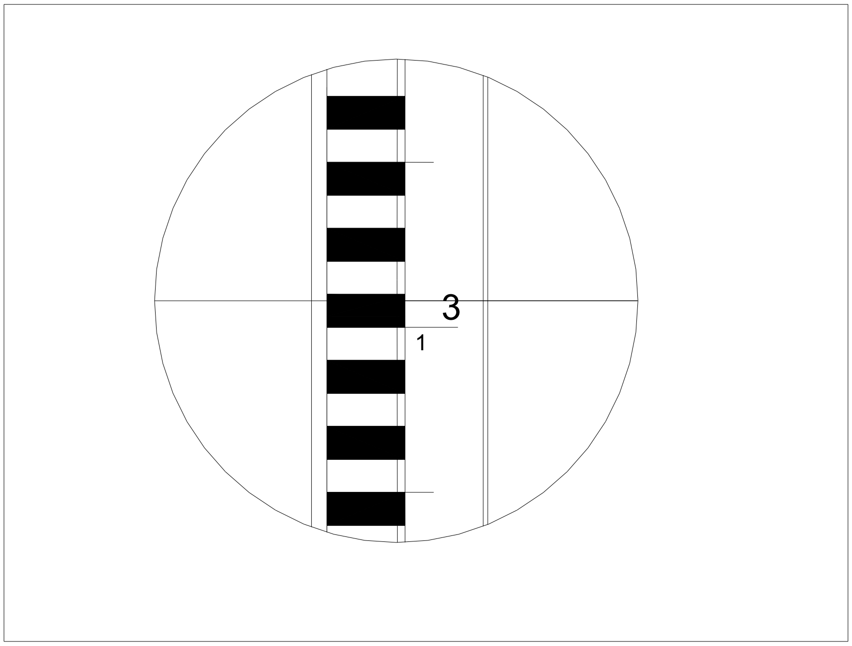


The rod is delineated to the nearest centimeter.

For instance, if you see this in your sights, you’re reading 2.363 m.



This would be 1.308 m. Get it?


3
1

The rod must be plumb to give a correct reading. No matter how much care is taken by the instrument person when reading the rod, if the rod is not perfectly vertical when read, errors will result.

Waving

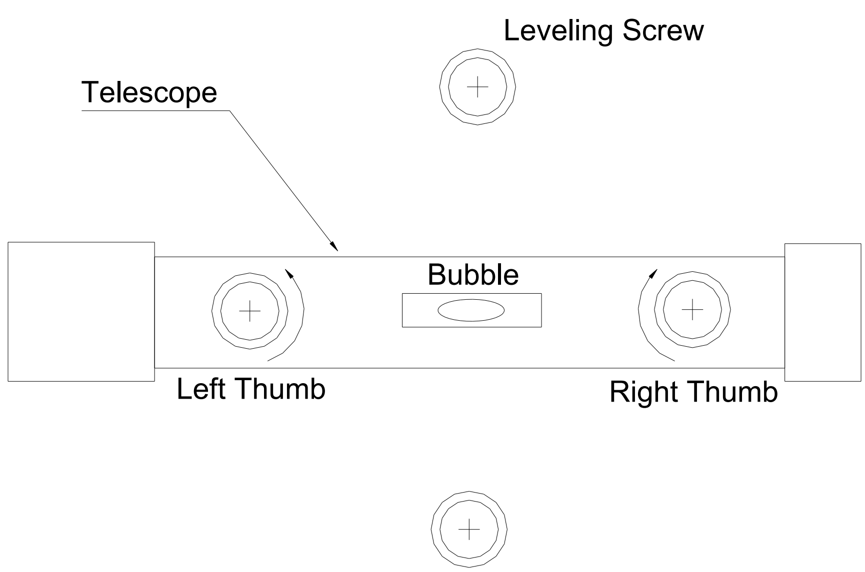
Waving is the procedure used to ensure that the rod is plumb when a reading is taken. The method consists of slowly rocking the top of the rod, back and forth. The instrument person continuously reads the rod and selects the lowest value.

Closure

For all differential leveling, it is good practice to close the leveling loop. Closing the loop is accomplished by returning to the original starting point. If we were to complete our level loop with complete accuracy, our computed final elevation would be exactly the same as the benchmark elevation used to initiate the survey. This comparison of the starting elevation and the computed ending elevation is termed closure. The accuracy of the survey can be easily determined by comparing the sum of the backsights with the sum of the foresights. They should be equal. Depending on the precision required, permissible values for the closure of a level loop can be specified.

Setting Up the Level

1) The legs of the tripod must be tightened securely.
2) The legs of the tripod should be firmly pressed into the ground with the tripod base plate roughly horizontal.
3) When leveling a four-screw level, the telescope is rotated until it is over two opposite screws as shown below.

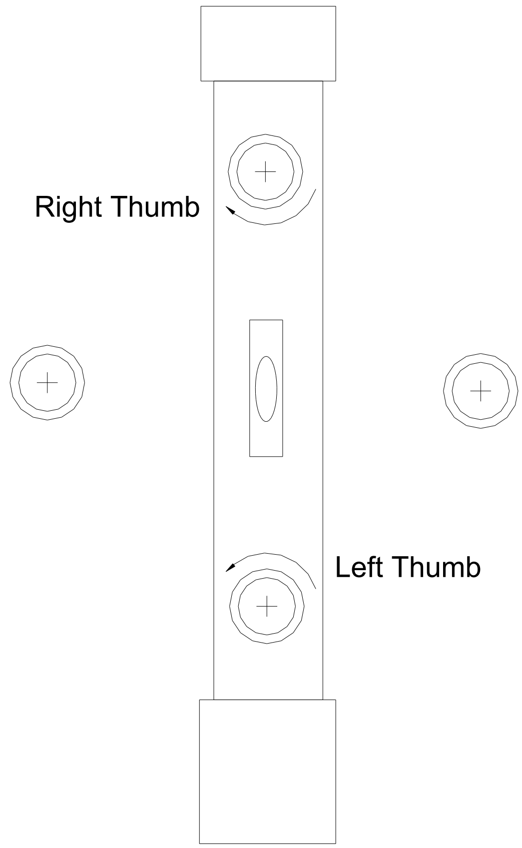


The telescope is leveled by using the thumb and first finger of both hands to adjust the leveling screws until the bubble is approximately centered.

Rule #1: The leveling screws are ALWAYS turned in opposite directions by equal amounts simultaneously. If one screw is rotated faster than the other, the screws will either bind or the telescope will loosen.

Rule #2: The left thumb rule: The leveling bubble will always move in the direction of your left thumb.

4) Rotate the telescope 90 degrees until it is located over the other two leveling screws as shown.



Again, level the telescope using the leveling screws.

5) When the scope is level, rotate the telescope another 90 degrees and make any minor adjustments to level the instrument.
6) Rotate the scope another 90 degrees and again, make any minor corrections as required.
7) Continue rotating and leveling the scope until the instrument is fully level along both axes.
8) As a final check, gently spin your telescope and allow it to come to rest, no matter what direction it faces. Examine your leveling bubble. It should be exactly centered. If it is not, repeat the entire leveling procedure.

Summary of Exercise:

1. Consider the four wells in the Shale Hills CZO. Upon locating the well, open it, and sound it (measure its depth).
2. Measure the relative elevation of the top of casing (the usual location from which water levels are measured) using the surveying gear (see instructions, above).
3. Measure the static depth to water from your benchmark.
4. Calculate the hydraulic head at each location given the above data.

Slug Tests & Pump Tests

Provided equipment that needs to come back with us:

- Meter tapes (4)
- Depth sounding strings (2)
- Electric water level indicators (4)
- Downwell pump
- Buckets for slug testing (2)
- Transducers (3)
- Stopwatches (7)

During this field trip, we will conduct slug and pump tests. The learning goals of this exercise are that you:

1. Determine two methods of estimating hydraulic conductivity in the field.
2. Observing changes in groundwater table as a result of pumping, and quantifying orders of magnitude of ground water flow velocities
3. Strengthen and develop mathematical skills by computing hydraulic conductivity using hand calculations and spreadsheet analysis.
4. Make #1-2 more meaningful by having you collect your own field data.
5. Learn to perform error analysis on replicate measurements.

SLUG TESTS

A slug test consists of the insertion or removal of a "slug" or known volume of water, or the displacement of water by a solid object. The displaced water causes a stress on the aquifer formation which is monitored through the change and recovery of the water level. An advantage of using slug tests is that estimates of hydraulic conductivity can be made in-situ, thereby avoiding errors incurred in laboratory testing of disturbed soil samples. Second, tests can be performed quickly at relatively low costs because pumping and observation wells are not required. Limitations to slug testing include: 1) only the hydraulic conductivity of the area immediately surrounding the well is estimated which may not be representative of the average hydraulic conductivity of the area, and 2) the storage coefficient, S, usually cannot be determined by this method.

If slug tests are used as part of site characterization, it is important that multiple slug tests be performed. The tests should be performed with replicates and in as many test or monitoring wells as feasible. One of the biggest advantages of slug tests over the pumping tests is that a large number of tests can be conducted in the amount of time and cost it takes for one pumping test. Therefore, these can be used to estimate the spatial variations in permeability at heterogeneous sites. A description of the theory and application of slug testing is provided in Fetter.

To conduct a slug test, determine the static water level in the well by measuring the depth to water periodically for several minutes and taking the average of the readings. After you have established the initial water level, introduce or remove a known volume or slug of water to the well (or introduce a solid cylinder of known volume to displace and raise the water level, allow the water level to restabilize and remove the cylinder). It is important to remove or add the volumes as quickly as possible because the analysis assumes an "instantaneous" change in volume is created in the well.

At the moment of volume addition or removal assigned time zero, measure and record the depth to water and the time at each reading. Depths should be measured to the nearest 0.01 foot (or meter, depending on the water level tape you're using). The number of depth-time measurements necessary to complete the test is variable. It is critical to make as many measurements as possible in the early part of the test. The number and intervals between measurements will be determined from earlier previous aquifer tests or evaluations.

Continue measuring and recording depth-time measurements until the water level returns to equilibrium conditions or a sufficient number of readings have been made to clearly show a trend on a semi-log plot of water level versus time. Note: The time required for a slug test to be completed is a function of the volume of the slug, the hydraulic conductivity of the formation and the type of well completion. The slug volume should be large enough that a sufficient number of water level measurements can be made before the water level returns to equilibrium conditions. The length of the test may range from less than a minute to several hours.

Summary of Exercise 1

1. Sound the well. How deep is it?
2. Measure the "static" depth to water from your benchmark, before any water is removed from the well (Figure 1)
3. Remove the beeper tape from the well.
4. Introduce a known volume of water instantaneously (or as close as possible) to the well.
5. Record water level recovery of the slug test data form (attached).
    a. make first measurement (H_0) as soon as possible after adding water to the borehole
    b. initially make frequent measurements, e.g., every 5 seconds
    c. when measurements at consecutive time steps differ by less than a few percent, double the time interval between measurements
    d. continue reading levels until about 2/3 of the initial drawdown has been recovered
6. Make a plot of the results in the field on both standard and semi-log paper. We'll look at these data back on campus.

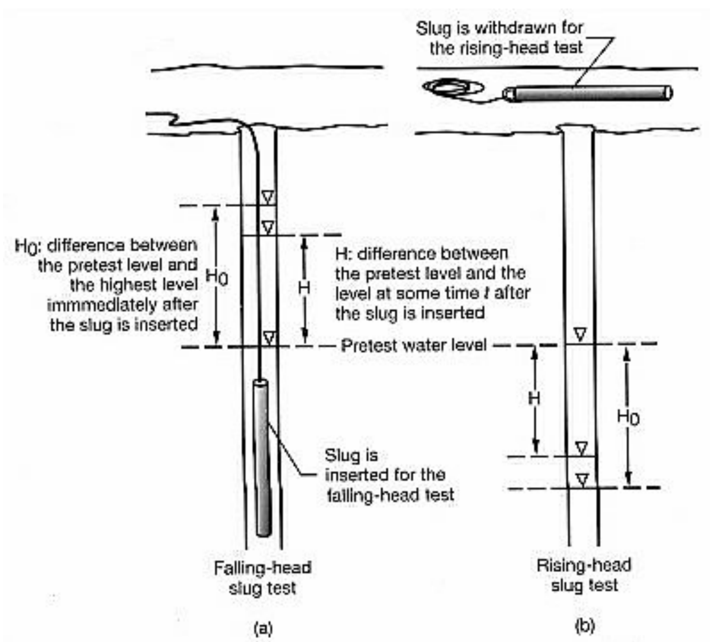


Figure 1: Cartoon of slug test geometries.

PUMPING TESTS

The most reliable type of aquifer test usually conducted is a pumping test. Although some site studies involve the use of short term slug tests to obtain estimates of hydraulic conductivity, these are usually only good for a specific zone or very limited portion of the aquifer. Slug tests provide limited information on the hydraulic properties of the aquifer and often produce estimates which are only accurate within an order of magnitude. In this exercise, we will determine some of the hydraulic characteristics of the material at the Shale Hills CZO using pumping tests, which we can compare to our slug test data. If we wanted to use water from this aquifer for irrigation or other purposes, we would need to know how much water is present, how deep the water lies, and whether or not the water would flow readily to a well. We can determine many of these factors by conducting a pump test, in which one well is pumped and the water level in other wells is monitored. We will use a series of four open wells which have been drilled to a depth of approximately 16 m, and are cased to ~3 m.

Conducting the pump test

Split into three smaller groups. Each group will monitor the water level in one of the observation wells. It is important to note the depth of the water table below the ground surface before starting the test. Drop the beeper tape into the water and determine the water level. Note the number on the worksheet (in centimeters) to the nearest mm.

After we begin to pump, each group will take readings of water table depth at one minute, two minutes, four minutes, and at two minute intervals thereafter. Fluctuations in pumping rate make the test analysis very difficult and raise questions as to whether deviations in the data are actually a result of flow boundaries or other hydrogeologic features. Control of the pumping rate during the test requires an accurate means for measuring the discharge of the pump and a convenient means of adjusting the rate to keep it as nearly constant as possible. Common methods of measuring well discharge include the use of an inline flow meter, or, for low discharge rates, observing the length of time taken for the discharging water to fill a container of known volume (e.g. 5 gallon bucket; 55 gallon drum).

While pumping, record the water level changes within the well as well as the discharge. We will pump for about 30 minutes and then allow the system to recover (continuing the readings) 90% of the way. **Water level measurements obtained during the recovery phase are of equal or greater importance than those collected during the pumping phase** because they can confirm any disturbances to flow. In addition, unlike the pumping phase where variation in discharge rate can affect the observations, the recovery phase is not subject to induced variations and can provide more reliable information. *Water level measurements made during the recovery phase of the aquifer after the pump has been turned off should be taken at the same frequency as the drawdown measurements during the pumping phase.* Do not remove the pump until the test is completely done, including the recovery phase. Measurements should commence immediately upon pump shut down and continue for the same duration as the pumping phase, or until the water levels have reached 95% of the initial, pre-pumping static water level. Record your data on the accompanying worksheet.

While two or three people in each group monitor the well during the drawdown phase, other people can convert the measured distance from the top of the pipe into depth of water table below the surface and begin to plot curves of drawdown versus time for that well. After pumping ceases, quickly calculate the total drawdown (in millimeters) and final saturated aquifer thicknesses (in meters, to two decimal places). Continue to plot drawdown versus time for the recovery phase. To determine the hydraulic conductivity of the aquifer below the field, you will need the calculation of the final saturated aquifer thicknesses from the nearest and furthest observation well, as shown on the accompanying worksheet. Many interesting results can be derived while still in the field. We will then calculate hydraulic conductivity (**bring a calculator!**) and draw some graphs of the drawdown.

<u>Conveyance of Pumped Water</u>: There is no hard-and-fast rule on how far the water produced during the pumping test should be discharged from the vicinity of the well. It is best to pipe the water outside of the area likely be influenced by the pumping test. The objective of conveying pumped water as far from the site as possible is to minimize the possibility of artificially recharging the aquifer and producing an erroneous pumping test or at least affecting the later stages of the test. This is particularly important when conducting pumping tests in shallow unconfined aquifer settings. Considerations for determining a suitable distance include:

- Is the aquifer confined? If so, less distance will be necessary.
- The duration of the pumping test: the shorter the test, the less distance necessary.
- Depth to water and nature of geologic materials overlying the water producing materials: the greater the depth to water, the less distance necessary; and, the more transmissive the aquifer materials, the greater distance necessary.
- If at all possible, do not discharge conveyed water between the pumping test well and any observation wells or any suspected flow boundaries.

Summary of Exercise 2

1. Sound the well. How deep is it?
2. Measure the "static" depth to water from your benchmark, before any water is removed from the well (Figure 1)
3. Remove the beeper tape from the well.
4. Measure water levels in observation wells, and measure distance from pumping well for each.
5. Start pump, carefully selecting discharge location. Measure discharge rate throughout the test. Also record water level change in pump test data form (attached).
    a. make first measurement as soon as possible after pump starts
    b. initially make frequent measurements, e.g., every 5 seconds
    c. when measurements at consecutive time steps differ by less than a few percent, double the time interval between measurements
    d. continue reading levels until drawdown stabilizes
6. Stop pump. Record water level change in recovery data form (attached).
    a. make first measurement as soon as possible after pump stops
    b. initially make frequent measurements, e.g., every 5 seconds
    c. when measurements at consecutive time steps differ by less than a few percent, double the time interval between measurements
    d. continue reading levels until drawdown stabilizes
7. Make a plot of the results in the field on both standard and semi-log paper. We'll look at these data in a few weeks.

SLUG TEST DATA COLLECTION FORM

Note: Collect WL measurements every 20 seconds for the first 5 minutes, then at 1 minute intervals for another 15 minutes, and finally at 2-4 min intervals from then on.

Well Name:	Conducted By:	Date:
Static Water Level (as measured from reference point):		
Well Elevation (MSL):		
Initial water level (note units):		

Time	Time (t) since pumping began (min)	Depth to Water Level (units?)	Drawdown (units?)	Comments		

PUMPING TEST DATA COLLECTION FORM

Note: Collect WL measurements every 20 seconds for the first 5 minutes, then at 1 minute intervals for another 15 minutes, and finally at 2-4 min intervals from then on.

Pumped Well Name:	Conducted By:	Date:
Static Water Level (as measured from reference point):		
Observation Well Name:		Well Elevation (MSL):
Distance of observation well (r) from pumped well (note units):		
Initial water level (note units):		

Time	**Time (t) since pumping began (min)**	**Depth to Water Level (units?)**	**Drawdown (units?)**	**t/r^2**	**Pumping Rate (Q) [gpm]**	**Comments**

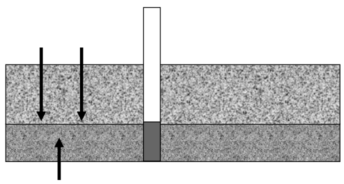
RECOVERY DATA COLLECTION FORM

Note: Collect WL measurements every 20 seconds for the first 5 minutes, then at 1 minute intervals for another 15 minutes, and finally at 2-4 min intervals from then on.

Pumped Well Name:		Conducted By:			Date:	
Static Water Level (as measured from reference point):					County:	
Observation Well Name:					Well Elevation (MSL):	
Distance of observation well (r) from pumped well (note units):						
Time	**Time (t) since pumping began (min)**	**Time (t') since pumping stopped (min)**	**t/t'**	**Depth to Water Level (units?)**	**Residual Drawdown (units?)**	**Comments**

Storage and the GWFE

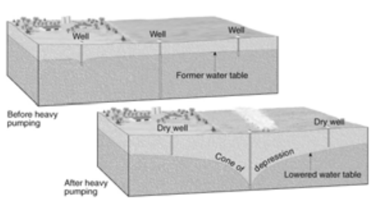
- **Outline:**
  - **Specific yield**
  - **Specific storage**



So What?

- **Aquifers are defined by transmission and storage characteristics**
- **Transmission: permeability/hydraulic conductivity**
- **Storage: for unconfined, we have specific yield. For confined: ???**

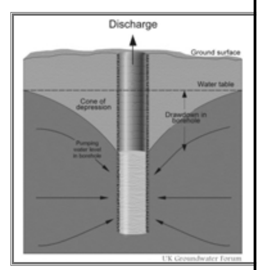
What happens when you pump from an unconfined aquifer?



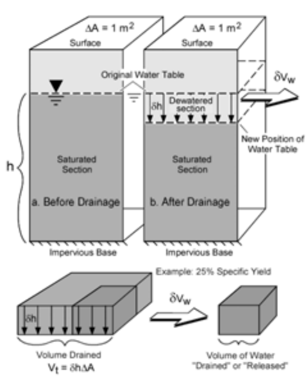
You empty pore space of water, draw down water table around the well

Recall

- Water comes from drainage of the pores
- Specific yield (S_y, dimensionless): volume of pores per unit volume that drain under the action of gravity alone
- Water that remains is "specific retention" (S_r)



$$n = S_y + S_r$$

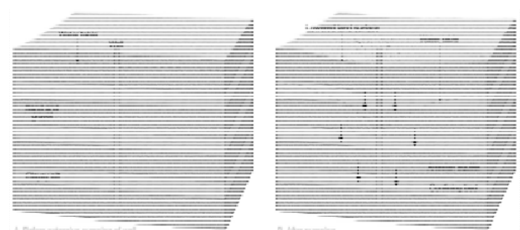


$$dV_w = A(-dh)\cdot S_y$$

$$S_y = -\frac{dV_w}{Adh}$$

volume of water that an aquifer will absorb or expel per unit surface area per unit change in head

What happens when you pump from a confined aquifer?

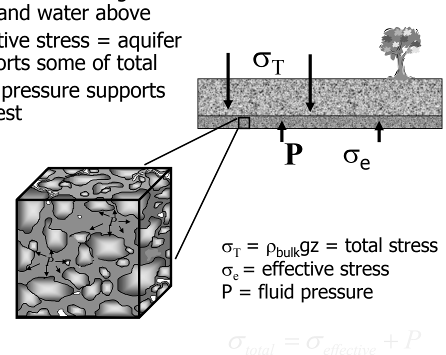


Water pumped from a confined aquifer is coming from expansion of water and compression of aquifer materials→subsidence!!!!

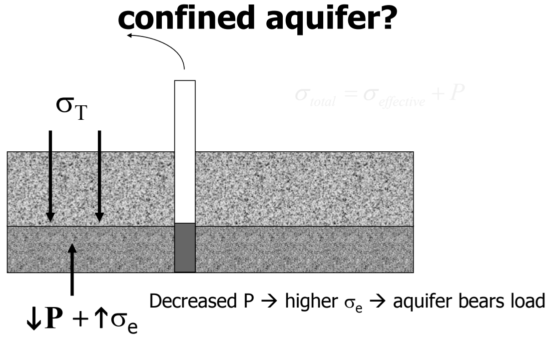
Water Release Mechanisms from a Confined Aquifer

- Aquifer remains saturated!
- Fluid expansion due to decrease in fluid pressure.
- Reduction in *n* (porosity) due to an increase in σ_e (effective stress).

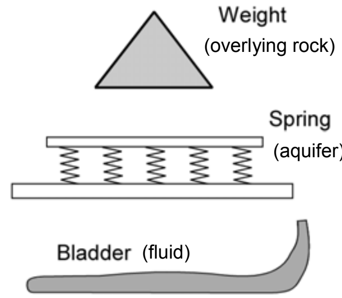
- Total stress = weight of rock and water above
- Effective stress = aquifer supports some of total
- Fluid pressure supports the rest



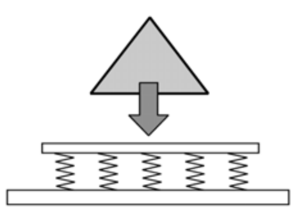
What happens when you pump a confined aquifer?

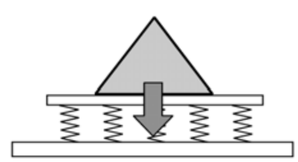


Illustrating Effective Stress another way.

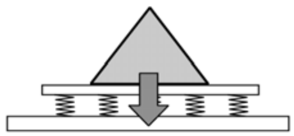


Place weight on platform.



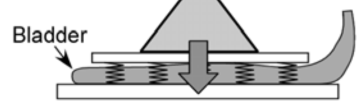


Springs compress.

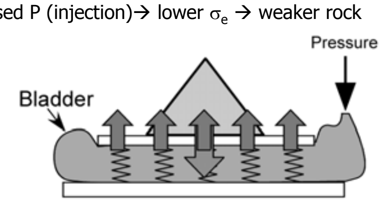


Insert bladder.

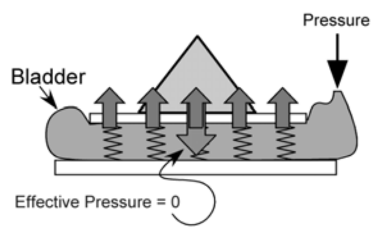
$$\sigma_{total} = \sigma_{effective} + P$$



Pump up bladder (inject water INTO aquifer).
Total stress doesn't change! (weight is the same)
Increased P (injection)→ lower σ_e → weaker rock



$$\sigma_{total} = \sigma_{effective} + P$$

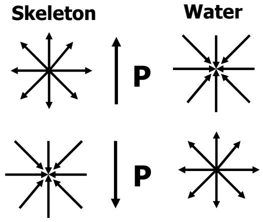


Confined aquifers are like a tire

Skeleton **Water**

If pressure increases,
Mineral skeleton will expand
Water will contract

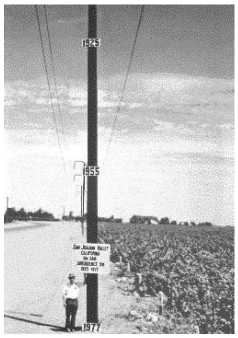
If pressure drops,
Mineral skeleton will contract
Water will expand



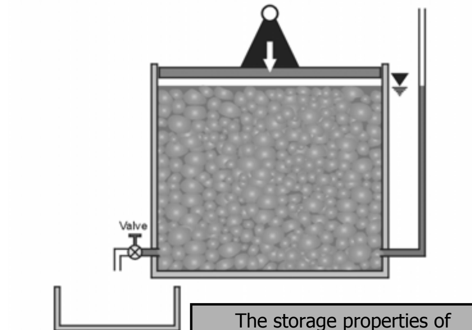
When Pumping Pressure decreases → Expansion of Water; → Compaction of the Aquifer Skeleton

- Groundwater pumping reduces P, but σ_T remains constant.
- σ_e must increase which leads to consolidation and land subsidence.
- Need to measure aquifer and fluid compressibilities to estimate potential for land subsidence and aquifer storage capacity.

Land subsidence in San Joaquin Valley (CA).
Approximate altitude of land surface
in 1925, 1955, 1977 (USGS).

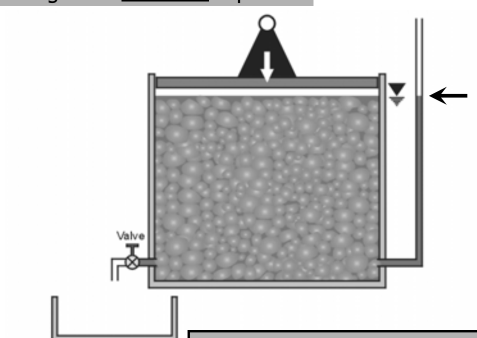


Storage in a Confined Aquifer



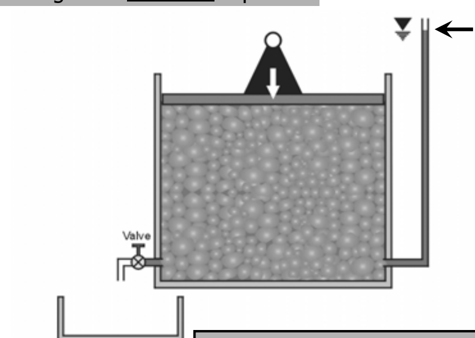
The storage properties of confined aquifers are usually dominated by elastic effects.

Storage in a Confined Aquifer



We "pressurize" the "aquifer".

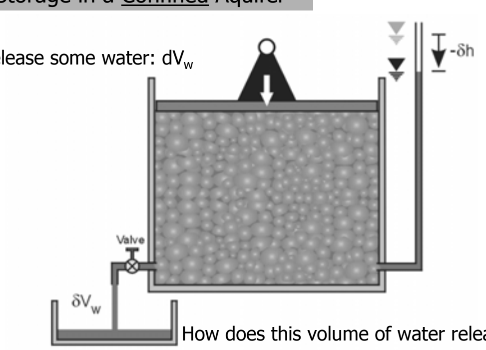
Storage in a Confined Aquifer



We "pressurize" the "aquifer".

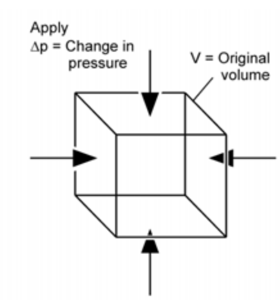
Storage in a Confined Aquifer

Release some water: dV_w



How does this volume of water released relate to compressibility and storage?

What happens when we compress this cube of water?



The volume will change by an amount ΔV given by

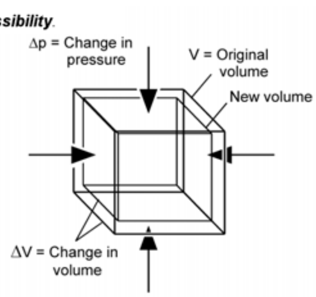
$$\Delta V = -\text{Constant} \cdot V \cdot \Delta p$$

In differential form

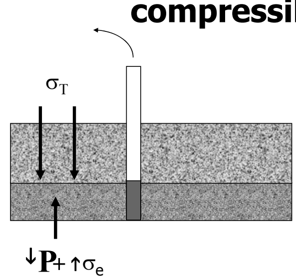
$$dV/dp = -\text{Constant} \cdot V$$

where Constant = β, the ***compressibility***.

$$\beta = -\frac{\Delta V_w / V_w}{\Delta P}$$



Amount of water is a function of compressibilities



$$\beta = -\frac{\Delta V_w / V_w}{\Delta P}$$

$\beta = 4.6 \times 10^{-10}$ m²/N

$$\alpha = -\frac{\Delta V_T / V_T}{\Delta \sigma_e}$$

α of clay > sand > rocks

Storage is dependent on compressibilities

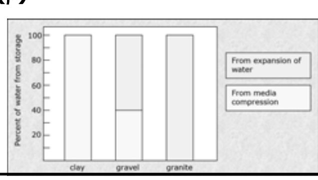
α = compressibility of aquifer skeleton
n = porosity
b = thickness
β = compressibility of water

- Units of compressibility: 1/pressure (1/Pascals, ft²/lb)

What contributes more to storage, compressibility of water or compressibility of matrix?

Compressibility of Materials

Clay	**10^{-6} to 10^{-8}**	**($m^2\ N^{-1}$)**
Sand	**10^{-7} to 10^{-9}**	
Gravel	**10^{-8} to 10^{-10}**	
Hard Rock	**10^{-9} to 10^{-11}**	
Water (β)	**4.6×10^{-10}**	



It depends.

To the board!

Storage

- If aquifer were rigid (α=0): water given up would be entirely due to expansion of water
  $\beta n \rho_w g$ units: (L^2 M) / (M L^3) = 1/L
- If water were rigid (β=0): water given up would be entirely due to compression of aquifer
  $\alpha \rho_w g$ units: (L^2 M) / (M L^3) = 1/L

The sum of these define the available storage, called "specific storage":

What defines the storage coefficient?

The storage coefficient (S) consists of two components:

- pore fluid draining of the aquifer
- water released from compressibility (elasticity) of aquifer

$$S = S_y + S_s b$$

S_y = specific yield
Ss = specific storage (1/L)
b = saturated thickness (L)

So what defines storage for an unconfined aquifer?

For unconfined aquifers, most of the water is from draining; the contribution from compressibility is very small in comparison

$$S = S_y + S_s b$$

usually, $S_y >> S_s b$

S ~ Sy

S_y = specific yield
Ss = specific storage (1/L)
b = saturated thickness (L)

S = 0.02 to 0.30

So what defines storage for a confined aquifer?

For confined aquifers, there is no draining of the pores, so all storage comes from the elastic component

$$S = S_y + S_s b$$

$S = S_s b$

S_y = specific yield
Ss = specific storage (1/L)
b = saturated thickness (L)

S < 0.005

To clarify:

- Specific storage (Ss): volume of water that an aquifer will absorb or expel per unit volume per unit change in head—an elastic storage coefficient [units: 1/L]

$$S_s = \frac{V_w}{V_T \Delta h}$$

- (Note difference to storativity: volume of water that an aquifer will absorb or expel per unit surface area per unit change in head [units: -])

$$S = \frac{V_w}{A \Delta h}$$

What is the total volume removed?

- For an unconfined aquifer:
- For a confined aquifer:

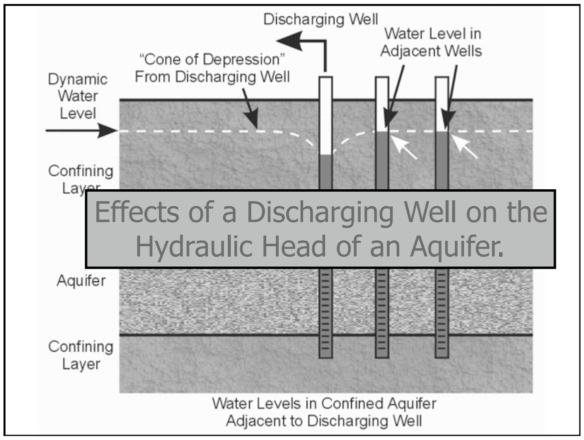
$$V_w = SA\Delta h$$

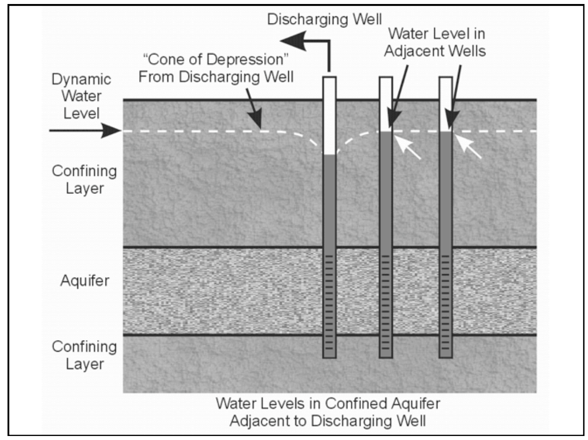
storativity, aka storage coefficient

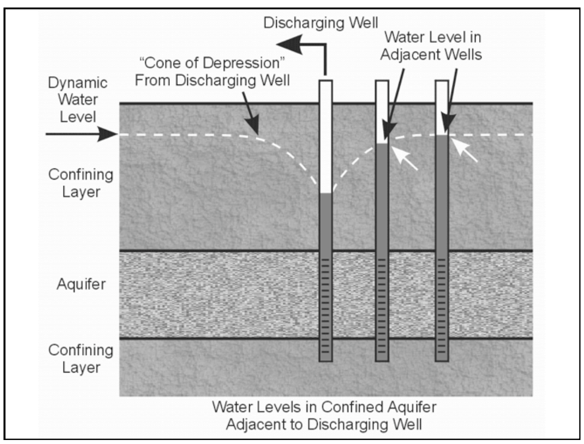
Per unit change in head, why do unconfined aquifers yield more water than confined aquifers?

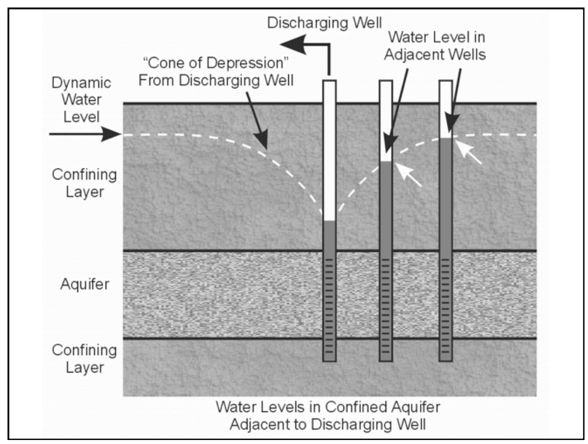
$$V_w = SA\Delta h$$

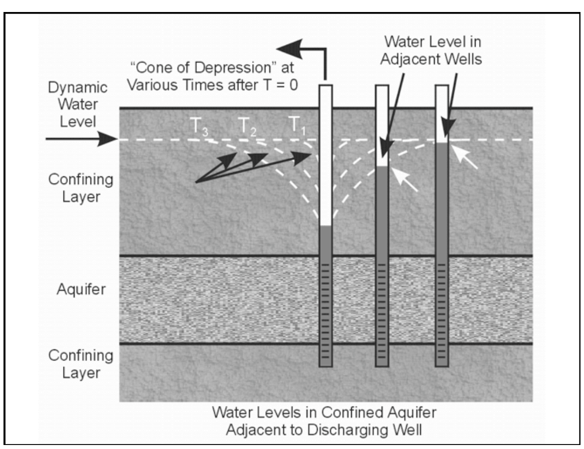
Confined Aquifers	**S < 0.005**
Unconfined Aquifers	**S = 0.02 – 0.30**

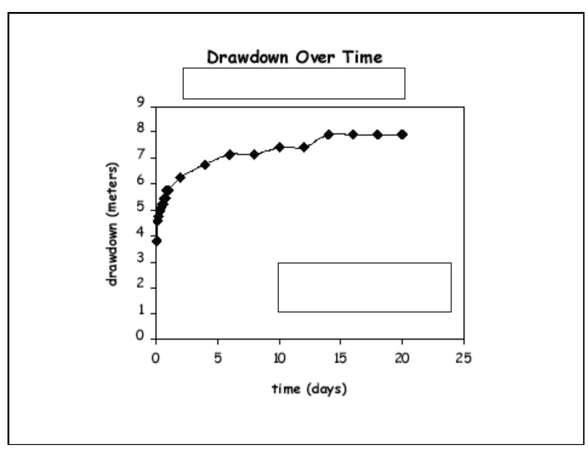

Effects of a Discharging Well on the Hydraulic Head of an Aquifer.
Discharging Well
Water Level in Adjacent Wells
"Cone of Depression" From Discharging Well
Dynamic Water Level
Confining Layer
Aquifer
Confining Layer
Water Levels in Confined Aquifer Adjacent to Discharging Well


Discharging Well
Water Level in Adjacent Wells
"Cone of Depression" From Discharging Well
Dynamic Water Level
Confining Layer
Aquifer
Confining Layer
Water Levels in Confined Aquifer Adjacent to Discharging Well

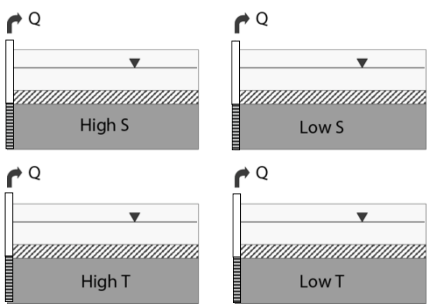

Discharging Well
Water Level in Adjacent Wells
"Cone of Depression" From Discharging Well
Dynamic Water Level
Confining Layer
Aquifer
Confining Layer
Water Levels in Confined Aquifer Adjacent to Discharging Well


Discharging Well
Water Level in Adjacent Wells
"Cone of Depression" From Discharging Well
Dynamic Water Level
Confining Layer
Aquifer
Confining Layer
Water Levels in Confined Aquifer Adjacent to Discharging Well


Water Level in Adjacent Wells
"Cone of Depression" at Various Times after T = 0
Dynamic Water Level
T3
T2
T1
Confining Layer
Aquifer
Confining Layer
Water Levels in Confined Aquifer Adjacent to Discharging Well


Drawdown Over Time
drawdown (meters)
time (days)
0
1
2
3
4
5
6
7
8
9
0
5
10
15
20
25

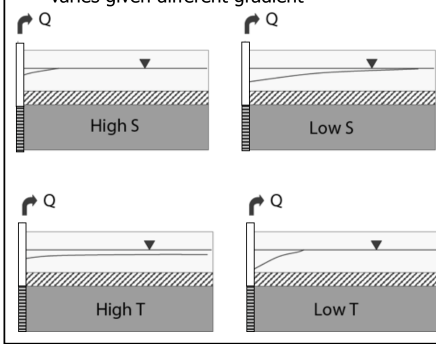
- Sketch the relative drawdown cones for the cases below 2min
- Pair up with a partner, compare your sketches to discuss differences and try to come to a consensus 3min



Same T, Q, t

Same S, Q, t

- Different S yields different volume drawdown cones
- Different T yields different gradient at well bore
- Same S yields same volume drawdown cone but shape varies given different gradient



Steady state:
- T differences persist
- S differences do not

Assumptions of Pumping Tests

- Aquifer is homogeneous, isotropic, areally infinite
- K (or T) is constant in space and time
- Darcy's Law is valid
- Well has infinitesimal diameter
- Water removed from storage is discharged instantaneously with decline in head
- Pumping well fully screened (receives water from the entire thickness of the aquifer)

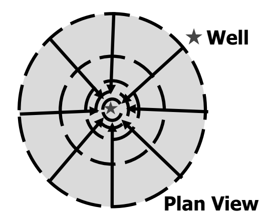
Transient Solution: The Theis Equation

equation, and the given initial and boundary conditions, the drawdown is given by:

$$s = h_o - h = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-u}}{u}du$$

where

$$u = \frac{r^2 S}{4Tt}$$



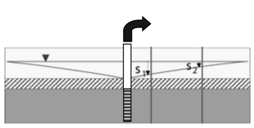
This exponential integral can be approximated by an infinite series

---

The Theis Equation

$$\int_u^\infty \frac{e^{-u}}{u}du = W(u) = -0.5772 - \ln(u) + u - \frac{u^2}{2\cdot 2!} + \frac{u^3}{3\cdot 3!} - \frac{u^4}{4\cdot 4!} + \ldots$$

the "well function"



$$s = h_o - h = \frac{Q}{4\pi T}W(u)$$

$$u = \frac{r^2 S}{4Tt}$$

s = drawdown [L]
h_0 = initial head at r [L]
h = head at r at time t [L]

r = distance from pumping well [L]
T = transmissivity [L^2/T]
Q = discharge from pumped well [L^3/T]
S = storativity [-]

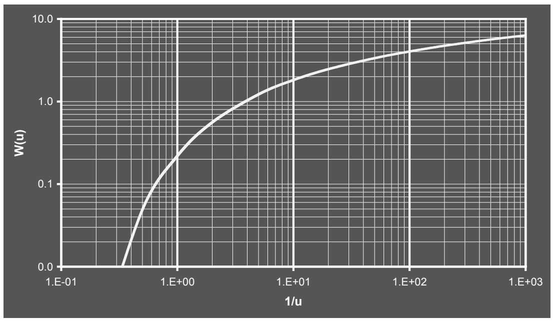
Table 1. Values of the Well Function W(u) for Values of u

u	W(u)	u	W(u)	u	W(u)	u	W(u)
1×10^{-10}	22.45	7×10^{-8}	15.90	4×10^{-5}	9.55	1×10^{-2}	4.04
2	21.76	8	15.76	5	9.33	2	3.35
3	21.35	9	15.65	6	9.14	3	2.96
4	21.06	1×10^{-7}	15.54	7	8.99	4	2.68
5	20.84	2	14.85	8	8.86	5	2.47
6	20.66	3	14.44	9	8.74	6	2.30
7	20.50	4	14.15	1×10^{-4}	8.63	7	2.15
8	20.37	5	13.93	2	7.94	8	2.03
9	20.25	6	13.75	3	7.53	9	1.92
1×10^{-9}	20.15	7	13.60	4	7.25	1×10^{-1}	1.823
2	19.45	8	13.46	5	7.02	2	1.223
3	19.05	9	13.34	6	6.84	3	0.906
4	18.76	1×10^{-6}	13.24	7	6.69	4	0.702
5	18.54	2	12.55	8	6.55	5	0.560
6	18.35	3	12.14	9	6.44	6	0.454
7	18.20	4	11.85	1×10^{-3}	6.33	7	0.374
8	18.07	5	11.63	2	5.64	8	0.311
9	17.95	6	11.45	3	5.23	9	0.260
1×10^{-8}	17.84	7	11.29	4	4.95	1×10^{0}	0.219
2	17.15	8	11.16	5	4.73	2	0.049
3	16.74	9	11.04	6	4.54	3	0.013
4	16.46	1×10^{-5}	10.94	7	4.39	4	0.004
5	16.23	2	10.24	8	4.26	5	0.001
6	16.05	3	9.84	9	4.14		

Source: Adapted from L. K. Wenzel, *Methods for Determining Permeability of Water-Bearing Materials with Special Reference to Discharging Well Methods*. U.S. Geological Survey Water-Supply Paper 887, 1942.

See Appendix 1 in Fetter text for W(u)

Type Curve : 1/u vs W(u)



How do we find T and S from s?

- of drawdown: 2 unknowns, 1 equation
- Consequently, we use curve matching techniques
- Type curve is W(u) vs u OR W(u) vs 1/u
- Plot field data as s vs 1/t or s vs r^2/t or s vs t
- Type curve & field data must be plotted on same log-log paper
- Field curve is overlaid on type curve
- Axes must be kept parallel
- Best match of curves is found
- Pick any convenient point
- Read corresponding W(u), u, s and r2/t (or t, 1/t)
- Solve Theis Equation for T & S

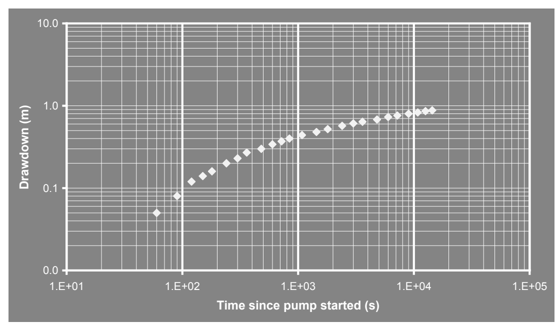
$$s = h_o - h = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{r^2 S}{4Tt}$$

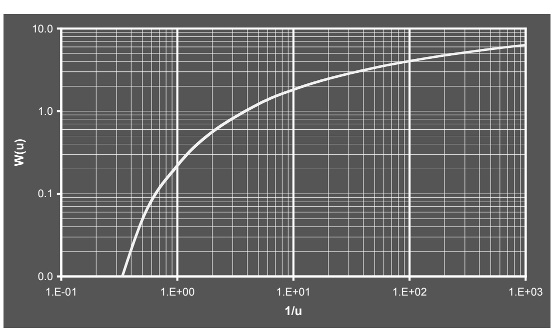
Example Problem

- at a rate of 10 gpm (55 m^3/d) for 3 hours. The aquifer is 15 m thick and the observation well is 120 m from the pumping well. Find T, K, and S.

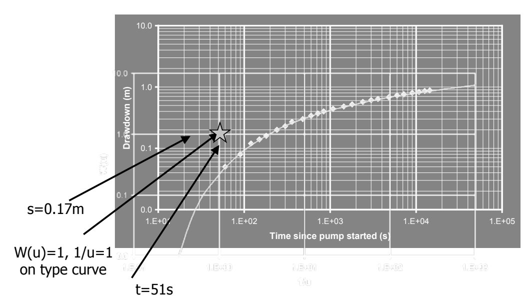
Data: Log(s) vs Log(t)



Type Curve : 1/u vs W(u)



Theis Curve Matching



Calculations

- Recall Q = 55 m^3/d, r = 120 m.
- Match point values are
  - W(u) = 1,
  - 1/u = 1
  - s = 0.17 m, and
  - t = 51 seconds

$$s = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{r^2 S}{4Tt}$$

Take 1 minute to do the calculations…

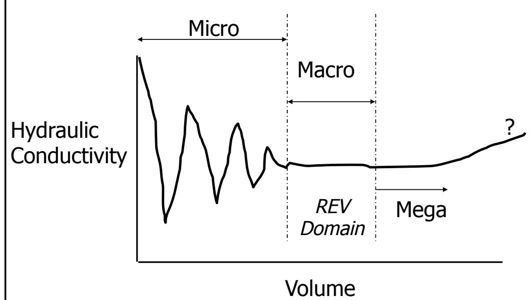
Values of T, K, and S are

- T = 26 m^2/d
- K = T/b = 1.7 m/d
- S = 1.1 x 10^{-6}

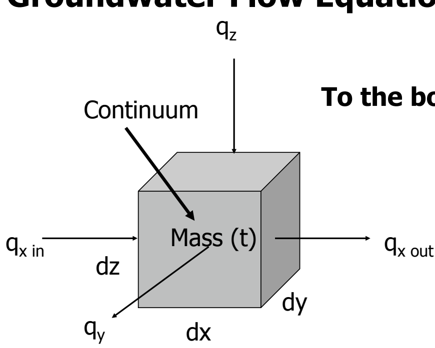
So What?

- storage properties
- The problem: Darcy's law tells us nothing about variations in time, storage
- How do we predict flow in the real world?
- The groundwater flow equation…

Darcy is a macroscopic law



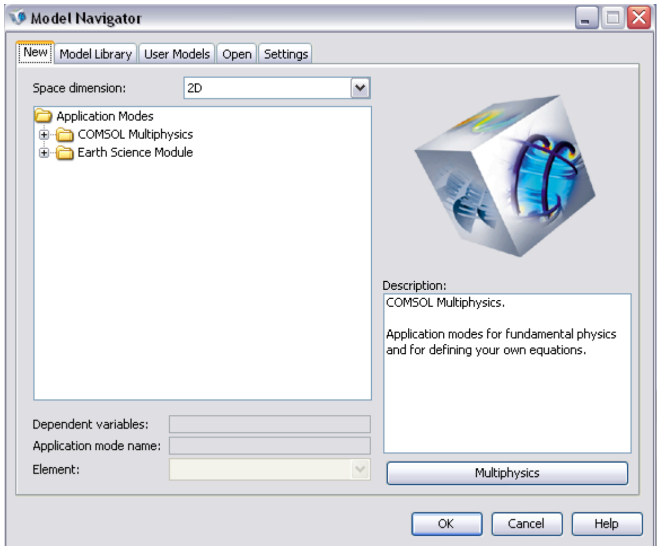
Groundwater Flow Equation



To the board!

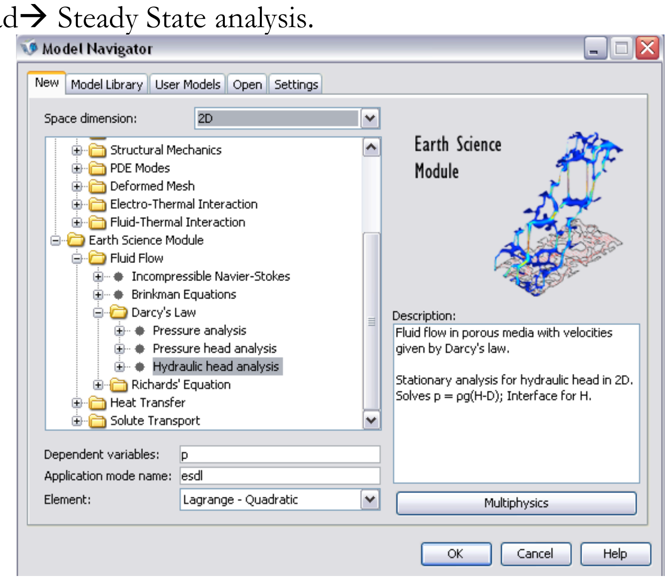
An Introduction to Numerical Modeling with COMSOL

Today you'll build your first numerical model of flow and transport from scratch. We'll put together what we've learned in class about the groundwater and advective-dispersive equations with our conceptual understanding of these processes from flownets and the Ogata equation. For instance, we know from flownets that to solve a differential equation, we need to know WHAT equation we're solving and the boundary conditions. For transient models, we also need to know the parameters controlling flow (like the hydraulic conductivity). To start, click on the COMSOL Multiphysics shortcut under Start → Programs. The Model Navigator will open:

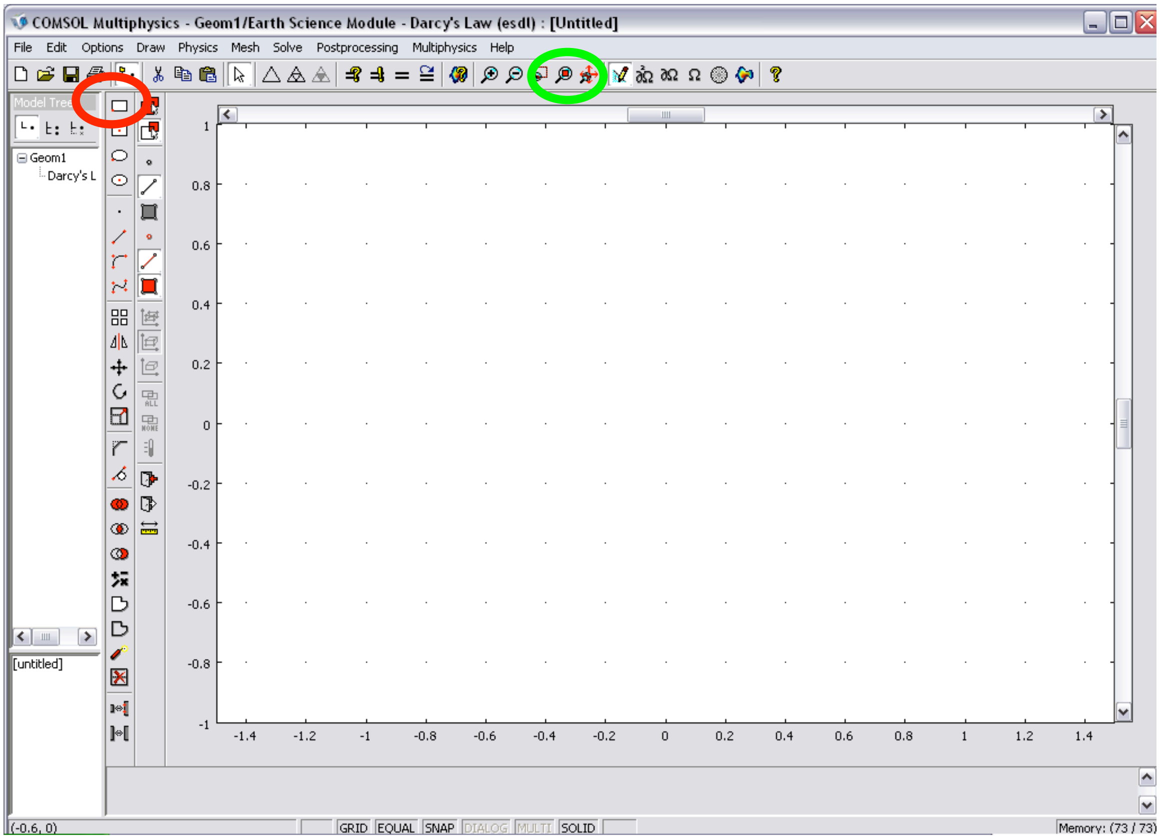


1. MODELING FLOW

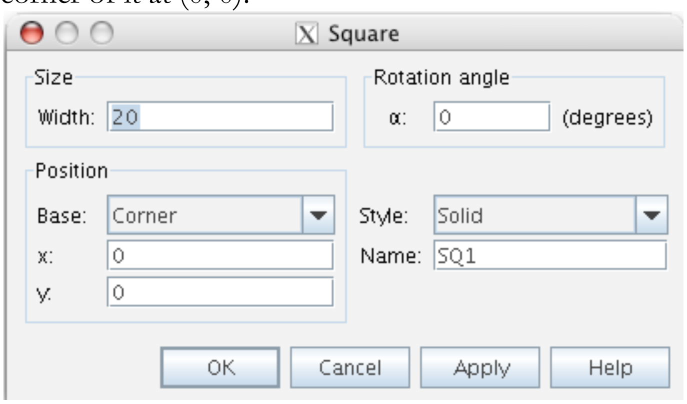
From here, choose the New tab, and make sure the space dimensions are set to 2-D. We will be creating map view models today. You'll now select your Application Mode. Under the Earth Science Module, choose Fluid Flow → Darcy's Law → Hydraulic Head → Steady State analysis.



Hit OK. SI units (kg, m, s) are the default values. From here, the Default Window will open, showing the Drawing Environment. Click the Rectangle tool (circled in red) to draw your domain; alternatively you can use the Draw → Specify Objects → Square menu.



Set the width to 20 m and the corner of it at (0, 0):



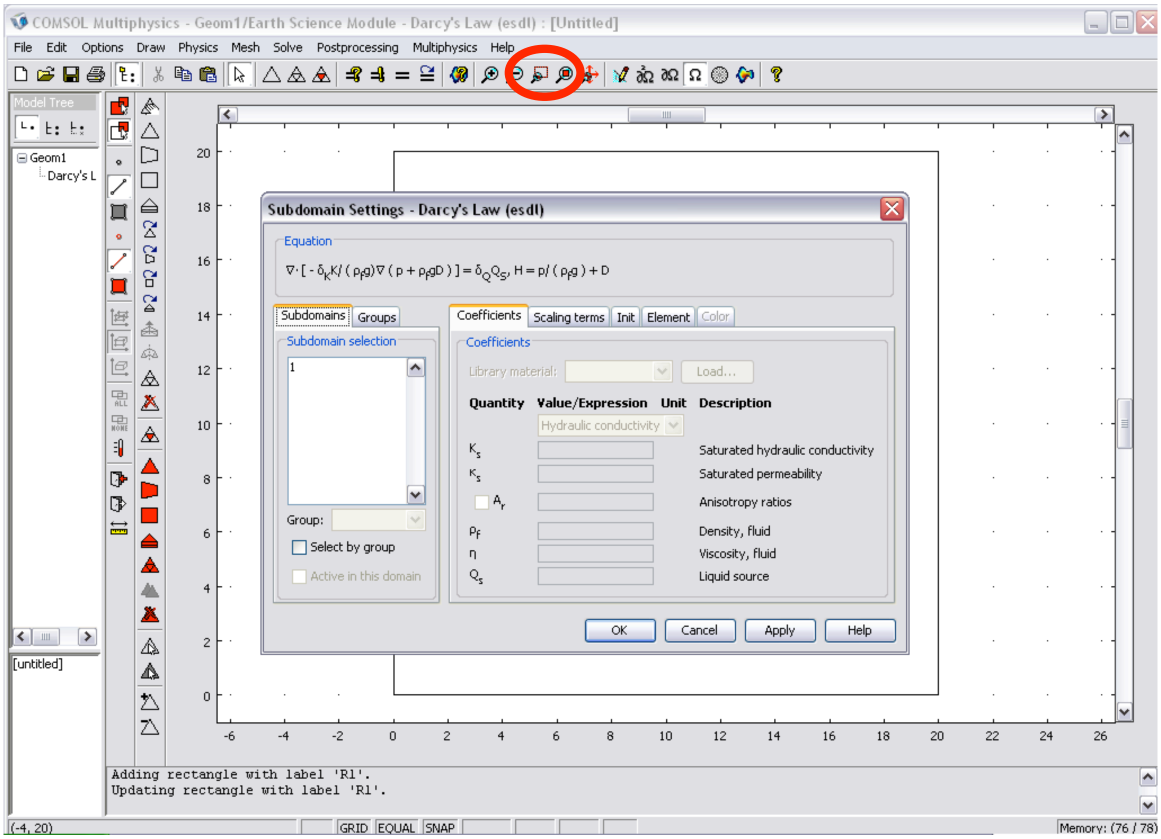
This will be your flow and transport domain. Fit your new rectangle to screen by selecting the Zoom tool circled in green.

1.1 Defining parameters, initial conditions

We now need to set the properties within this domain, specifically the hydraulic conductivity and initial heads. To do this, go the Physics → Subdomain Settings menu, or click the button highlighted in red below. You should see the GWFE written out at the top of the menu. This is the equation we'll solve!

Select the only subdomain we have (#1), and in the main Coefficients Menu, assign a saturated hydraulic conductivity of 1e-4 m/s, which is a reasonably high hydraulic conductivity like what you would find in a clean sand.

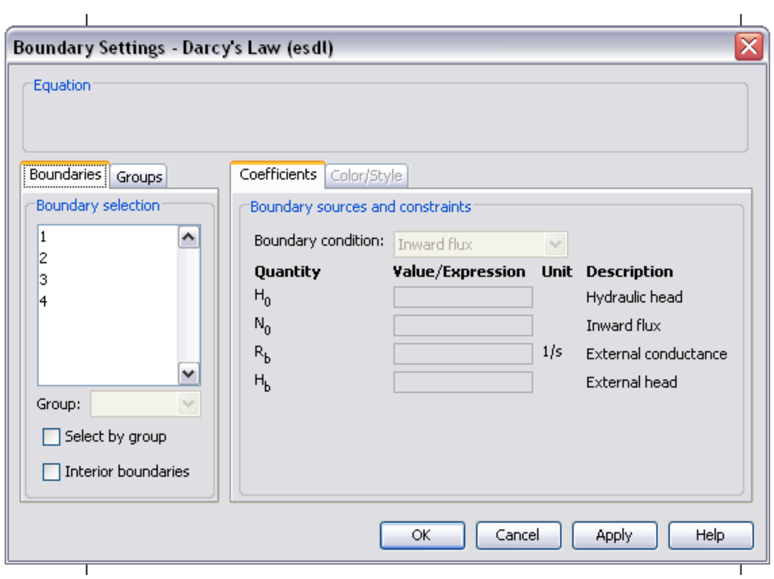
Click the Init tab and set your initial heads. Let's assume we have an initial head of 10 m. This parameter won't matter much, although we must set it. The sensitivity of our results to initial conditions is not high in a well-behaved system like the ones we have here.



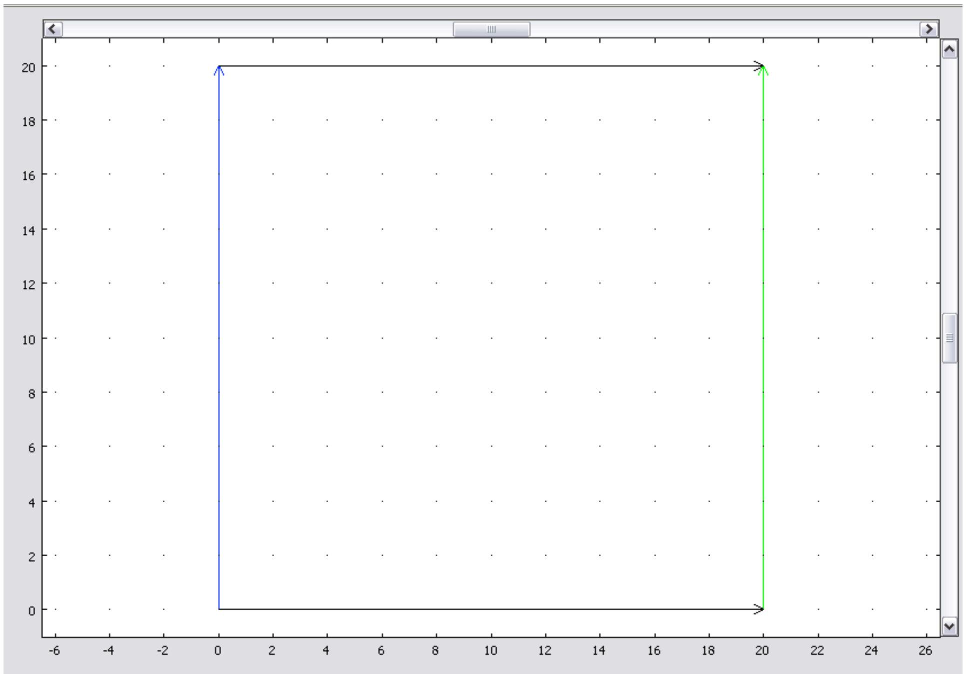
1.2 Defining boundary conditions

Next, we need to assign the behavior at our boundaries. To do so, click on Physics → Boundary Settings. Click on the four edges of your rectangle to figure out with boundary is defined as which number.

We'll set up a system where flow goes from left to right, although we could do whatever we'd like. To do this, we'll set the top and bottom boundary to the default values (No Flux) such that no flow goes through them (like in our flownets!) and the left and right boundaries to fixed head. Let's set a natural gradient of 0.01. Over a 20 m domain, this would be a head change of 0.2 m. To do this, click on the number associated with the left boundary and assign a hydraulic head of 10.2 m. Click the number associated with the right boundary and assign it a hydraulic head of 10.0 m. This will establish your gradient of 0.01. Does that make sense?

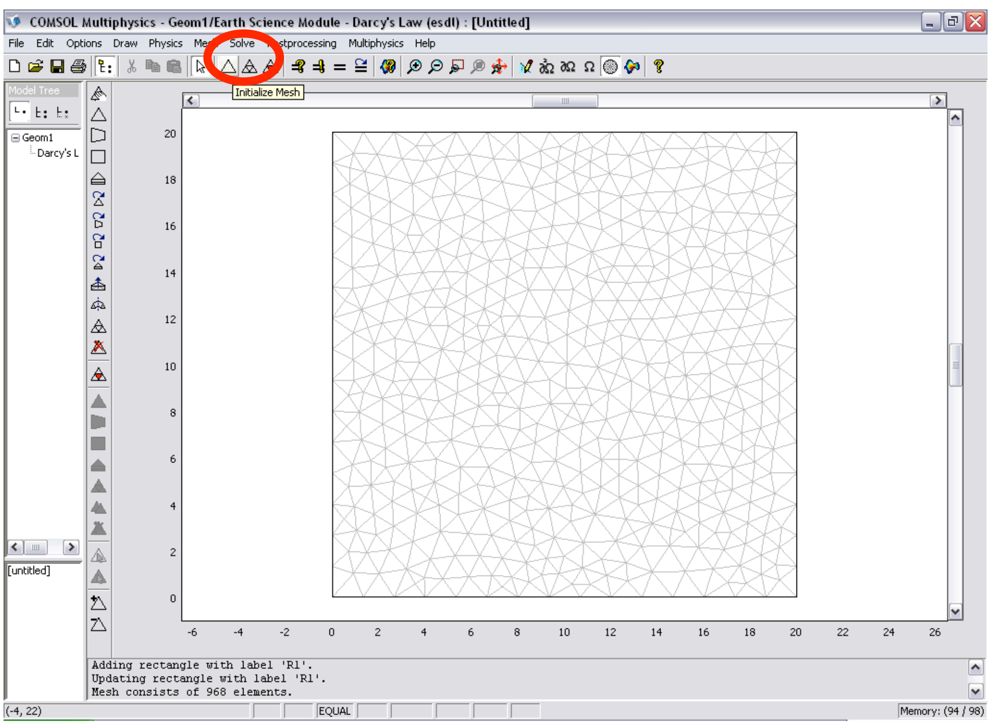


Once you've set the boundary conditions, you'll note that COMSOL colors the no-flow boundaries black, and the two head boundaries are in color.



1.3 Defining the mesh

We are almost ready to simulate: we have our domain, our boundary conditions, our initial conditions, and our differential equation of interest. We've assigned the parameters we need. From here, we just need to mesh. Click the left button in the red to generate a freeform mesh (you could also use Mesh → Generate Mesh).



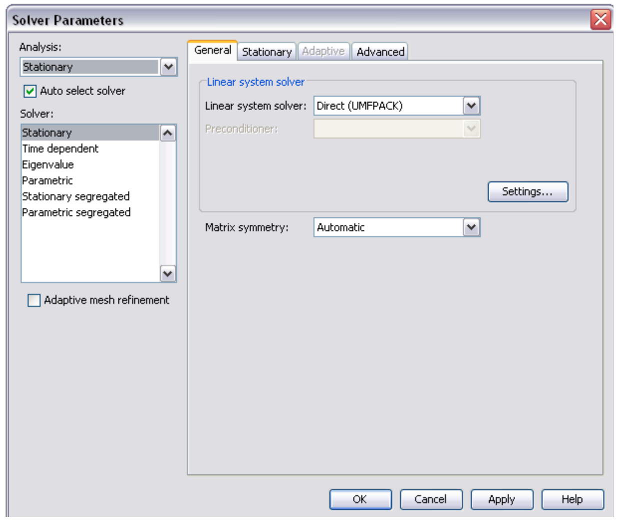
Behind the scenes, what's happened here is that COMSOL has discretized our differential equations so that we can solve in numerically rather than analytically (like we did with flownets). We don't need to know the details of this to use this model. All we really need to know is that COMSOL is going to solve for the values of head at every node, and interpolated to the mesh for us.

If you choose to, you can refine the mesh by clicking the right button in the red ellipse (or Mesh→ Refine Mesh). This makes your solution more accurate but your model run a bit slower.

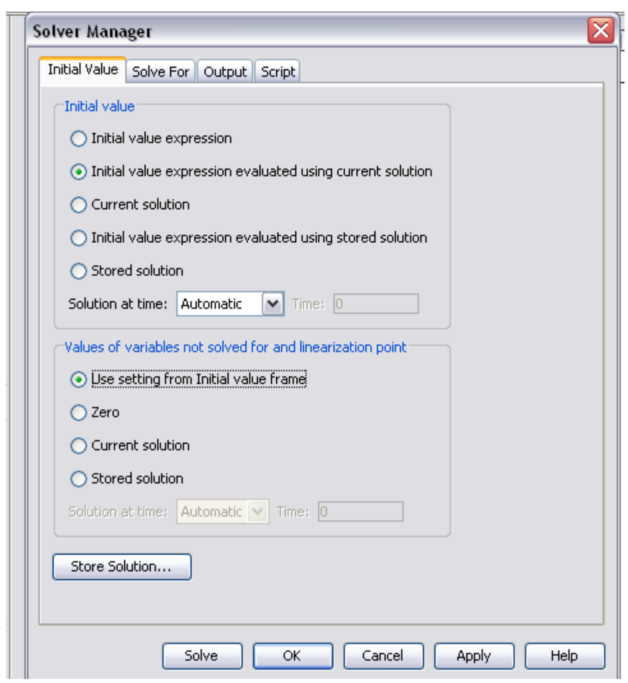
1.4 Solving model for hydraulic heads

From here, we can click the equal sign (or use the Solve menu) to find hydraulic heads at each point. Before we do this, let's look at the inner workings of the COMSOL Solve Menu as we'll be using it a lot.

First, go to Solve → Solver Parameters. Note that the solver is set to Stationary—this means we are looking for the steady-state solution.



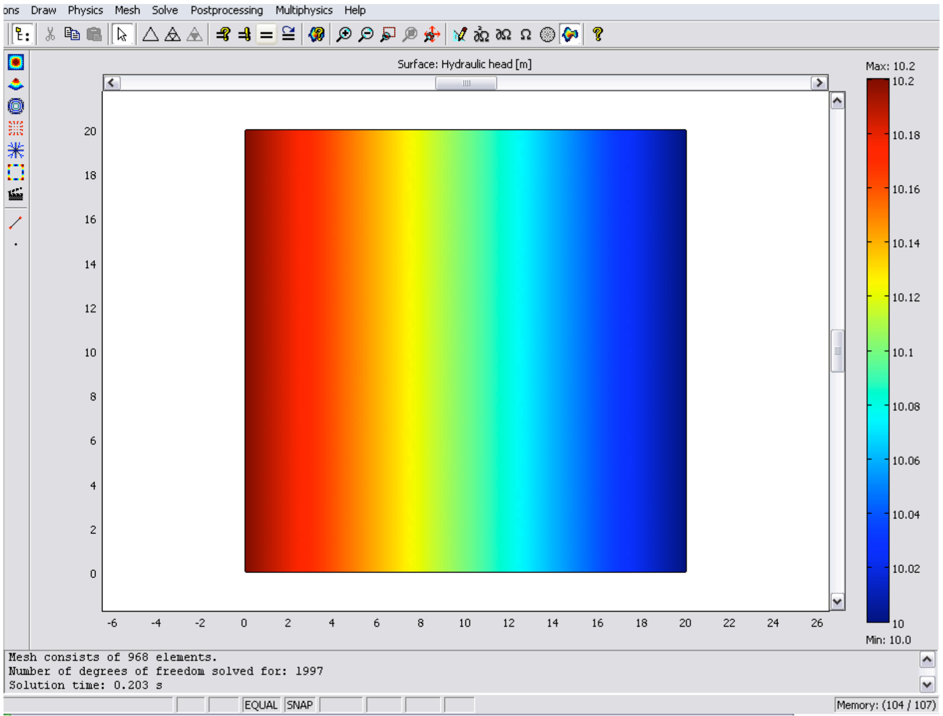
Click OK. Go into Solve → Solver Manager. We won't mess with the Initial Value setting today, but we will change the Values menu at the bottom. For now, we want it to Use Setting From Initial Value, meaning we're solving from our initial conditions.



Under the Solve For tab, you'll see our only option at the moment, and that is to solve the Darcy's Law module for p (pressure). To solve from this menu you can click Solve, or hit OK and the equal sign button.

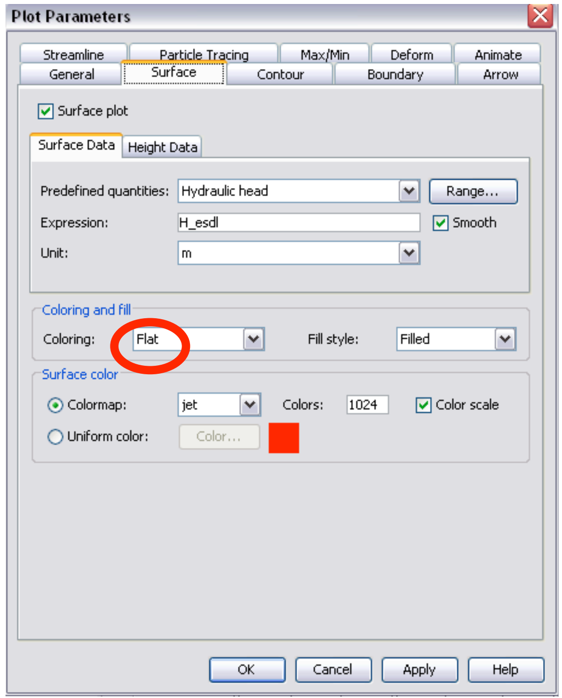
1.5 Plotting hydraulic heads

The hydraulic head field plots instantly after running the simulation.



We see that we've produced a map of hydraulic head that has high head (10.2 m, to be precise) at the left-hand boundary, grading to lower head (10.0 m) on the right hand side. This is no surprise, as we could have done this with a flownet. But we'll build from here. For instance, we'll build in transport. Transport is dependent on the velocities from the flow model, so let's save this solution. Go into Solve → Solver Manager and click Store Solution.

We have a lot of other plot options. You can find them in Post-Processing → Plot Parameters. For instance, COMSOL has interpolated the results for you. Perhaps a more honest image is to turn off the interpolation. To do this, go to Post Processing → Plot Parameters and click the Surface tab. Under Coloring and Fill, change the coloring to flat. You now see the value of each triangle shown independently.



Notice the resultant image is much more ragged. You can also plot velocity vectors in the General tab, if you so chose, or under the Arrow menu. Which way to the arrows point? Why? Go back to Plot Parameters, and under the Arrow tab, change the Subdomain data to the velocity field.

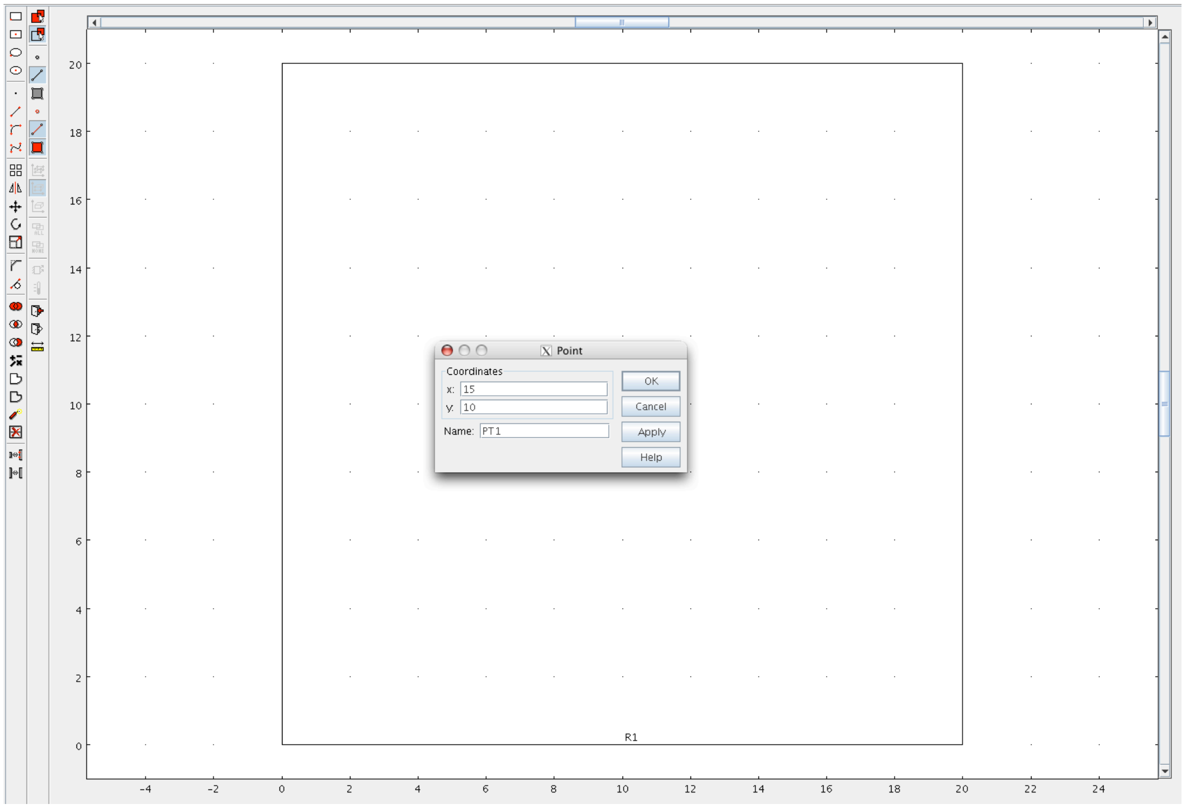
Go back into Plot Parameters and turn off the arrows. Go under Contour and click the box to show the head lines. How does the spacing of the head lines across the field change? Why?

Let's add something to this model to make it a little more interesting. Let's include a well.

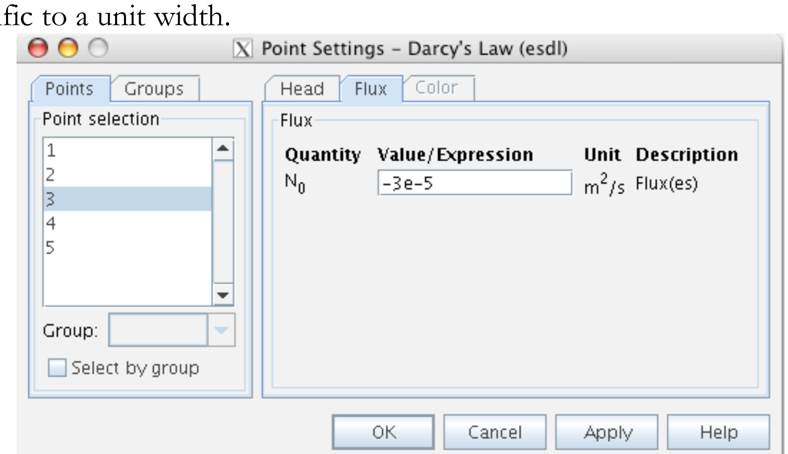
2. ADDING A POINT SOURCE WELL

There are a couple of ways to add a well in COMSOL. We will go through two possible ways here. First, go to File → Reset Model to delete the mesh and clear the previous solutions. Go under Multiphysics and put yourself back in the Darcy's Law mode.

The most common way to introduce a well is as a point source. To do so, go the Draw → Specify Objects → Point. Place the well at (15,10).



We now need to assign a pumping rate to this well. Go to Physics → Point Settings to assign a pumping rate. Select your well point in the list of points (note every subdomain has points at its corners), and use the Flux tab. Note that pumping rate isn't in volume/time as expected, but area/time. That's because in this 2-D model, there's an implicit "width" of the model, which is assigned to be 1. This is similar to the fluxes we considered in the flownet, which were specific to a unit width.



Assign a pumping rate of -3e-5 m^2/s (~0.5 gpm). The minus sign indicates that we are pumping, not injecting. The start and end times shouldn't matter, as we're dealing with a steady-state problem. It wants start/end times because it thinks we're still solving a transient problem! To leave this menu, we need to assign some dummy times (put in any value > 0 for both), but then we need to change back to a steady-state solver. We can do this by going through the process we've previously done.

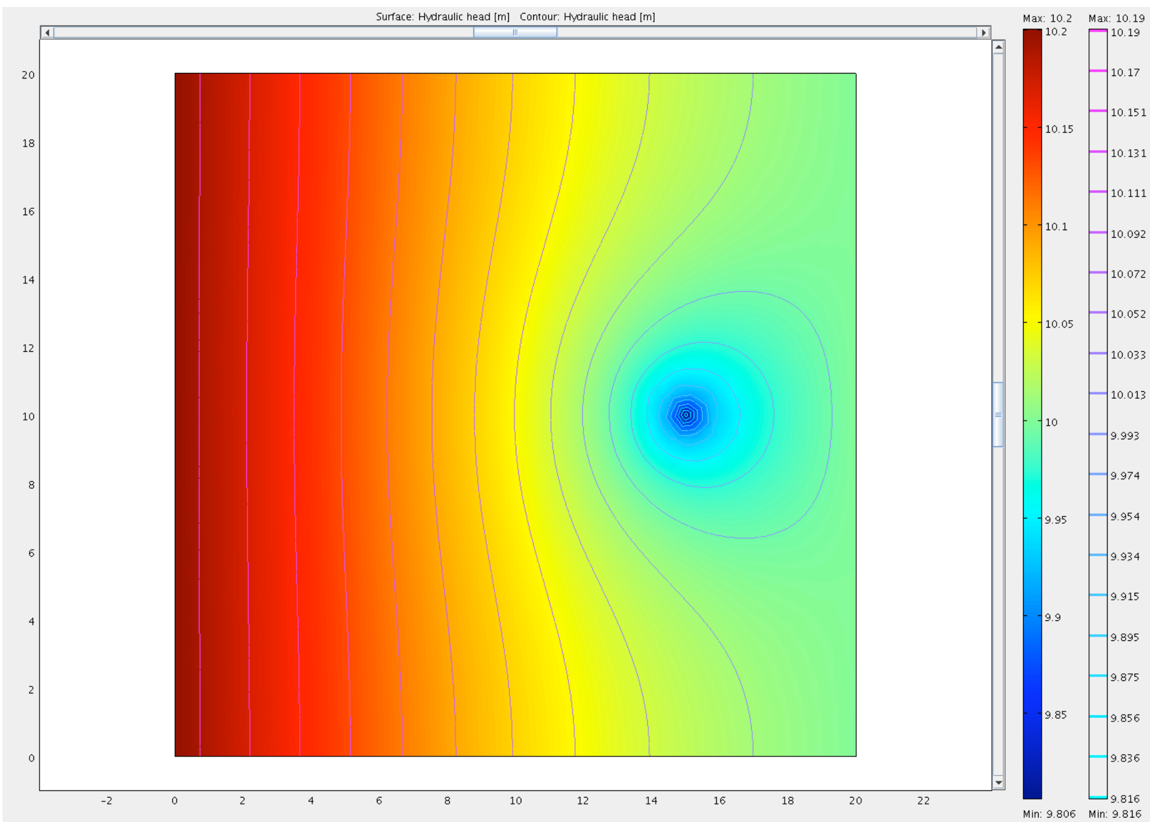
2.1 Create a mesh

Go back to section 1.3 and follow the instructions to make a mesh. Refine it if you haven't before. Because we are pumping from a well, there will be large gradients in concentration near the well, which is hard for a numerical model to capture.

2.2 Solve for flow

Follow section 1.4 to set the Solver Parameters back for a Stationary flow model. Under the Solver Manager, click the Solve For tab to solve the Darcy's Law module.

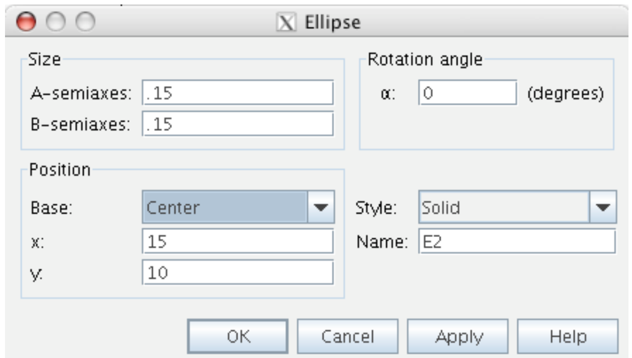
Click OK and Solve. Notice how much more slowly this goes with the refined mesh. Display the calculated heads in the Post Processing menu. The head field should look something like this:



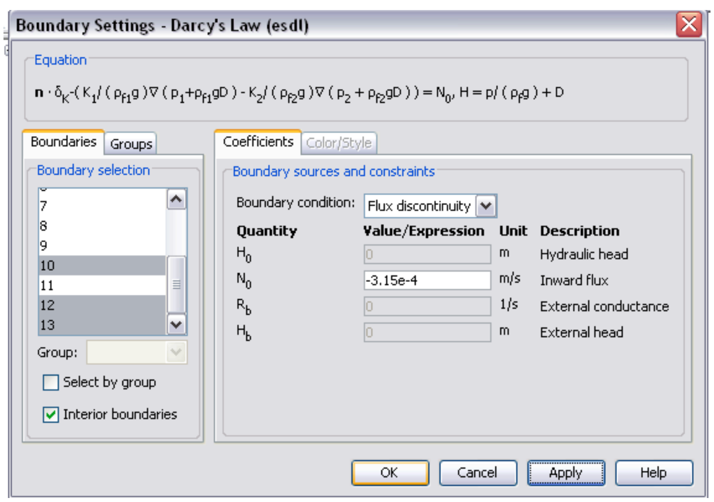
3. ADDING A NON-POINT SOURCE WELL (OPTIONAL SECTION)

In this example, we'll make a well with a fixed diameter. This might be useful in particular when wanting to get the physics right associated with an open well in the ground, rather than assuming that the well is infinitely small. Start by going to File → Reset Model.

To start, first delete your point well (click on it and hit delete) and then draw a circle using Draw → Specify Objects →Circle. Give it a radius of 6" (a common well diameter, which is equal to 0.15 m) centered at (15,10).

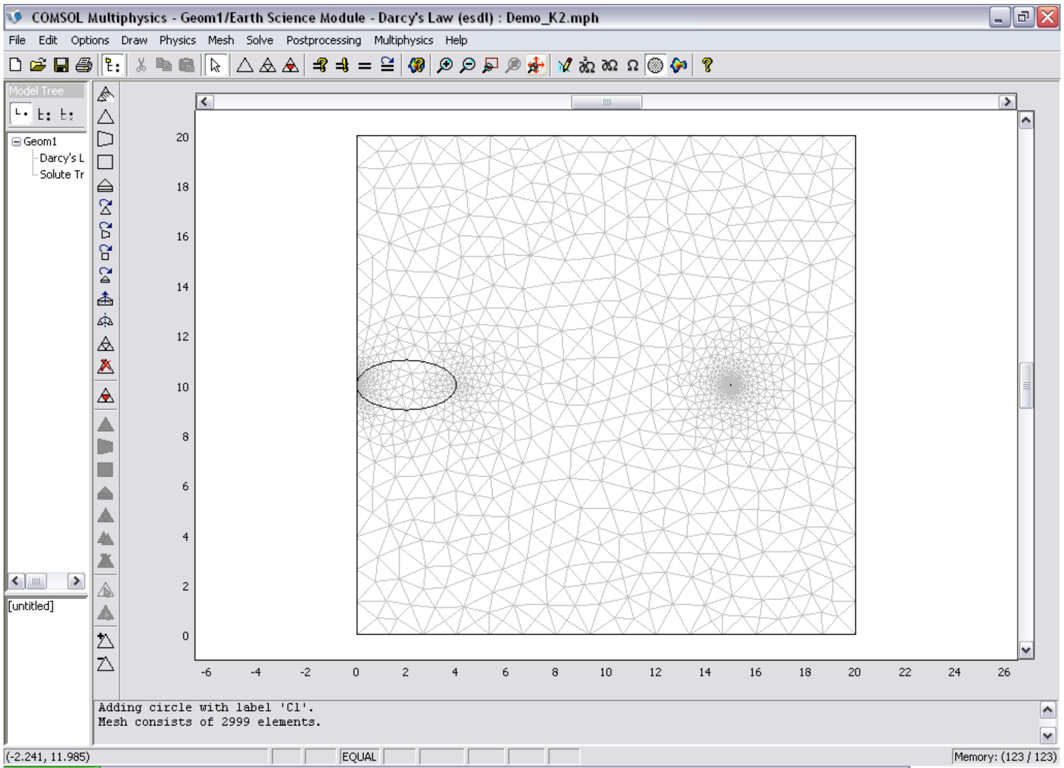


Make sure the Subdomain Settings in the new well are the same as they are in the rest of the mesh. Select any of the domains and hit control-C without clicking on anything. Click on the new domain, and use control-V to paste all the same parameters in. Set the hydraulic conductivity to a higher value, say 1 m/s, and assign a pumping rate using the liquid source term such that Qs = -5e-4/s. (There is an implicit volume here—what is it? Note that Qs = pumping rate / thickness of the aquifer, assumed to be 1.)



3.1 Create a mesh

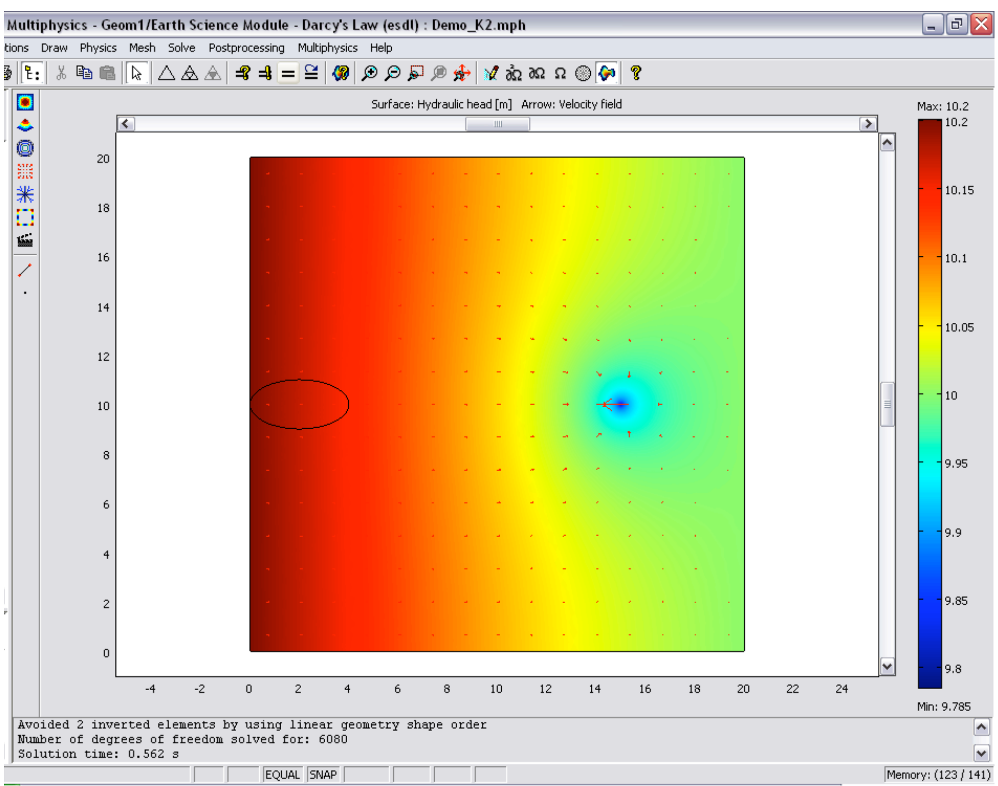
Create and refine you mesh as you did previously. Notice how the pattern of meshing is different when using a point source well and a well defined by a subdomain.



3.2 Solve for flow

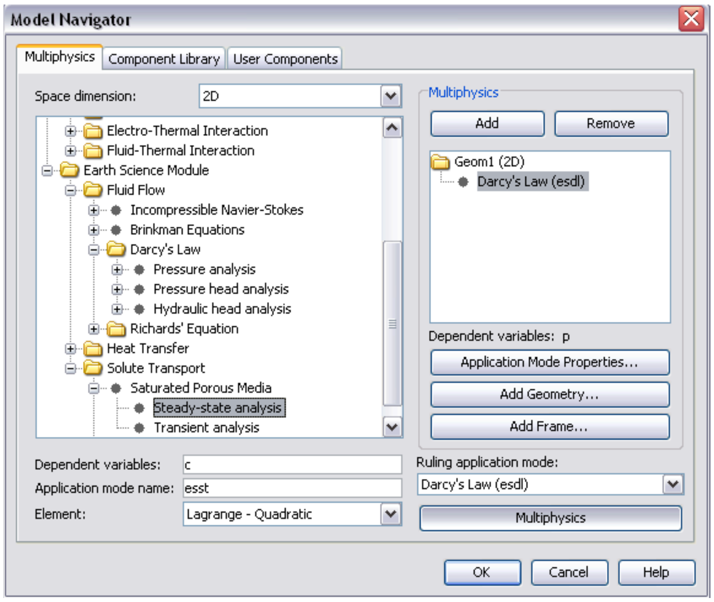
Like in the last example, we'll need to solve for the stationary head field and the transient transport. This pattern should start looking familiar! Follow section 1.4 again. Go into Solver Parameters to put the analysis and solver type back to Stationary. Then go to the Solver Manager to make sure we use the initial values. Click the Solve For tab to solve the Darcy's Law module only. Click OK and Solve. Display the calculated heads.

The head field should look something like this:



4. MODELING TRANSPORT

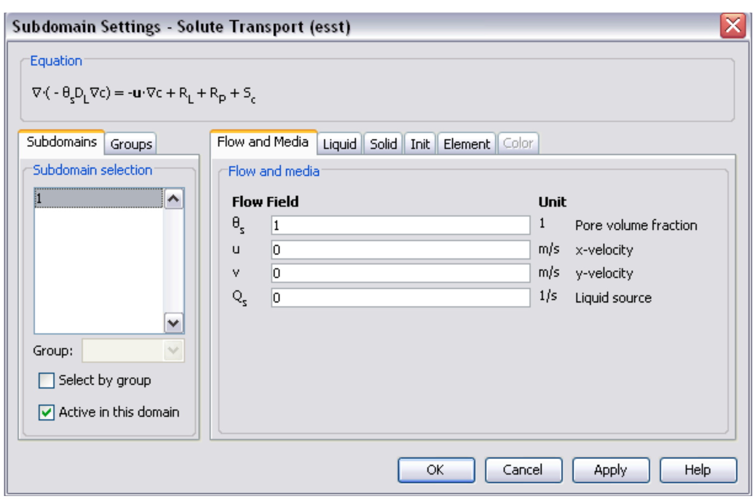
To add transport, we need to choose the advective-dispersive equation to model. To do this, we need to head back out to the Model Navigator. To do this, click Multiphysics→ Model Navigator, and select Saturated Porous Media → Transient Analysis option under the Solute Transport module. When you click Add in the right-hand corner, you should now see both the Darcy's Law and Solute Transport applications in the window on the right hand side.



4.1. Defining parameters, initial conditions

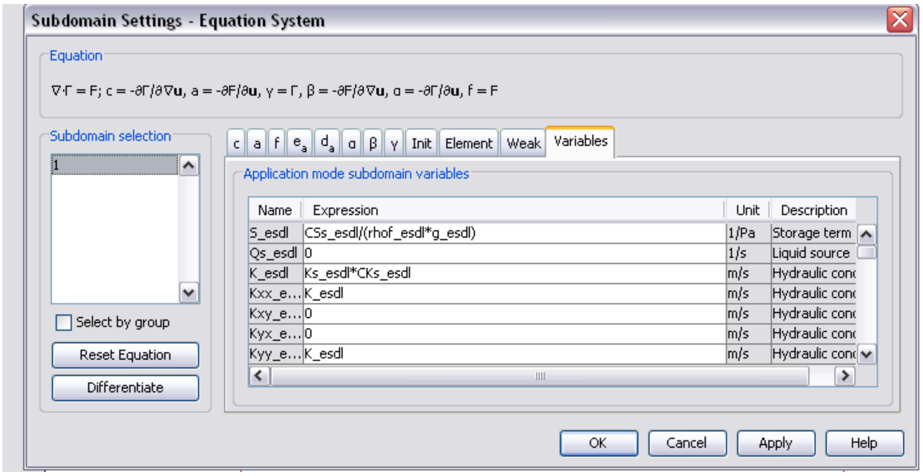
Like with the flow model, we now need to define the properties controlling transport. Think about the advective-dispersive equation: what parameters do we now need to add? Porosity and dispersivity are the big ones. We also need to pass the velocities from the flow model to the transport simulation. To make things easy, start by deleting the well.

Under the Multiphysics menu, make sure you are in the Solute Transport application. If so, go to Physics → Subdomain Settings to set the parameters of interest.

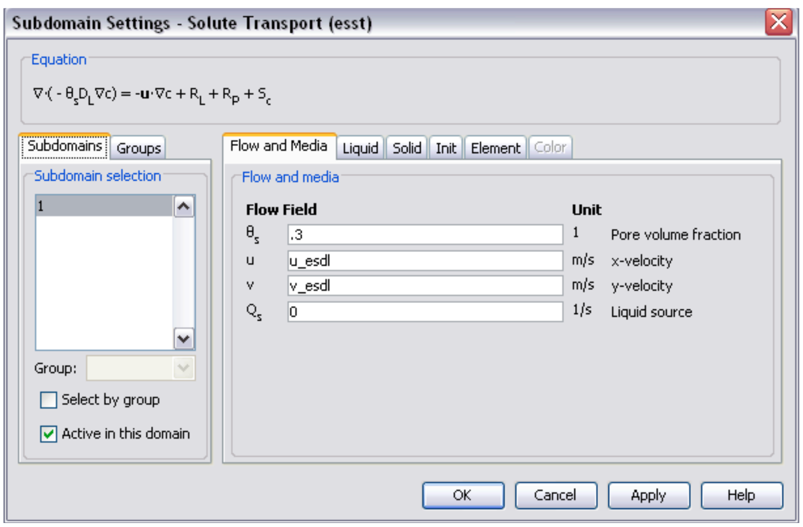


Click on the only subdomain (#1) and assign a porosity of 0.3. Under Liquid, set the Dispersivity in Direction 1 to 0.2 and in Direction 2 to 0.02. Under Init, set the background initial concentration to 1 kg/m3.

How do we connect the flow and transport models? Through Darcy's velocity, right? So we need to somehow tell the Solute Transport module what the groundwater velocities in x and y are (labeled u and v). To do so, we go back into the Darcy's Law application, and select Physics → Subdomain Settings → Equation System. Click the Variables tab.



Here, we see all the parameters that have been defined. We can scroll through to find the x- and y- velocities by their description. They're called u_esdl and v_esdl. From here, go to Multiphysics, select Solute Transport again, and go under Physics → Subdomain settings to pass these velocities to the transport simulation. Insert u_esdl (the latter part stands for Earth Science Darcy's Law) and v_esdl into the Flow and Media settings.

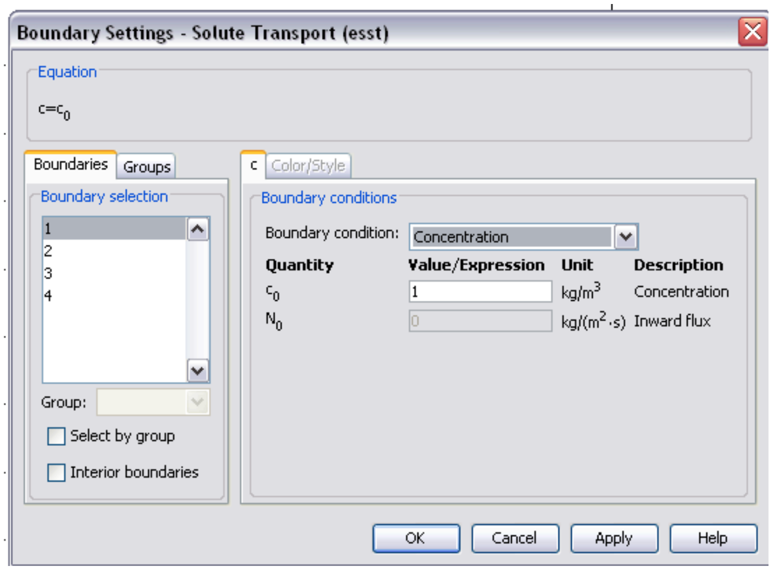


Click OK. The two models are now connected!

4.2 Defining boundary conditions

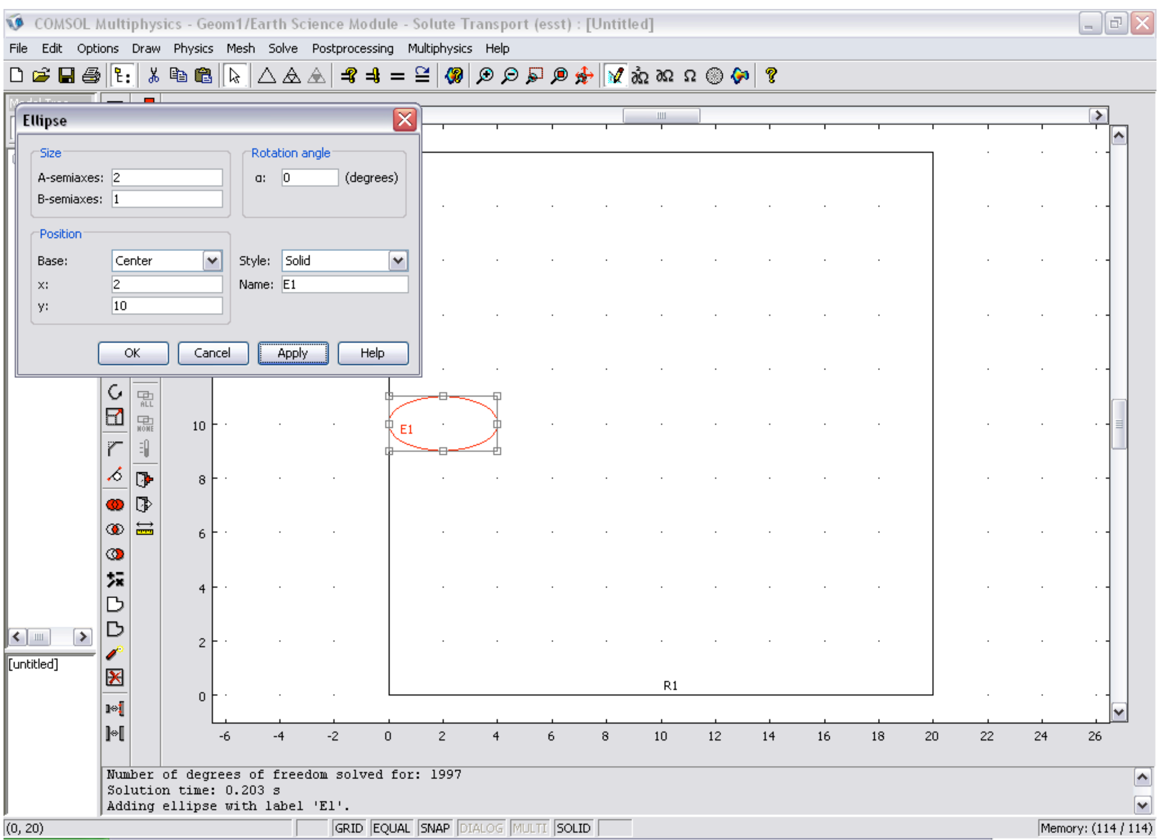
Like with the flow model, we need to define the boundary conditions for the ADE. Since we are coupling the two model systems, we will keep the boundaries similar in nature. The top and bottom boundaries will be no flux (since they are no flow). We need to fix the left-hand boundary such that it maintains our initial concentration, so we'll see it as a fixed concentration boundary with a values of 1 kg/m3.

The right-hand boundary we'll see to an "Advective Flux" condition. This basically allows the solute that arrives at the right-hand boundary to escape. You'll note there are other options here; you will explore these later.

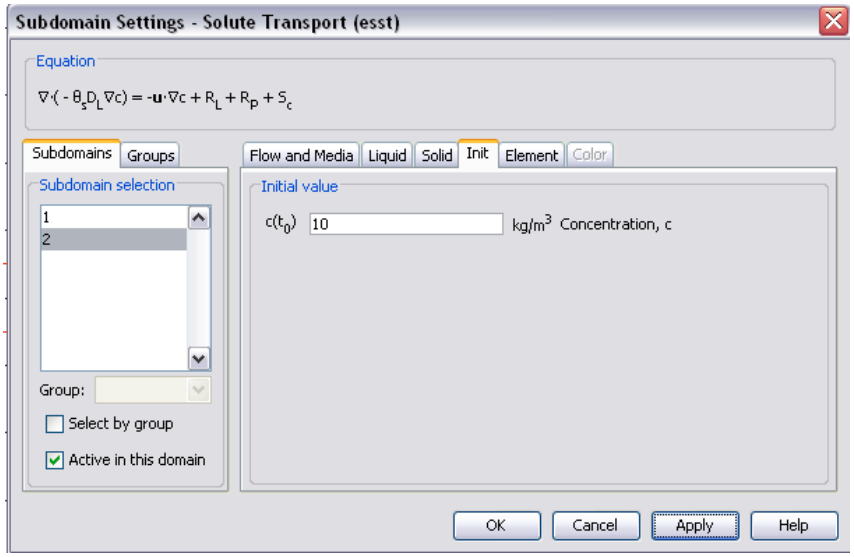


4.3 Defining the source location

Let's pretend we have a spill—a plume of methyl-ethyl bad stuff at the left hand side of our domain. Let's define the plume as an ellipse that is 2m in length and 1m in height. To define it, go to Draw → Specify Objects → Ellipse/Circle (centered), and define the long axis as 2 and the short axis as 1 as shown in the menu below. You can center the ellipse anywhere you'd like. I put it at (2, 10). If you'd like it elsewhere, that's fine, just keep it on the left-hand side so it's got some distance to transport itself.



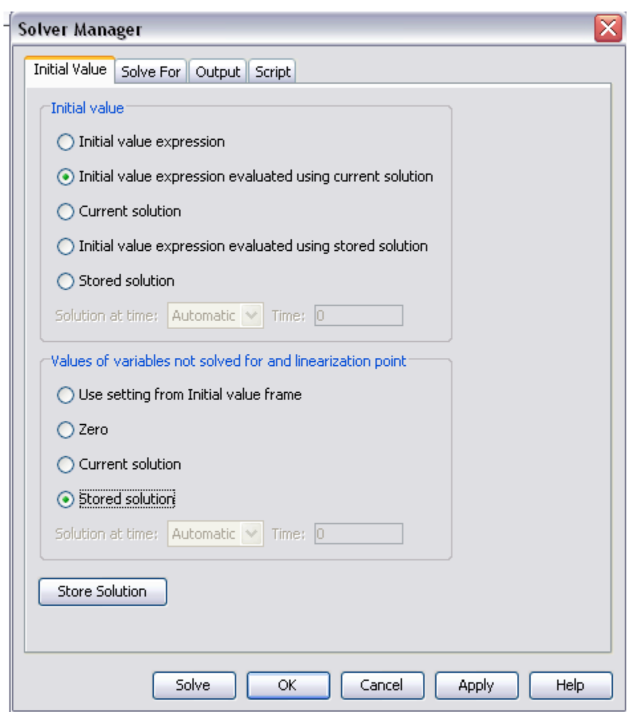
You now need to define the concentration within the "spill". To do so, go to Physics → Subdomain Settings, and select the 2nd subdomain (our ellipse) under the Init menu. " Let's define it as 10 kg/m3. Click Apply, and double check that the Initial Value in Subdomain 1 (the background) is still 1.

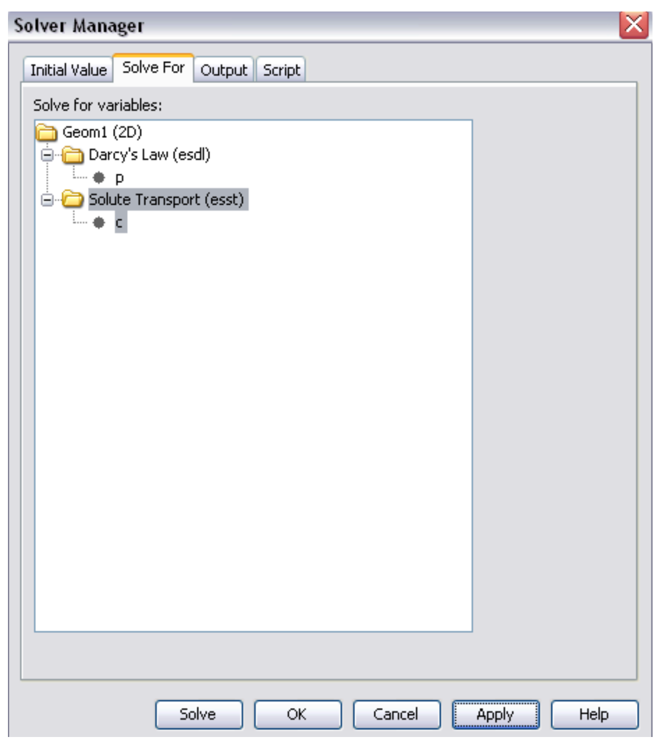


4.4 Solving for concentration

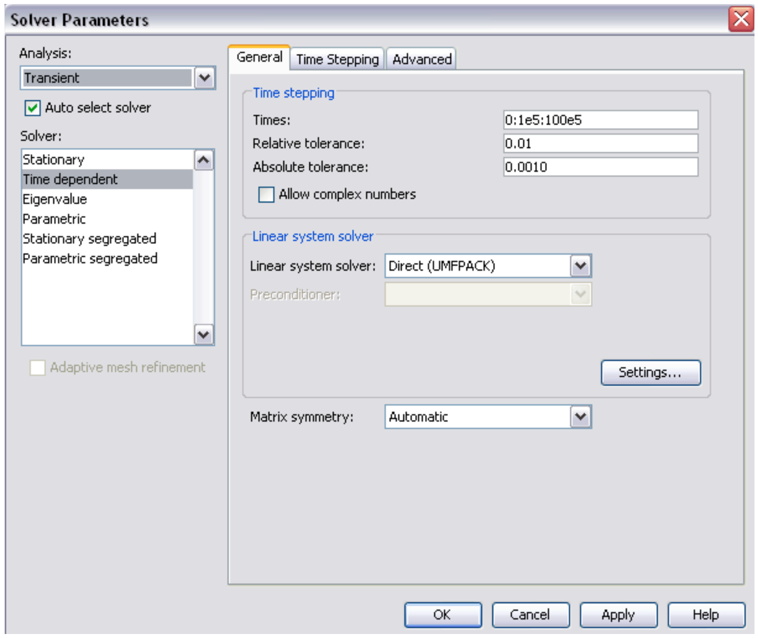
We now have two simulations we need to run: (1) flow (to get velocities), which we'll pass to the (2) transport model. Because our flow model is steady-state (meaning there are no changes with time) and our transport model is transient (as we're tracking a tracer with time) we will need to solve these slightly differently.

To set these solver parameters, we'll go to Solve → Solver Manager. First thing we'll do is save the head solution was solved for in Part 1 by clicking on "Store Solution". We'll then click "Stored solution" to let COMSOL know that we'll be running our transport model based on the stored flow model. This tells COMSOL to use the stored solution (the head data) when solving for transport by setting the controls as shown below. We'll then click Solve For to choose the Solute Transport application.





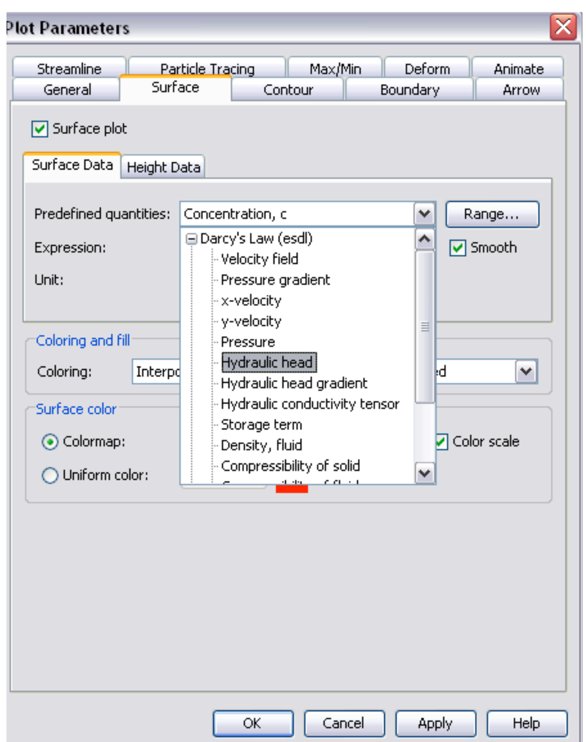
From here, go into Solve → Solver Parameters to set the parameters for the transient transport model. Choose Transient analysis, the Time dependent solver, and then decide on output times (in seconds) that you would like to see. We'll run this test for 100 days, outputting results every day. In the Times window, you need to type the start time, a colon, the time step, a colon, and then the final time. Rather than use 86400 seconds to indicate a day, let's just use 1e5 to approximate the right number of seconds. So for daily output for 50 days, type 0:1e5:100e5.



Hit OK, then Solve.

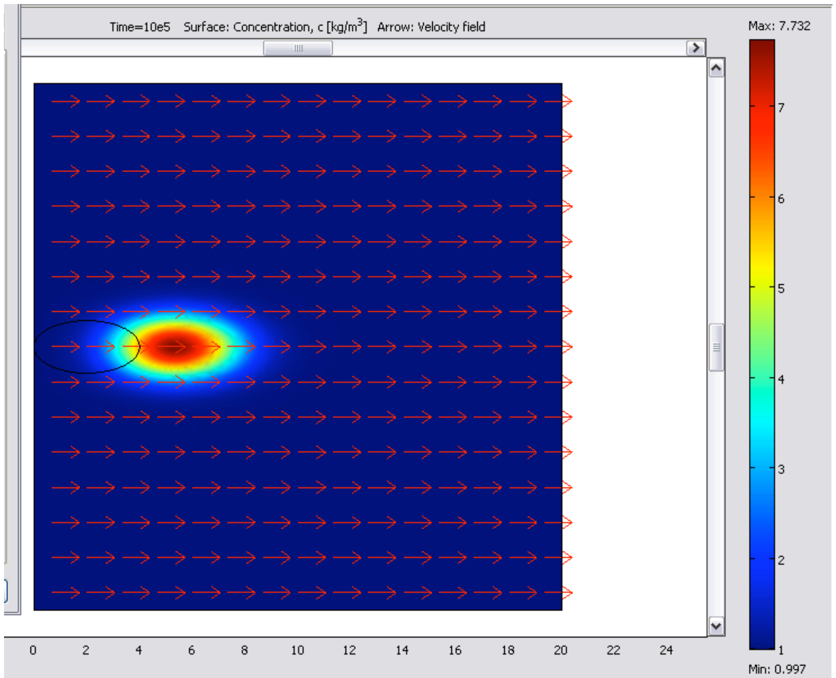
2.5 Plotting Concentration

From within the Post Processing →Plot Parameters menu, select to plot concentration data from the drop down menu.

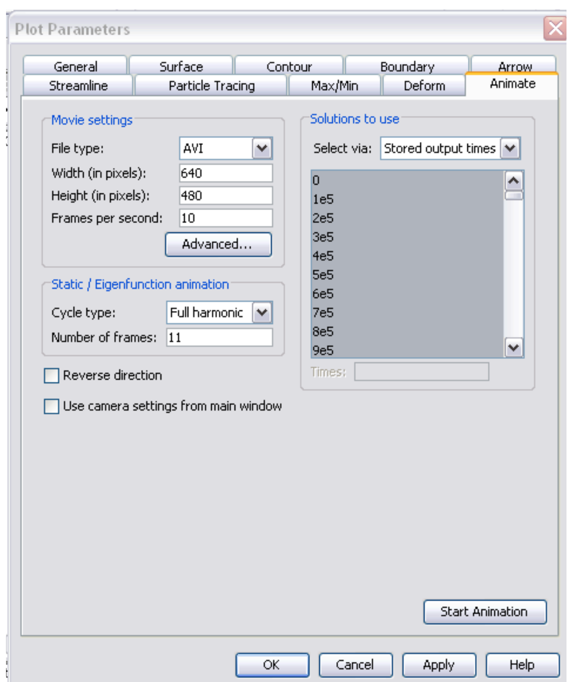


This will only plot the last time step. It may look like your concentration plume is still there, but take a look at the colorbar—most of the concentration has already been swept out of the field.

To explore the concentration fields at each day, go to the General tab and select whichever data you'd like, and click Apply. You should see the initial ellipse advect and disperse across the field as you move to later and later dates.



One way to see results from all times is to create a movie. To do so, click the Animate tab, select all output times, and click Start Animation.



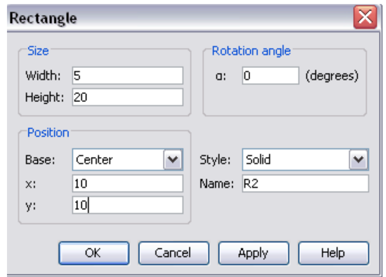
Notice how when the colorbar is held constant like this that not much happens after Day 70.

Save this model. Reinsert the well (set its pumping rate, etc., as before), and rerun your flow and transport models.

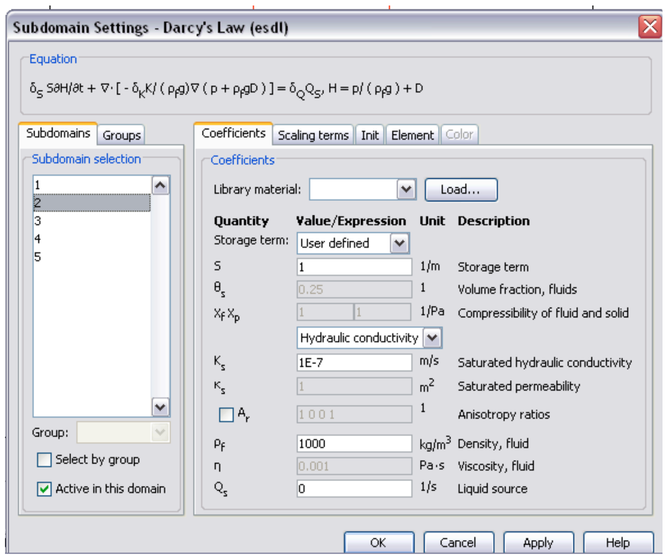
5. ADDING BLOCKED HETEROGENEITY IN K

Let's explore what happens if the hydraulic conductivity field had been heterogeneity. Go to File → Reset Model.

Start by creating a block of material of lower K. Go to Draw → Specify Objects → Rectangle and add a rectangle of width 5 and height 20 centered at (10, 10).

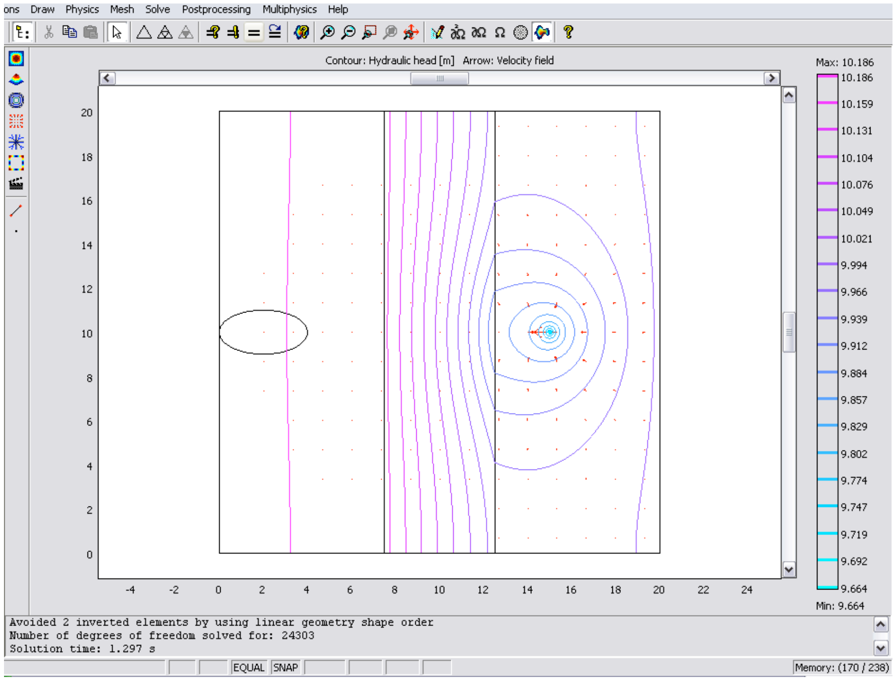


After doing this, go into subdomain settings in the Darcy's law menu. Select any of the domains that is NOT the concentration plume, and hit control-C without clicking on anything. Click on the new domain, and use control-V to paste all the same parameters in. The one thing you will change is the hydraulic conductivity…set it to 1e-5.



5.1 Create mesh, solve for flow

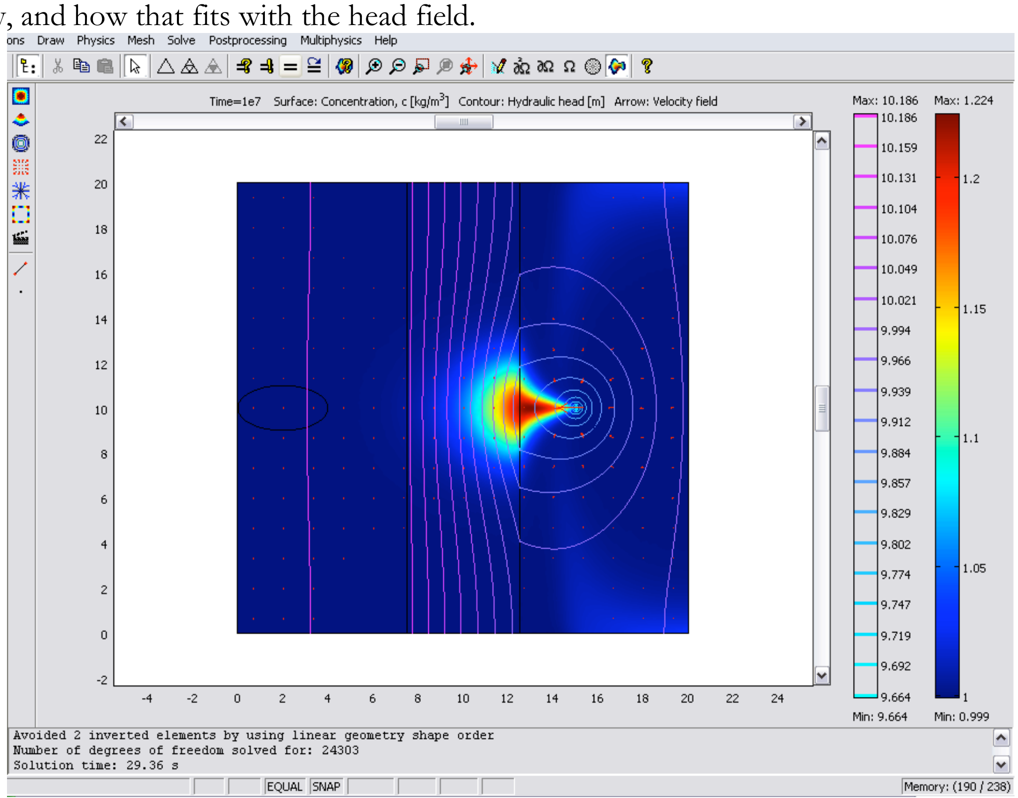
Follow steps 1.3 and 1.4 to create your mesh and solve for steady-state flow. Note how the head field differs from the earlier simulations. Click on contour plot to show the head lines to see clearly the differences…your plot should look something like the following.



5.2 Solve for transport

To solve for transport, change to the Solute Transport module, and copy the parameters from the background domain into the new subdomain. Select any of the domains that is NOT the concentration plume, and hit control-C without clicking on anything. Click on the new domain, and use control-V to paste all the same parameters in. Check to make sure all the initial concentrations, etc., are still correct.

Follow section 2.4 again to solve for concentration. Plot and animate. Note how the pattern has changed due to the heterogeneity, and how that fits with the head field.

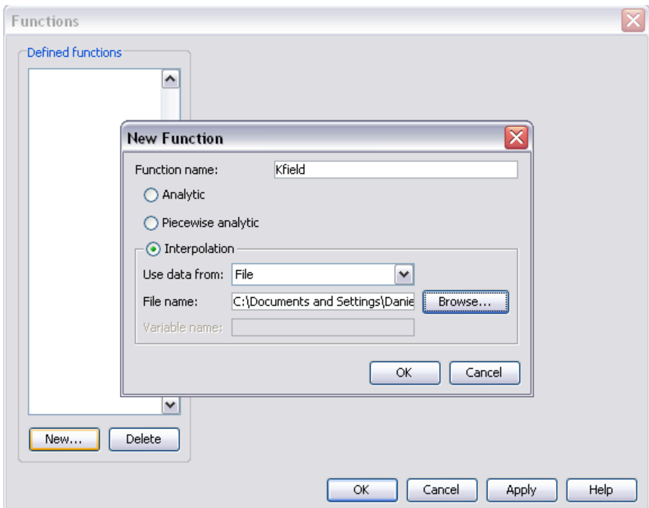


Save this model.

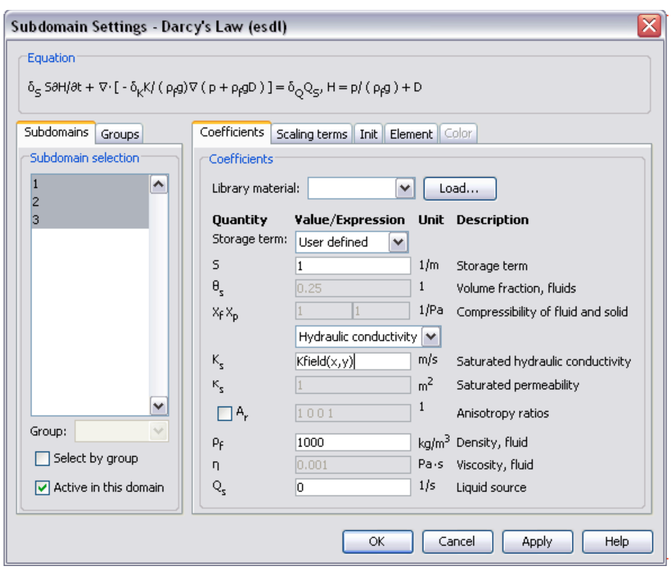
6. ADDING GEOSTATISTICAL HETEROGENEITY IN K

Let's consider more realistic heterogeneity. To do so, we'll read in a map of hydraulic conductivity that I created geostatistically using GSLIB. Take a look at the text file Kfieldc.txt. In it, you'll find a grid, and then the values of hydraulic conductivity on that grid. The mean K is 1e-4 m/s, the same as what we were using in our homogeneous model. To start, delete the new subdomain we made in section 5, and go to File → Reset Model.

Go to Options→ Functions, and click New. Select the name of the function (Kfield or something similar is fine, just anything so that you know what it is), and click interpolation. Use data file from a File, and select the location of your file with the Browse menu. We'll interpolate that text file to your mesh. Click OK. You can leave the interpolator as linear. Click OK again.

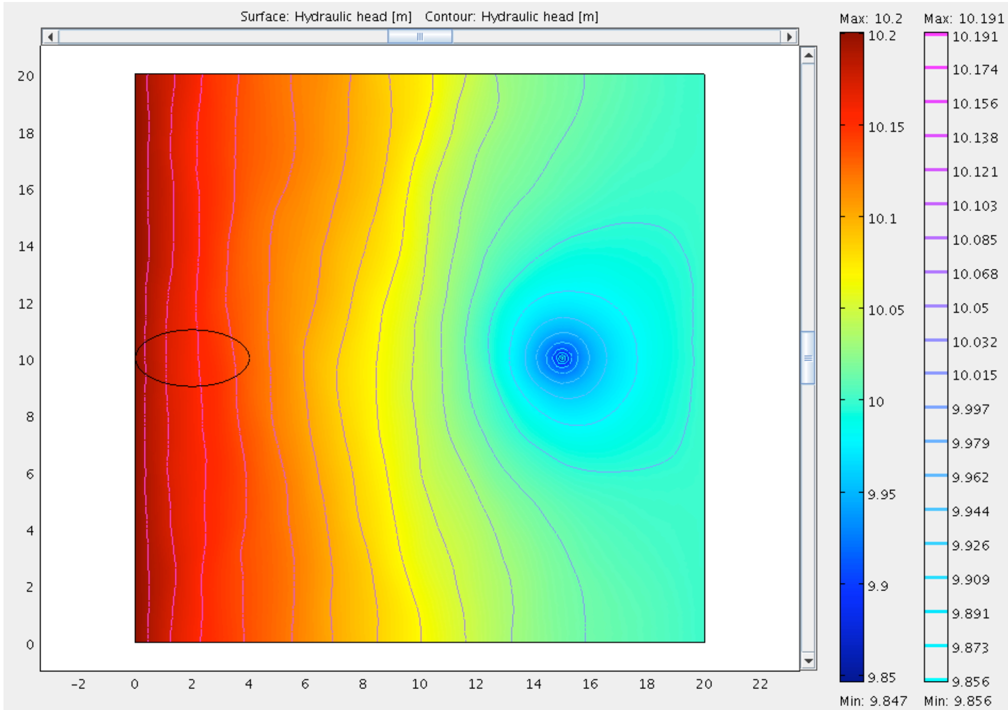


From here, go into the Subdomain Settings, select all subdomains, and change the hydraulic conductivity to our new function. Type in the Ks line the name of the function you created (I called mine Kfield) with (x,y) after it to indicate that it is a function of x and y—it changes with location.

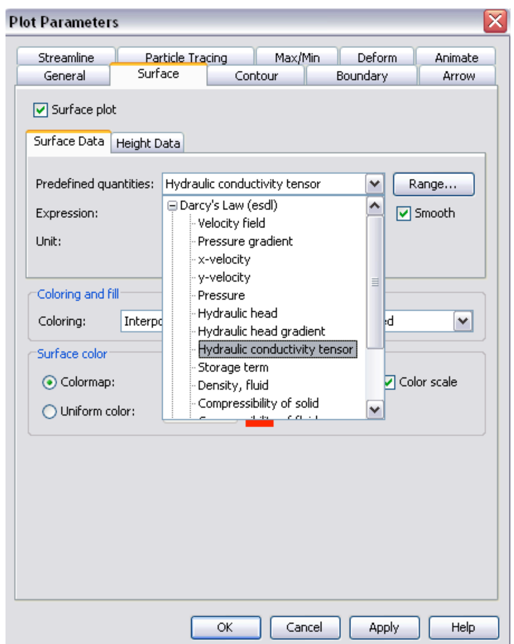


6.1 Create mesh, solve for flow

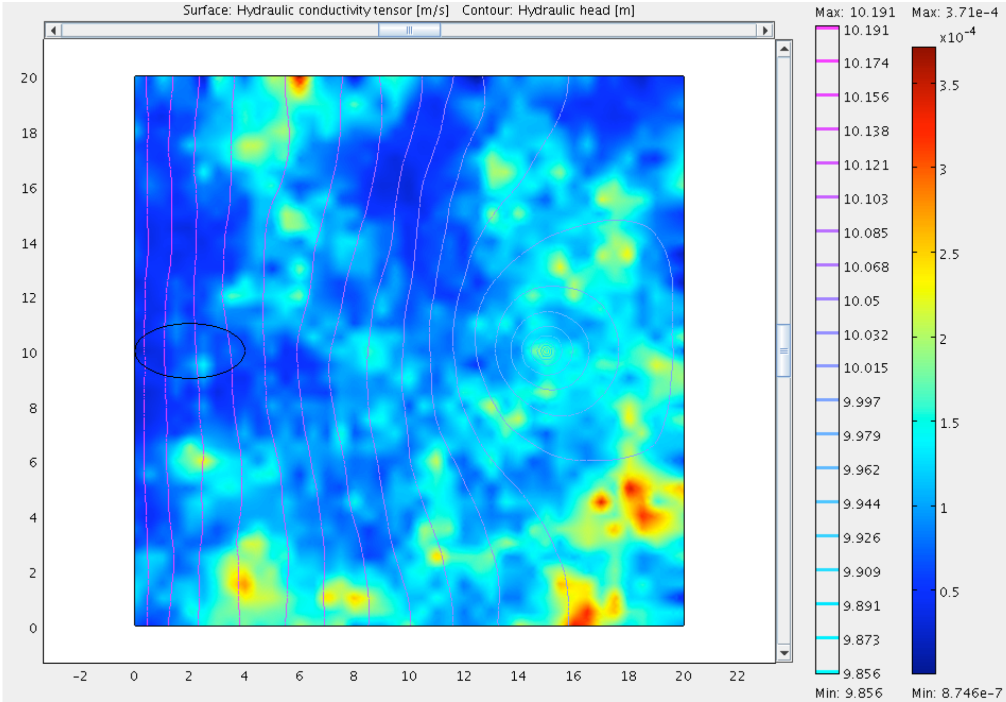
Follow steps 1.3 and 1.4 to create your mesh and solve for steady-state flow. Note how the head field differs from the earlier simulations. You can see how the variability in the K-field affects the flow lines.



You can also plot your K field, so you know what it looks like, by selected it from the dropdown menu under Surface Data.

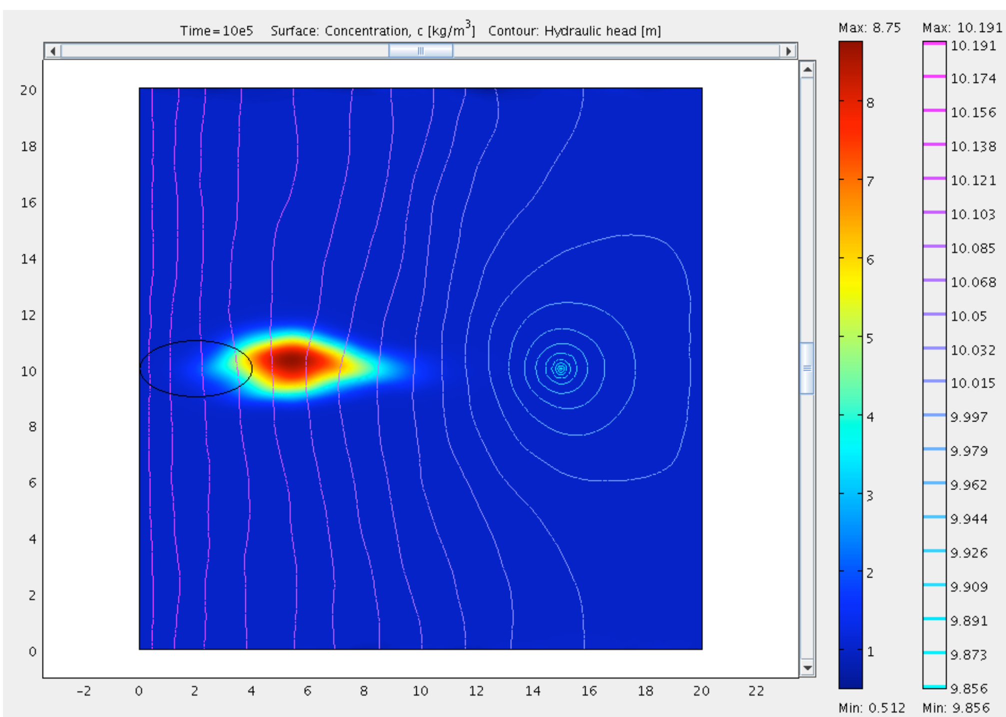


Your K-field should look like this:



6.2 Solve for transport

To solve for transport, follow section 2.4 again to solve for concentration. Plot and animate. Note how the pattern has changed due to the heterogeneity, and how that fits with the head field.

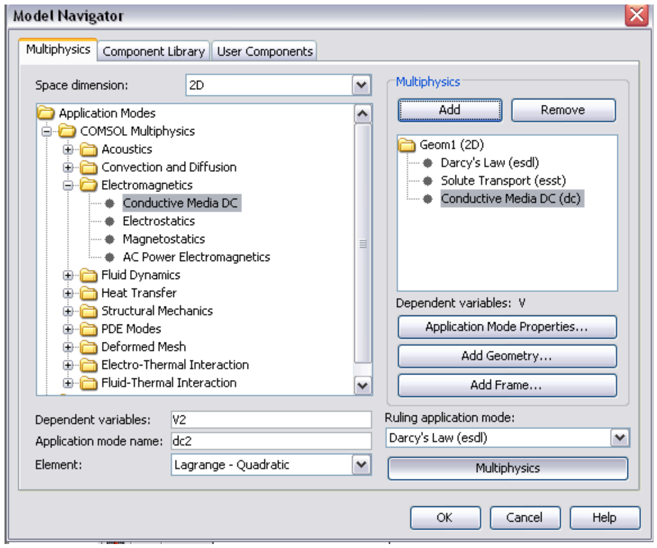


Save this model.

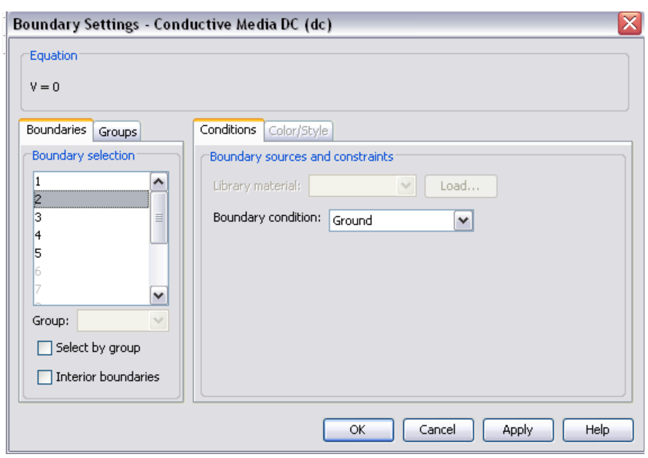
7. ADDING ELECTRICAL FLOW

Go back to a homogeneous K-field of 1e-4 m/s, and rerun your simulations of flow and transport. What we'll add now is the electrical flow. Let's pretend this is a map view of our solute transport…how would our electrical geophysical data change as the plume went by? To make things simple, we'll pretend we only have four electrodes in the field, and will collect data using a simple Wenner array. Bring up your homogeneous model, and Reset it.

To start, we'll need to add another application mode. Go to Multiphysics →Model Navigator to add the Conductive Media DC application. It is either under Electromagnetics (as shown here) or under the AC/DC Module → Statics. Add the application using the Add button and click OK.



From here, we'll set boundary and subdomain settings as we've done earlier. Go to Physics → Boundary Settings. In this case, we're going to set constant "head" boundaries (in this case, constant voltage) where the voltages are equal to 0. In Comsol, this is called a Ground boundary condition, as shown below. Check the equation that is used: V = 0!



After this, go to Physics → Subdomain Settings. Select all subdomains available (2 or 3, depending on how your well was defined). Make sure the Init voltage is set to 0 in all cases. Then go to Physics, to define the conductivity.

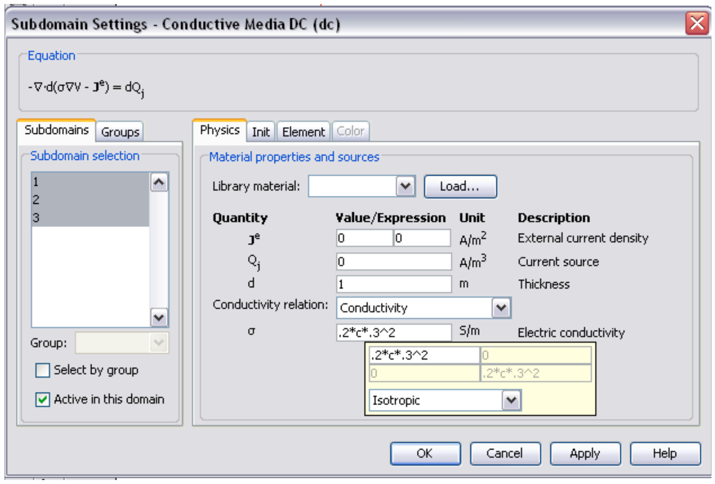
The electrical conductivity of the medium is going to be dependent on the concentration of electrically conductive tracer present, right? So to do that, we need to convert concentrations to fluid conductivity, and fluid conductivity to bulk conductivity. How do we do that? To start, let's convert the concentrations in g/L to fluid conductivities in S/m using the empirical relation we talked about in class:

$$\sigma_f \approx 0.2 \cdot TDS\,.$$

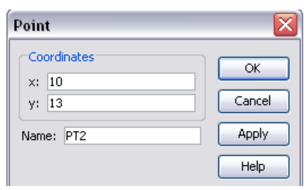
We can then convert our fluid conductivity to bulk conductivity through Archie's Law,

$$\sigma_b = \sigma_f a \phi^m$$

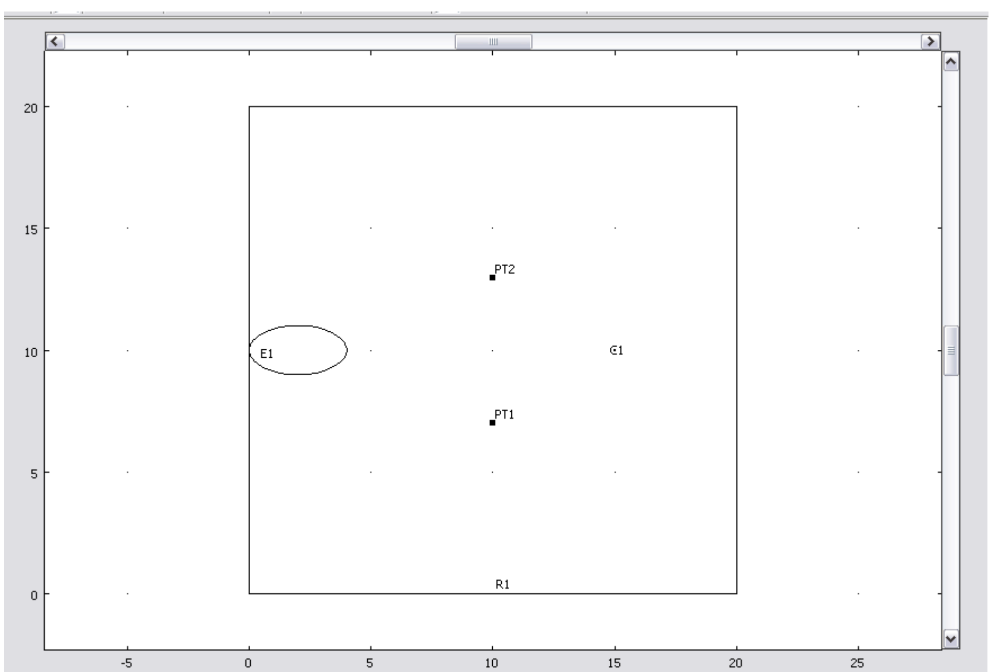
in this case allowing a = 1 and m = 2. Our porosity was equal to 0.3. Insert into the conductivity block, then: 0.2*c*0.3^2. Hit OK.



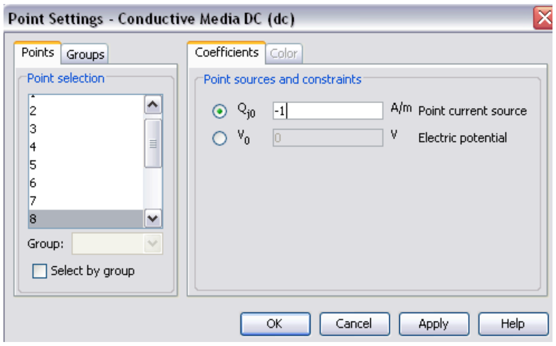
We now need to add some electrodes to drive current and measure potential. We need to explicitly simulate the current electrodes, but not the voltage electrodes (why?). To add the current electrodes, go to Draw → Specify Objects → Point. Put one at (10,7) and one at (10, 13).

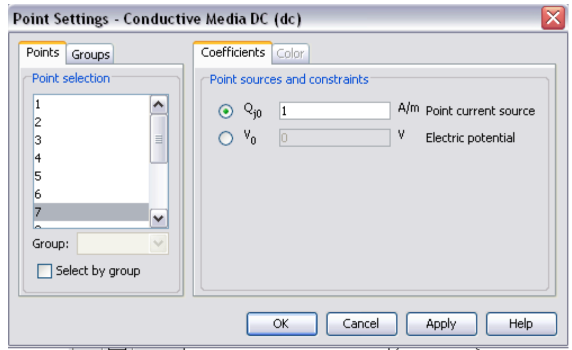


The field should now look like the following:



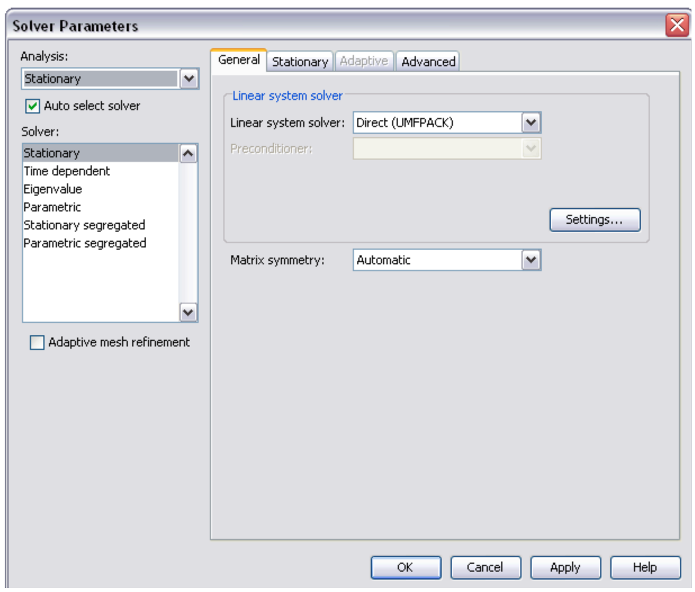
Define the two electrodes as source/sink locations using Physics → Point Settings. Select each electrode. Set the point current source of one to a value of 1, the other to -1 (Why these values? Do magnitude and sign matter? Does it matter which is which?).



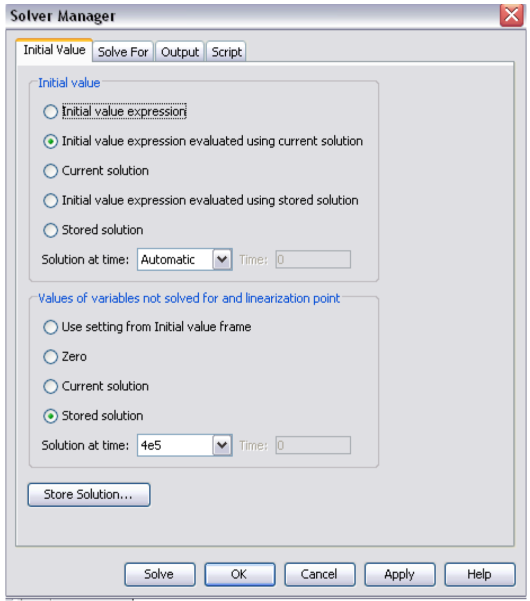


7.1 Create mesh, solve for flow

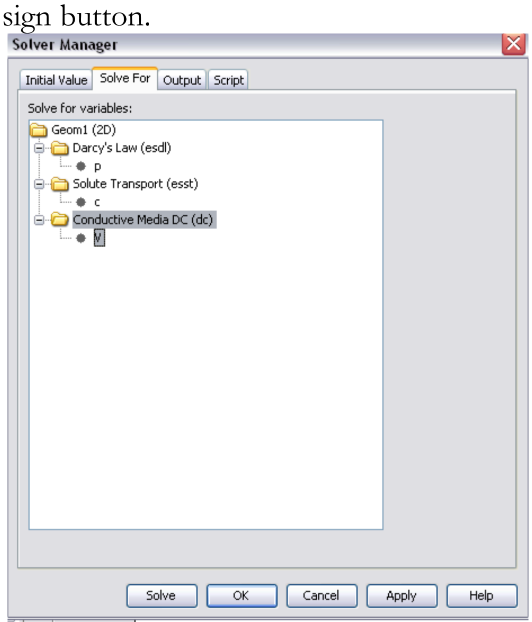
Follow steps 1.3 to create your mesh. Follow sections 1.4 and 2.4 to forward model fluid flow and transport again. After doing so, we'll solve for electrical flow. As we did when solving fluid flow and transport, go to Solve → Solver Parameters. Set the solver back Stationary—we are looking for the steady-state solution of electrical flow.



Click OK. Go into Solve → Solver Manager. Click Store Solution to store the concentration data. Go ahead and save all time steps. Select one time step to consider first—try 4e5 s. (You can plot the plume under Plot Parameters to see what it looks like at this time.) We can only consider transport at one step at a time (why?).

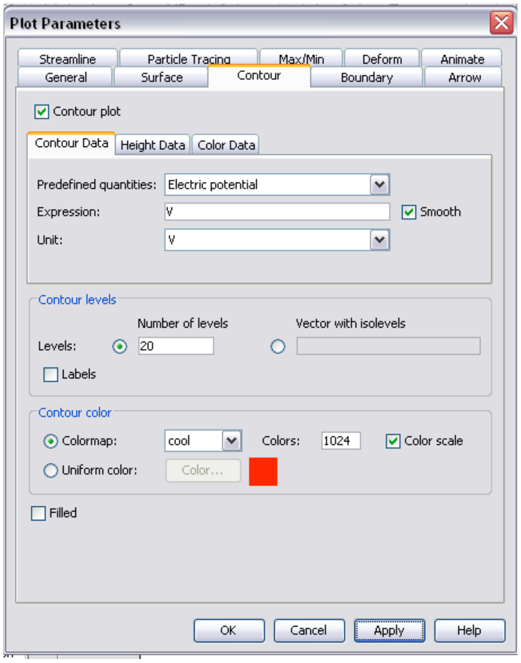


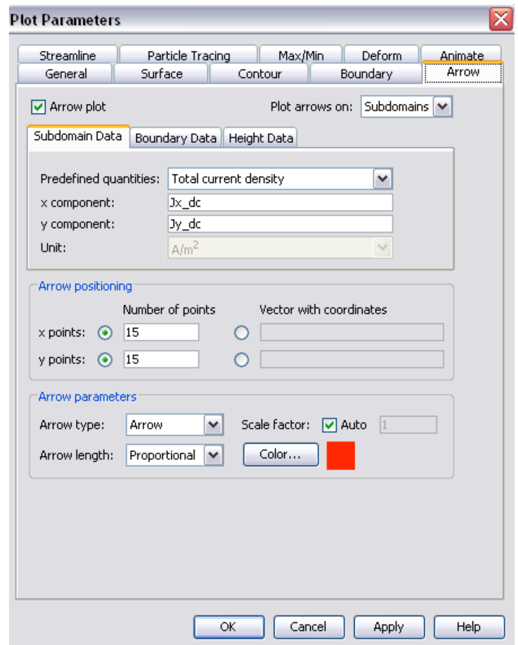
Under the Solve For tab solve the Conductive Media DC module for V (voltage). To solve from this menu you can click Solve, or hit OK and the equal sign button.



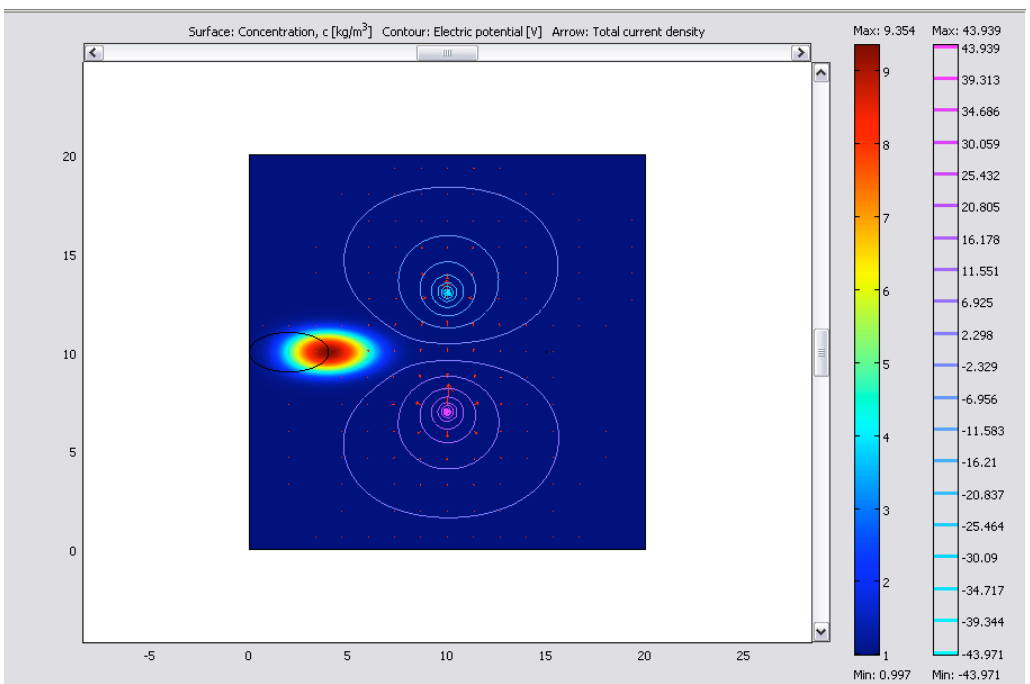
7.2 Plotting voltages

Go to Postprocessing → Plot Parameters. Using the Surface tab, plot the concentration data at 4e5 s. Using the Contour tab, plot the electrical potential. Using the Arrow tab, plot the Total Current Density.

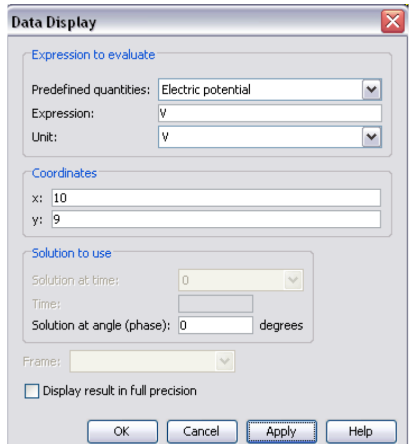




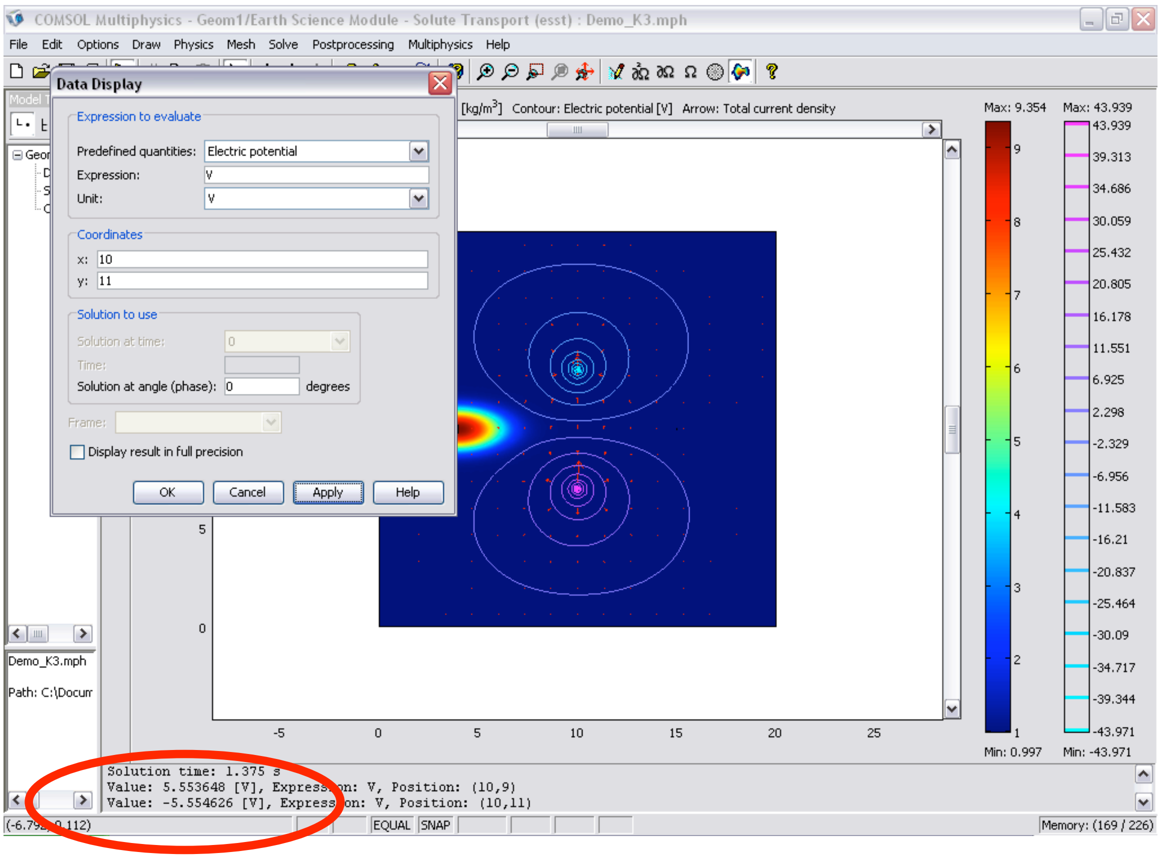
Note how the electrical potential bends due to the presence of the tracer!



We now need to find the voltage at our voltage electrodes, which we haven't simulated (why?). To do this manually, the easiest thing to do is go to Postprocessing → Data Display → Subdomain. From here, select Electrical Potential as the quantity of interest, and put in the coordinates where we want to know the voltage. Let's find the voltage and two location between our current electrode: (10,9) and (10,11). Insert the first location, and click OK.

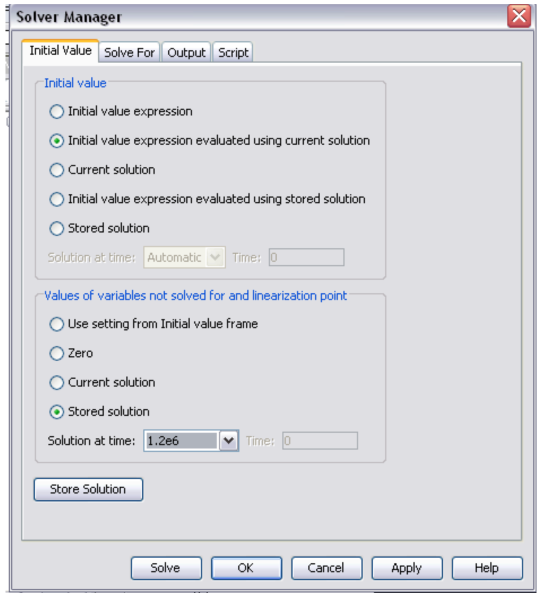


The voltage shows up at the bottom of the screen (circled in red). Repeat for the second case. Note the magnitude and sign of measurements. Does this make sense? Write down the values at both electrodes.

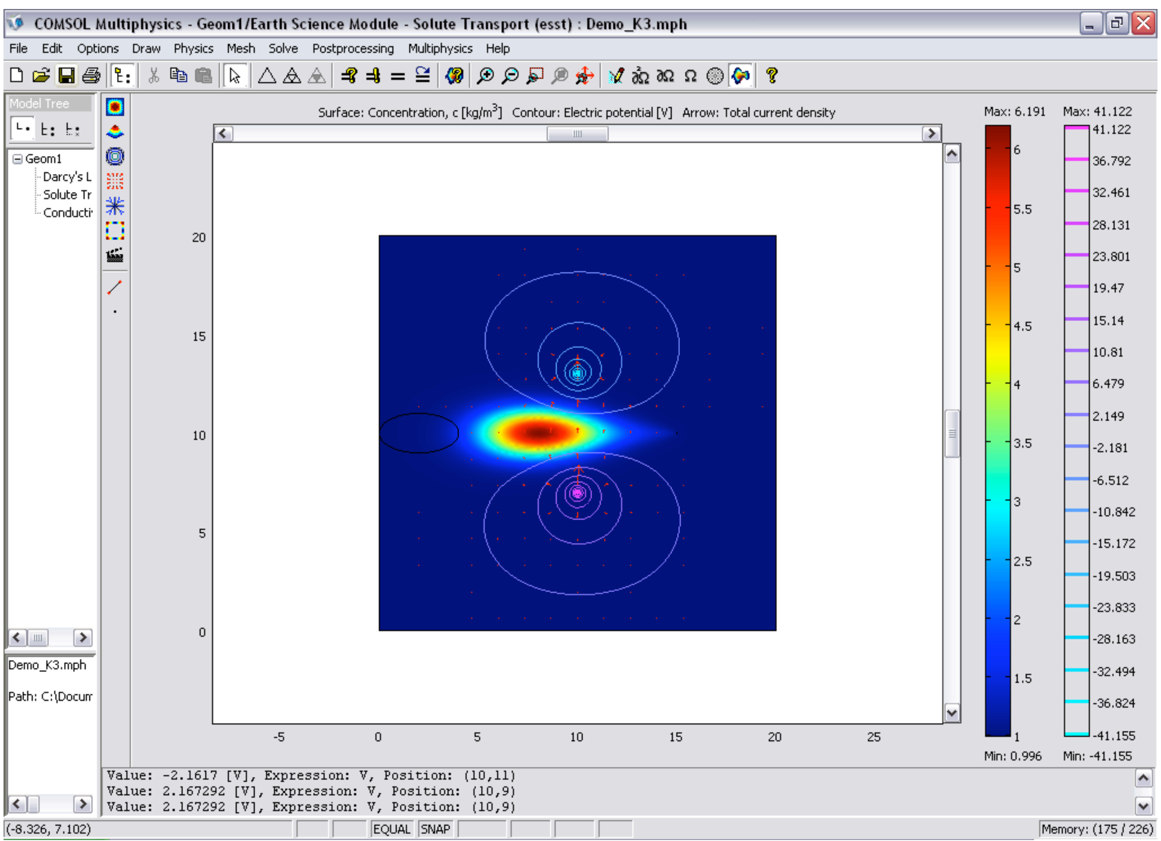


7.3 Solving flow at a second time step

Repeat the process in 7.1 and 7.2 but using the concentration simulation at 1.2e6 s.

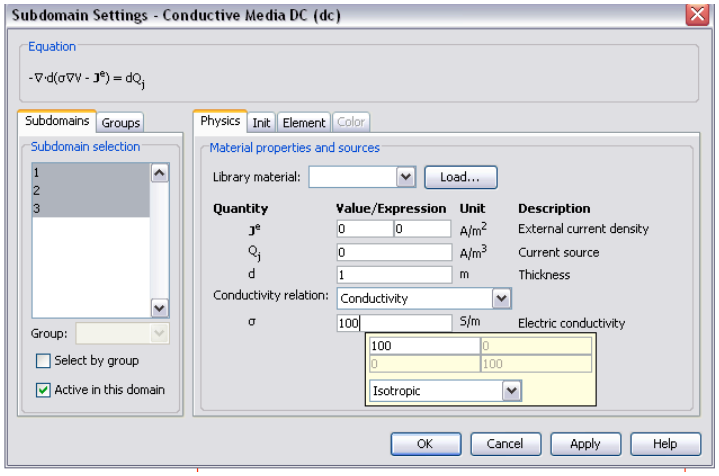


Find the voltages at the same two locations.

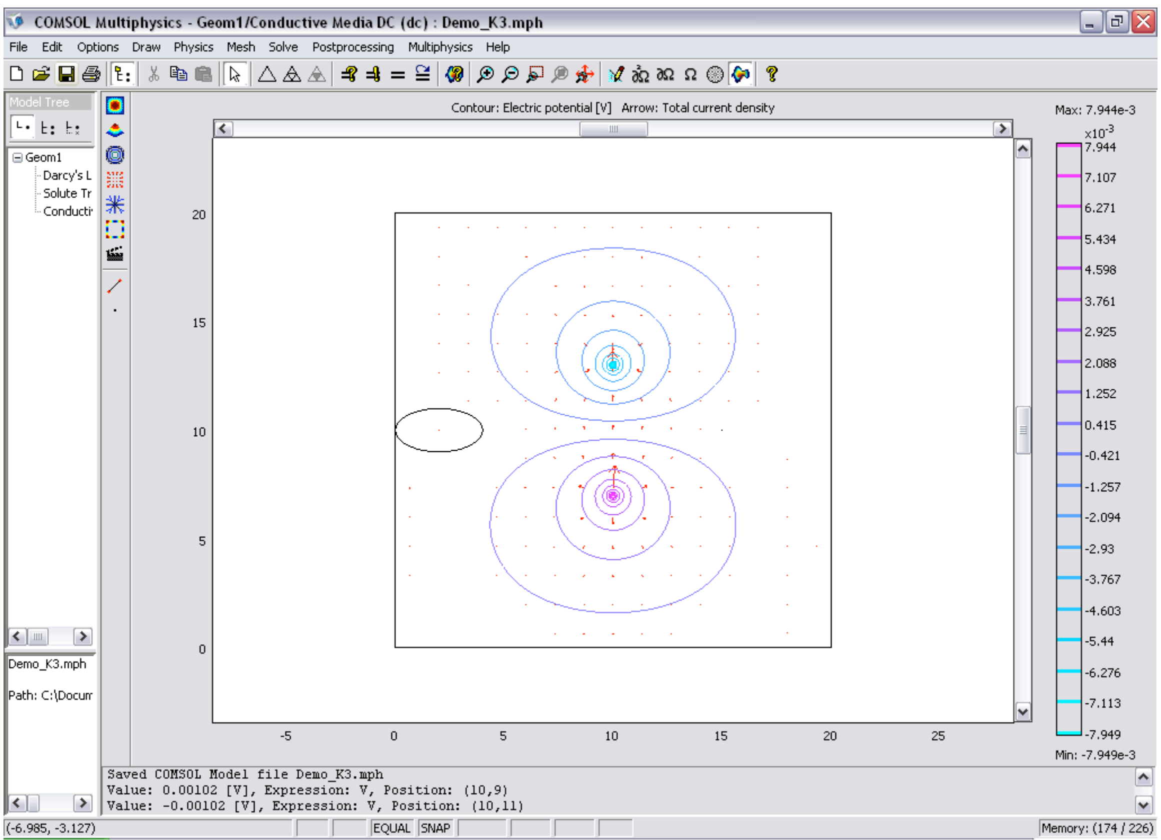


7.4 Calculating the geometric factor

As we know from the field data, we need a geometric factor to convert our voltages and currents into apparent resistivities. We can simulate the geometric factor by assuming a homogeneous conductivity and forward modeling the resultant voltages from a current of 1. Go back into Physics → Subdomain settings, and change the conductivity to a homogeneous value. Choose 1 or 100 or something easy to make the calculations simple.



Follow the steps in 7.1 to simulate flow again. There's no concentration data this time to affect our measurements, so just plot the voltages alone, and display the values of voltage at our two locations of interest. How do you calculate the geometric factor from this measurement?



EXPLORING COMSOL

Answer the following questions:

1. How does your hydraulic head map change, given a steady-state solution, if you increase the homogeneous hydraulic conductivity by a factor of 100? What if you decrease it by a factor of 100? Why does this occur?

2. How does the transport of your plume change given the above? Why?

3. What happens if you had defined the right-hand boundary as a concentration boundary? Explore the homogeneous model. Why?

4. How does the transport of the plume change for the block heterogeneity case if we had increased K by an order of magnitude? Why?

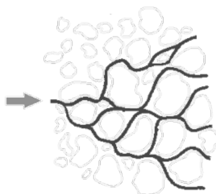
5. Draw your own zone(s) of heterogeneity. Follow through modeling flow and transport. Make a plot of your heterogeneity, the head field, and the subsequent concentration field at some later time. Do your results make sense? Why or why not?

6. Move the location of the tracer plume and rerun the heterogeneous case. Note where you moved the tracer and the subsequent behavior.

7. Calculate the apparent resistivity for the two time steps of concentration we simulated, given your geometric factor. Do these numbers make sense? Simulate a few other time steps and make a plot of apparent resistivity through time. What do you see?

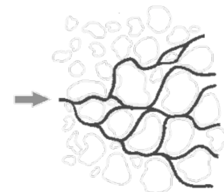
Solute Transport

- Outline:
  - Advection, diffusion, dispersion

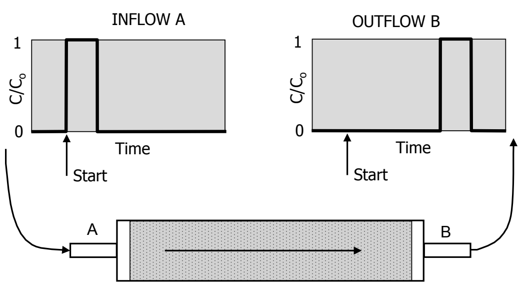


What controls the transport after the contaminant is present?

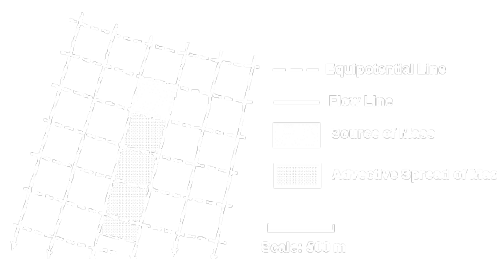
- Three controlling processes:
  - Advection
  - Dispersion
  - Diffusion



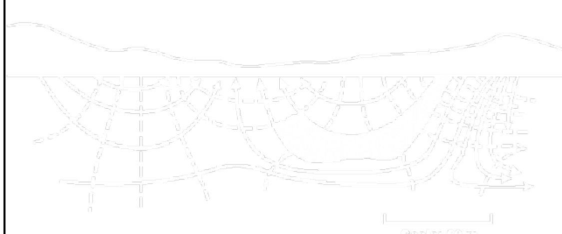
Experimental Pulse Tracer



Pure Advection



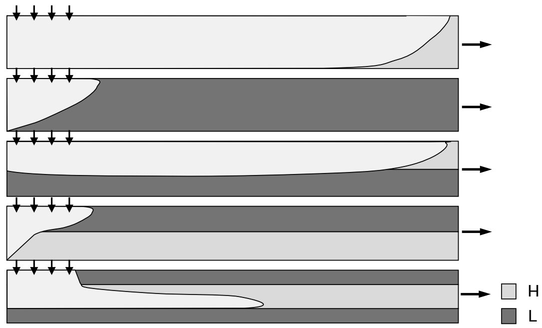
Advection in Stream Tube



Controls on Advection

- Magnitude and direction of advective transport is controlled by:
  - hydraulic conductivity field
  - potentiometric head distribution
  - distribution of sources and sinks
  - shape of the flow domain

Hydraulic Conductivity Field



Linear Advective Velocity

Recall from Darcy's Law:

$$v = \frac{q}{n} = -\frac{K}{n}\frac{dh}{dl}$$

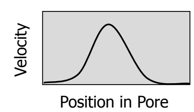
where *n* is the effective (or connected) porosity

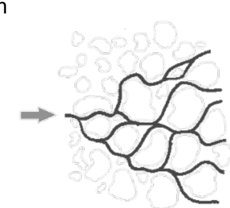
Take 2

- If we only consider advection and we start with a "point" of material with C_o=1000 mg/L, K = 0.1 cm/sec, dh = 10 cm, dl = 100 cm, n = 0.2
- How long will it take for the material to move 50cm?
- What will the concentration be at that location at that time?

Mechanical dispersion

- Mechanical dispersion spreads mass within a porous medium in two ways:
  - Velocity differences within pores on a microscopic scale.
  - Path differences due to the tortuosity of the pore network.

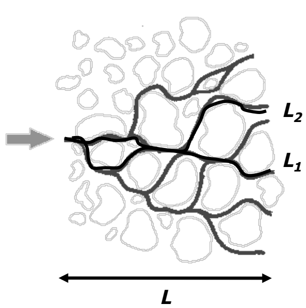




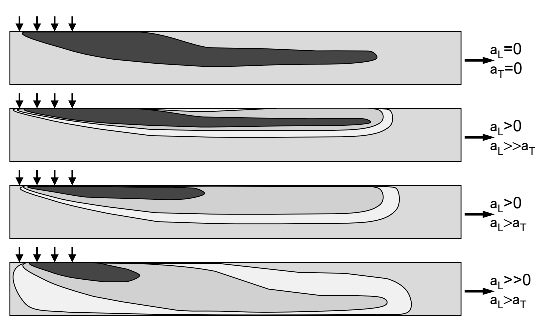
Tortuosity

- How "crooked" the pathway is
  t = L_n/L

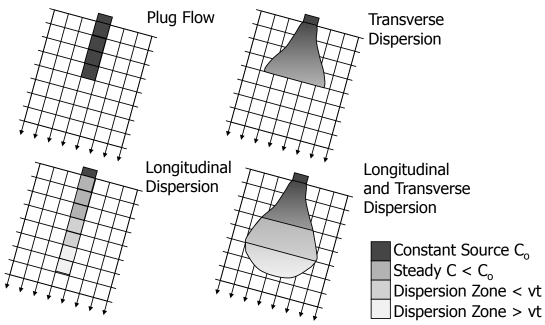
Note: t is sometimes shown as the reciprocal or the square of the above



Dispersion (Another Tensor!)



Multi-dimensional Dispersion



Diffusion

- Diffusion is the movement of dissolved species from areas of high concentration to low concentration.
- Mixing occurs from the random motion of solute molecules as a result of thermal kinetic energy or as a result of concentration gradients in porous media.
- Diffusion can occur when there is no hydraulic gradient driving flow and the pore water is static.
- Diffusion in groundwater systems is a very slow process, but may be the controlling process in very low permeability material.

Diffusion Law

- Fick's first law:

$$J = -D_d \frac{dC}{dl}$$

- D_d in open water $1\text{x}10^{-9}$ to $2\text{x}10^{-9}$ m^2/sec
- Diffusion in granular media is less than in open water
- D* used in porous media is reduced due to tortuosity and effective porosity; some suggest

$$D^* = D_d \frac{n}{\tau}$$

- D* ~ $2\text{x}10^{-11}$ to $5\text{x}10^{-10}$ m^2/sec

Diffusion Law

- Darcy's law for relates fluid flux to hydraulic gradient:

$$q = -K \frac{dh}{dl}$$

- For mass transport, there is a similar law (Fick's first law) relating solute flux to concentration gradient in a pure liquid:

$$J = -D_d \frac{dC}{dl}$$

where
J is the chemical mass flux [moles. $L^{-2}T^{-1}$]
C is concentration [moles.L^{-3}]
D is the diffusion coefficient in open water [L^2T^{-1}]

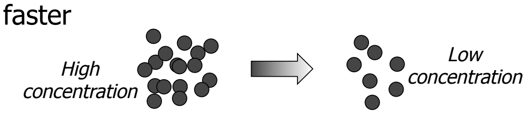
D_d for Common Ions

Cation	D_d (10^{-10} m^2/s)	Anion	D_d (10^{-10} m^2/s)
H^+	93.1	OH^-	52.7
K^+	19.6	Cl^-	20.3
Na^+	13.3	HS^-	17.3
		HCO_3^-	11.8
Ca^{2+}	7.93	SO_4^{2-}	10.7
Fe^{2+}	7.19	CO_3^{2-}	9.55
Mg^{2+}	7.05		
Fe^{3+}	6.07		

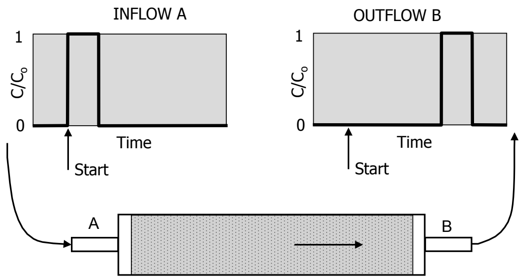
Notice that diffusion coefficients are smaller the higher the charge on the ion

Why is diffusion so small?

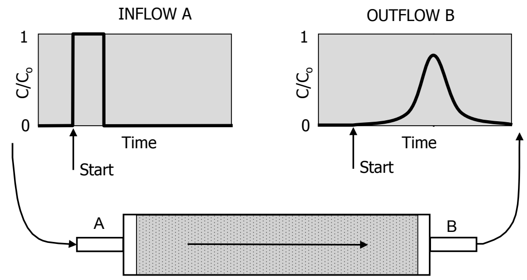
- D* is the diffusion, which is the movement of molecules from a high concentration to a low concentration.
- Mixing from diffusion (like perfume in an empty room) happens very slowly, so D* is very small. Advection is much much faster



Experimental Pulse Tracer

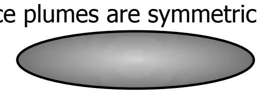


Experimental Pulse Tracer

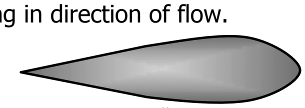


Plume Shape

- Typically, vertical transverse dispersion is small and plumes have a "surfboard" shape
- Pulse source plumes are symmetric about the centroid.



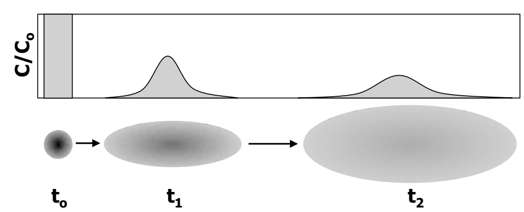
- Continuous source plumes are assymmetric, broadening in direction of flow.



- In 3D, plumes are often "cigar shaped"

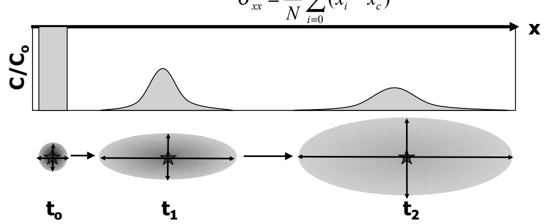
Two-Dimensional Pulse

- Two-dimensional spread of a pulse tracer in a unidirectional flow field results in an elliptically shaped concentration plume with a Gaussian mass distribution.



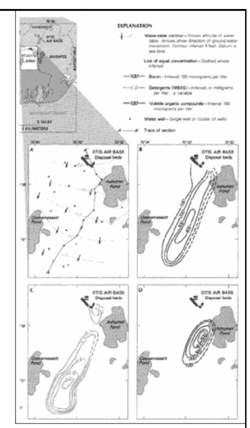
How do we describe this change in space and time?

-
  1) the center of mass and $x_c = \frac{1}{N}\sum_{i=0}^{N} x_i$
  2) the spatial variance $\sigma_{xx}^2 = \frac{1}{N}\sum_{i=0}^{N}(x_i - x_c)^2$



How to measure center of mass, variance?

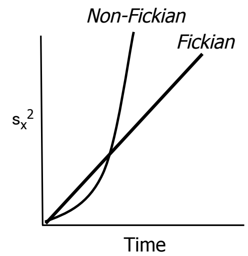
- Usually, we estimate from a limited number of wells



How do center of mass and spatial variance change with time?

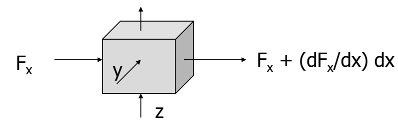
- COM increases linearly with time
- Variance can do any number of things—called Fickian if it increases linearly with time

$$D_x = \frac{1}{2}\frac{\partial(\sigma_x^2)}{\partial t}$$



Advective-Dispersive Equation

- The Advection-Dispersion Equation (ADE) can be derived by considering an REV as we did for the flow equations: combine Fick's law, advection, and continuity



F_x = total mass per area transported in x direction

F_y = total mass per area transported in y direction

F_z = total mass per area transported in z direction

To the board!

ADE

- Derived by combining Fick's law and continuity $J = -D\frac{dC}{dl}$

$$\frac{\partial C}{\partial t} = \nabla \cdot (D\nabla C) - \nabla \cdot (vC)$$

dispersion *advection*

3-D Transport (good for confined & unconfined aquifers)

where C = fluid concentration
t = time
D = dispersion tensor
v = average linear velocity

In one dimension…

$$\frac{\partial C}{\partial t} = D_x\frac{\partial^2 C}{\partial x^2} - v_x\frac{\partial C}{\partial x}$$

dispersion *advection*

1-D Transport (anisotropic, homogeneous D)

where
C = concentration
t = time
x = spatial coordinate
D = dispersion tensor
v = average linear velocity
n = porosity

1-D Equation

$$\frac{\partial C}{\partial t} = D_x\frac{\partial^2 C}{\partial x^2} - v_x\frac{\partial C}{\partial x}$$

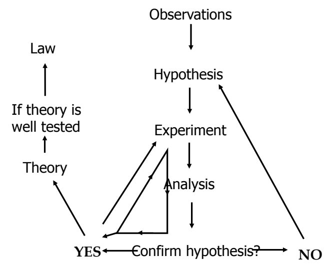
How is this different than the flow eqn?

$$\frac{\partial h}{\partial t} = \frac{T_x}{S}\frac{\partial^2 h}{\partial x^2}$$

Flow is diffusive only, transport is diffusive and advective

The Scientific Method

Outline: What science is, how to test hypotheses



1-D Equation

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x}$$

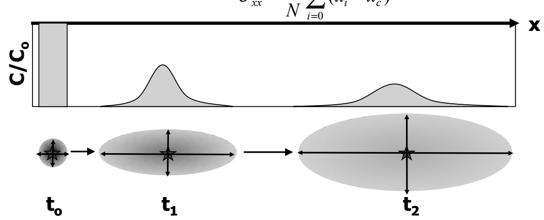
How is this different than the flow eqn?

$$\frac{\partial h}{\partial t} = \frac{K_x}{S_s} \frac{\partial^2 h}{\partial x^2}$$

Flow is diffusive only, transport is diffusive and advective

How do we describe this change in space and time?

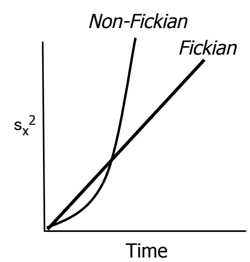
- 1) the center of mass and $x_c = \frac{1}{N}\sum_{i=0}^{N} x_i$
- 2) the spatial variance $\sigma_{xx}^2 = \frac{1}{N}\sum_{i=0}^{N}(x_i - x_c)^2$



How do center of mass and spatial variance change with time?

- COM increases linearly with time
- Variance can do any number of things—called Fickian if it increases linearly with time

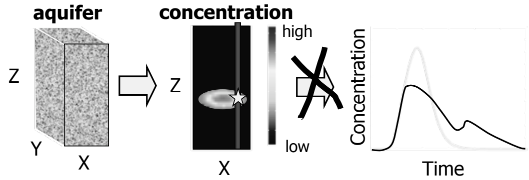
$$D_x = \frac{1}{2}\frac{\partial(\sigma_x^2)}{\partial t}$$



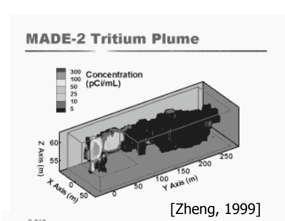
Motivation

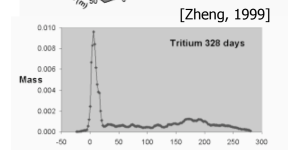
Need to understand flow and transport processes

- to assess risk
- create schemes for contaminant cleanup



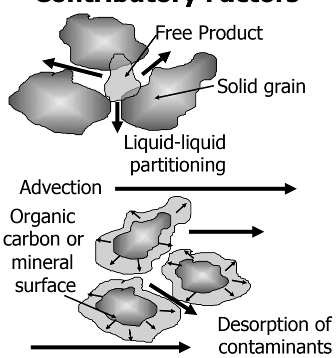
"Anomalous" Transport Behavior



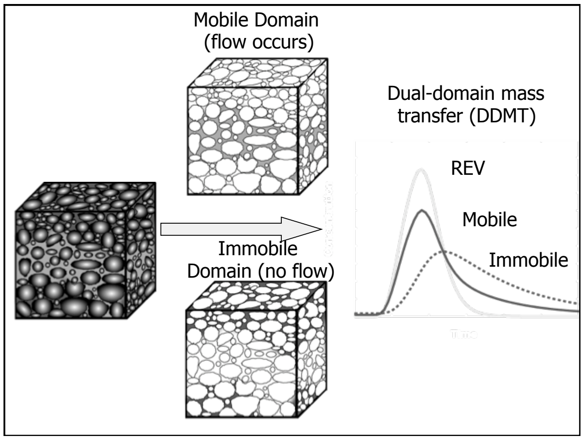


- MAcroDispersion Experiment Site, Mississippi
- Peak concentration stayed close to injection
- Highly asymmetric plume, non-Gaussian pattern
- Observed mass was overestimated early on, underestimated at the end of the test
- Why?

Tailing and Rebound: Contributory Factors

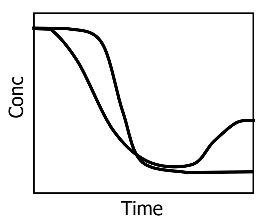


- out of a less-mobile domain
- Fast paths vs slow paths
- Precipitation-solution reactions
- Sorbed (stuck) contaminant released from OC or minerals

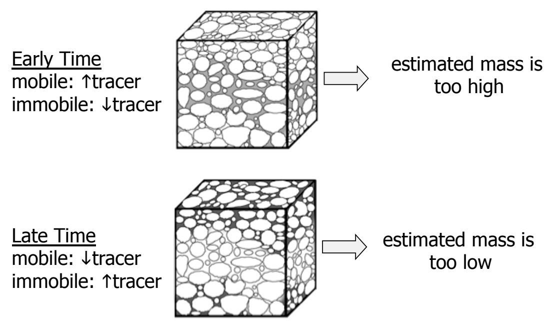


The Problem

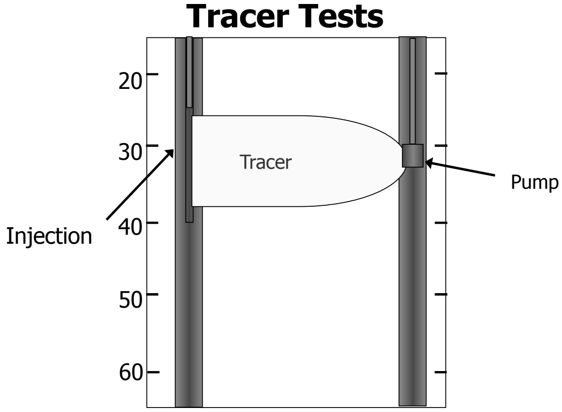
- ’ immobile domain, as there’s no flow
- DDMT is just a hypothesis
- Standard hydrologic measurements don’t provide enough information to determine the magnitude (or existence!) of the post-pumping rebound



What is the evidence for DDMT?



Tracer Tests



How Science Develops

Observation *or* pose a question

↓

Make a prediction, formulate a hypothesis

↓

Design a study, perform an experiment to test hypothesis

↓

Collect & analyze data

↓

Accept or reject hypothesis & draw conclusions

What is science?

⅄
1.
2.
infallible — knowledge about the universe
⅄
- "What we observe is not nature itself, but nature exposed to our method of questioning." (Heisenberg)

⅄
- Premised on development of falsifiable hypotheses
- Theory vs. Law

A **Non-Experimental** Approach

Observation: There appears to be a difference in gender in the students who are taking field camp

↓

Hypothesis:
- There are more males, or
- There are more females

↓

Experiment: Count all students and record their genders

↓

Data: Collect data from enrollment list, & run statistical analysis

↓

Accept or reject hypothesis & draw conclusions, i.e. why might there be a difference in gender?

An **Experimental** Approach

Question: Does Drug **A** increase the attention of students in field camp?

↓

Hypothesis: Students with drug **A** will have higher attention than students without it

↓

Experiment: **Experimental group**: X number with drug **A**
Control group: X number without drug **A**

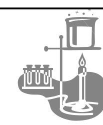
↓

Data: Perform the experiment, define "attention", then measure attention across both groups & run statistical analysis

↓

Accept or reject hypothesis & draw conclusions

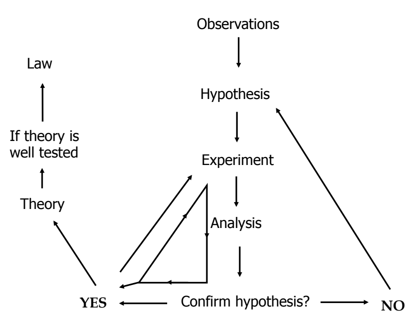
Scientific Process



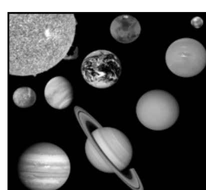
Replications lead to validation of results
- i.e., something might be special about the student body interested in geology
- Drug A works only over a short time period, or affects males different than females.

Results lead to new questions and scientific investigations.
- i.e., what causes the decrease in attention? Are alternative treatments without the expensive/harmful drug A possible?

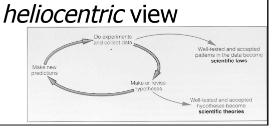
The Scientific Method



An Example



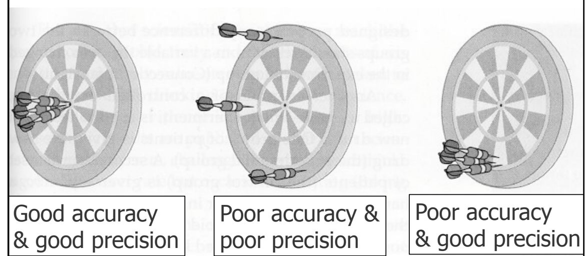
my hypothesized that the earth
the center of the universe in 140 AD
- Paradigm: model → geocentric view
- Copernicus, in 1580, showed that the movement of the stars were better explained by a *heliocentric* view



Current Controversies

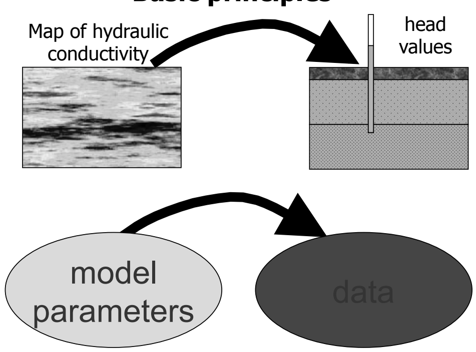
- Intelligent Design vs. Evolution / Big Bang
  - Were the ancient Greeks, Romans, etc. right?
- Embryonic Stem Cells vs. Adult Stem Cells
  - What can they do and how well?
- Anthropological contributions to climate change
  - Can humans affect global climate?
- Natural supplements vs. synthetic drugs
  - Which is better? Do they work? Are they safe?

Accuracy & Precision in Scientific Data



Forward Modeling

Basic principles



Forward Modeling

Basic principles

We need to solve the following for a given distribution of K and a pumping well W

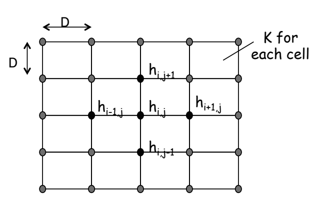
$$\frac{\partial}{\partial x}\left(K\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial h}{\partial y}\right)=W$$

This will give us values of h at the observed locations (positions of observation wells)

Forward Modeling

Solution through discretization
- basic principles of finite differences

$$\frac{\partial}{\partial x}\left(K\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial h}{\partial y}\right)=W$$

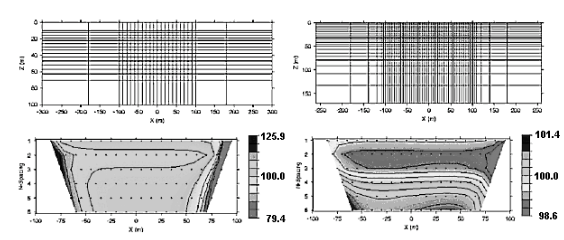


$$\frac{K\left(\frac{h_{i+1,j}-h_{i,j}}{\Delta x}\right)-K\left(\frac{h_{i,j}-h_{i-1,j}}{\Delta x}\right)}{\Delta x}+\frac{K\left(\frac{h_{i,j+1}-h_{i,j}}{\Delta y}\right)-K\left(\frac{h_{i,j}-h_{i,j-1}}{\Delta y}\right)}{\Delta y}=W$$

Forward Modeling

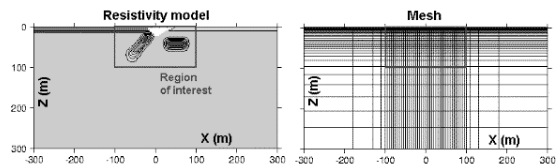
Discretization errors

Coarse Mesh — Fine Mesh

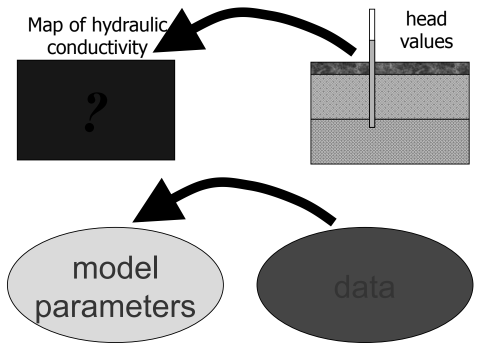


Forward Modeling

Solution through discretization
- dealing with boundaries



Inverse Modeling



How to determine if your model is a good one?

We could use the data misfit:

$$\phi = \sum_{i=1}^{N} \left(\frac{F_i(\mathbf{m}) - d_i}{\varepsilon_i} \right)^2$$

$F_i(\boldsymbol{m})$ is modeled head for measurement i,
d_i is the i^{th} observed head from the field,
e_i is error for measurement i,
N is number of measurements

Looks a bit like a variance—
called a "least squares" fit

Coefficient of Variation

- Measures relative variation
- Always in percentage (%)
- Shows variation relative to mean
- Can be used to compare two or more sets of data measured in different units

$$CV = \frac{\sigma}{\bar{x}}$$

Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model

Heidi Christiansen Barlebo
Geological Survey of Denmark and Greenland, Copenhagen, Denmark

Mary C. Hill
U.S. Geological Survey, Boulder, Colorado, USA

Dan Rosbjerg
Environment and Resources DTU, Technical University of Denmark, Kongens Lyngby, Denmark

Received 20 December 2002; revised 5 January 2004; accepted 30 January 2004; published 22 April 2004.

[1] Flowmeter-measured hydraulic conductivities from the heterogeneous MADE site have been used predictively in advection-dispersion models. Resulting simulated concentrations failed to reproduce even major plume characteristics and some have concluded that other mechanisms, such as dual porosity, are important. Here an alternative possibility is investigated: that the small-scale flowmeter measurements are too noisy and possibly too biased to use so directly in site-scale models and that the hydraulic head and transport data are more suitable for site-scale characterization. Using a calibrated finite element model of the site and a new framework to evaluate random and systematic model and measurement errors, the following conclusions are derived. (1) If variations in subsurface fluid velocities like those simulated in this work (0.1 and 2.0 m per day along parallel and reasonably close flow paths) exist, it is likely that classical advection-dispersion processes can explain the measured plume characteristics. (2) The flowmeter measurements are possibly systematically lower than site-scale values when the measurements are considered individually and using common averaging methods and display variability that obscures abrupt changes in hydraulic conductivities that are well supported by changes in hydraulic gradients and are important to the simulation of transport. *INDEX TERMS:* 1832 Hydrology: Groundwater transport; 1829 Hydrology: Groundwater hydrology; 1869 Hydrology: Stochastic processes; 3260 Mathematical Geophysics: Inverse theory; *KEYWORDS:* flow, groundwater, heterogeneity, hydraulic conductivity, hypothesis testing, inverse modeling

Citation: Barlebo, H. C., M. C. Hill, and D. Rosbjerg (2004), Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model, *Water Resour. Res.*, *40*, W04211, doi:10.1029/2002WR001935.

1. Introduction

[2] High-quality data sets from controlled tracer tests in natural environments can be used to test and enhance understanding of processes, and understanding of related field measurements. A useful framework for this purpose is to attempt to use field data in a predictive mode, in which field measurements of model inputs are used directly in the model. The predictive ability of the measured values and the processes embodied in the model are then judged based on how well model outputs correspond to measured values.

[3] Such a data set was collected to evaluate subsurface transport at a heterogeneous site near Columbus, Mississippi. Previous experiments had focused on relatively homogeneous systems, such as those at Borden [*Mackay et al.*, 1986] and Cape Cod [*LeBlanc et al.*, 1991], and had provided fruitful results. At the Mississippi site, the many flowmeter measurements of horizontal hydraulic conductivity clearly reveal the system heterogeneity (Figure 1). The most reliable and complete conservative tracer test used tritium and was conducted as part of the MADE 2 experiment from 1990 to 1991 by Tennessee Valley Authority and Armstrong Laboratory, Tyndall Air Force Base. Figure 2 shows horizontal and vertical sections through the tritium plume.

[4] Previous attempts to analyze the data set from the MADE experiments have focused on using the measured hydraulic conductivities directly in models. None have successfully used these values in conventional advection-dispersion models to predict the measured sustained high concentrations near the source and distant transport of low concentrations. The following paragraphs briefly present the previous analyses.

[5] *Adams and Gelhar* [1992] conducted a spatial moments analysis of concentration measurements. The

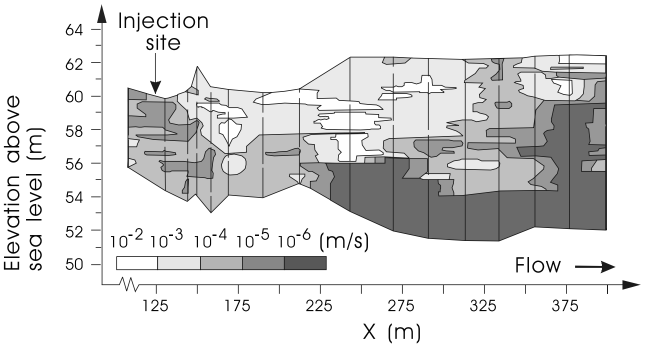


Figure 1. Distribution of hydraulic conductivity along plume centerline (y = 168 m) as determined from borehole flowmeter measurements. Vertical lines indicate rows of hydraulic conductivity measurements. Modified from *Adams and Gelhar* [1992].

moments information was interpreted by applying two different analytical transport models: (1) pure advection from a continuous source in a uniform flow field, and (2) advection and dispersion in a converging nonuniform flow field. The nonuniform flow advection-dispersion model represented the observed plume behavior best, but the computed skewness and kurtosis both increased monotonically with distance from the source, unlike the observed quantities. Of concern in this work is whether the nonuniform flow field model maintained the observed high concentrations at the source and produced the extensive spreading of low concentrations. Though not directly addressed by *Adams and Gelhar* [1992], the moments analysis suggests that it did not.

[6] Koch and Stauffer (Tyndall Air Force Base, written communication, 1995) used the hydraulic conductivity measurements directly to construct a numerical three-dimensional advection-dispersion model. The simulated plume was vastly different from the measured plume. Attempts to calibrate a subsurface flow and solute transport model by trial and error, first using the hydraulic head data to calibrate hydraulic conductivity, and then using the concentration data to calibrate dispersivity also failed in that progressively greater discrepancies between the observed and simulated plume occurred with increasing time of plume migration.

[7] *Zheng and Jiao* [1998] and one of the analyses conducted by *Feehley et al.* [2000] used the hydraulic conductivity measurements from two interpolation approaches to obtain three-dimensional hydraulic conductivity distributions. Applying a single-porosity model (equivalent to a classical advection-dispersion model) and two different values of longitudinal dispersivity produced three-dimensional simulated plumes that still failed to reproduce the observed significant spreading of low concentrations. *Zheng and Jiao* [1998] suggest that small-scale preferential flow paths not represented by the model affect the tracer field.

[8] *Eggleston and Rojstaczer* [1998] analyzed several methods of using the hydraulic conductivity data with a three-dimensional particle-tracking advection-transport model to investigate transport of the bromide plume from the MADE 1 experiment. The results indicated poor correspondence between the simulated results and basic features of the measured plume, even when accounting for the lack of dispersion in their advection-transport model. For example, high concentrations were not maintained close to the injection well. They suggest that small-scale (<10 m) hydraulic conductivity structures control bulk transport.

[9] *Mayer and Huang* [1999] used the MADE 2 data in an inverse model with both head and concentration data, like this study, but their purpose was only to test their algorithm [*Mayer and Huang*, 1999, pp. 845–846]. They simulated a $23 \times 90 \times 5$ m^3 volume of the system and suggest that a model that covers more of the system is needed.

[10] The models discussed thus far were based on the traditional advection or advection-dispersion equations. *Berkowitz and Scher* [1998] showed that non-Gaussian propagation of chemical transport in fracture networks results from subtle features of steady state flow through the network. Comparison with data from the MADE 1 experiment shows that the algorithm is capable of reproducing the basic plume characteristics. *Harvey and Gorelick* [2000] suggested that a double-porosity model without dispersion might explain the large-scale behavior of the solute plume at the MADE site. Their model, however, was unable to reproduce the distant transport of low concentrations at the site. In part they attribute this to their use of the simple convergent flow model of *Adams and Gelhar* [1992]. *Feehley et al.* [2000] used a double-porosity model with their interpolated hydraulic conductivity distribution to obtain a model that reproduced reasonably well the main features of the measured plume, including the maintained high concentrations at the source and the extensive spreading of the measured plume. They conclude that the classical advection-dispersion model can not reproduce the extensive spreading of the measured plume, but in this paper we show that this may not be true.

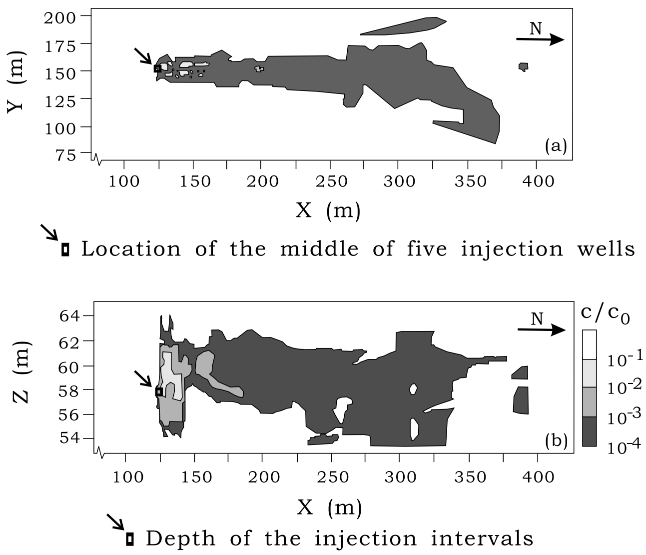


Figure 2. Planar profiles through a three-dimensional interpolation of measured tritium concentrations plume after 328 days. (a) Horizontal section at elevation 59.5 m. (b) Vertical section along center of plume. Concentrations were measured at the locations shown in Figure 4a. Modified from *Stauffer et al.* [1994].

[11] In hopes of improving our knowledge of how field measurements and model results relate, this work uses a model based on advection-dispersion theory (an early version of WATFLOW/WTC [*Molson and Frind*, 2002]) and nonlinear-regression methods [*Yeh*, 1986; *Carrera*, 1987; *Hill*, 1998], as implemented by *Barlebo et al.* [1998], and the data from the MADE 2 tritium experiment to identify subsurface heterogeneity and recharge characteristics capable of reproducing major characteristics of subsurface transport at the MADE site. Other processes such as dual porosity are not included. This work considers explicitly the possibility that the measured hydraulic conductivity values may be too noisy and biased to be used as directly in model development as has been done in other work. Possible bias has been suggested by those involved in data collection (S.C. Young, Environmental Consulting Engineers, Knoxville, Tennessee, USA, oral communication, 1996). In model development we emphasize measured hydraulic head and concentration data and de-emphasize measured hydraulic conductivities. This approach is considered to be valid because errors in the measured hydraulic conductivity values are expected to be much larger than errors in the measured heads and concentrations, an expectation common to many groundwater studies and supported for the MADE site by replicate hydraulic conductivity measurements presented by [*Rehfeldt et al.*, 1989] and discussed later in this work. In much of the literature cited above, rather crude flow fields or apparently less rigorous treatment of hydraulic head data than is pursued in this work have been accepted to obtain the reported results. The approach used here, in which measurements of hydraulic heads and concentrations are trusted more than the measurements of hydraulic conductivity, is a common approach for groundwater model calibration. This work demonstrates the utility of this common method.

[12] The approach considered here requires that the hydraulic conductivity field be parameterized. The distribution used is based on the observed abrupt spatial changes in hydraulic gradients (which suggests a pattern consistent with zones of constant value) and the basic features of transport. The subsurface hydraulic conductivities produced in this work, which largely reproduce the measured head and concentration distributions using an advection-dispersion model, are compared to measured hydraulic conductivities, which do not. The differences are investigated and possible explanations are explored, including possible bias in the measured hydraulic conductivity values. We also consider possible variations in areal recharge, and compare the recharge distribution suggested by this work to variations in recharge measured at other sites. The system considered is smaller than many groundwater systems of interest, but the results are considered to be broadly applicable because the issues involved are the same regardless of system size.

[13] The paper proceeds through the following steps. (1) The controlled tritium tracer test conducted in the MADE 2 experiment is described. (2) The three-dimensional inverse groundwater flow and transport model of *Barlebo et al.* [1998] is applied to data from the MADE 2 tritium tracer experiment. (3) The resulting model is examined, including parameter uncertainty, correlation, and plausibility, and simulated hydraulic heads and gradients, flows, and concentrations. (4) A framework for investigating random and systematic differences is introduced and used to compare the simulated hydraulic conductivity distribution to measured values. (5) Model results are used to investigate the following issues: the effect of random errors and apparent bias in the hydraulic conductivity measurements, the inverse approach used and its consequences, and if plume movement beyond the monitoring network can explain the apparent loss of mass during the experiment.

2. Field Experiment

[14] The Columbus site groundwater system is shallow, unconfined, approximately 11 m thick (extending approximately from 52 to 63 m above mean sea level), and consists of alluvial terrace deposits composed of sand and gravel with minor amounts of silt and clay [*Boggs et al.*, 1992]. Sediments are generally unconsolidated, and occur as irregular horizontal or nearly horizontal lenses and layers [*Rehfeldt et al.*, 1992]. Aerial photographs show a former river meander at the site that appears to correspond to the region of higher hydraulic conductivity in the central portion of the profile in Figure 1. This suggests that larger-scale geologic features are present but there is no indication that the flow is directed along the longitudinal axis of the channel [*Rehfeldt et al.*, 1992]. *Rehfeldt et al.* [1992] suggest treating the feature simply as a zone of larger hydraulic conductivity.

[15] The spatial distribution of horizontal hydraulic conductivity was measured during the MADE 1 and 2 experiments using a total of 5232 borehole flowmeter tests conducted in 67 fully penetrating, 5.2-cm-diameter wells. The flowmeter tests were conducted as follows. While the well was being pumped at a constant rate (in general, different rates in different wells), vertical flows were measured every 15.24 cm (6 inches) along the length of the well with an impellar flowmeter, and were used to determine the inflow to the well from each interval. Horizontal hydraulic conductivity for each interval was computed using well equations as being proportional to the measured flow from each interval [*Rehfeldt et al.*, 1992].

[16] Summarizing 2187 of the tests conducted in 49 of the wells during the MADE 1 experiment, *Rehfeldt et al.* [1992] estimated an overall variance of the natural logarithm of hydraulic conductivity ($\sigma^2_{\ln K}$) equal to 4.5, with measured horizontal hydraulic conductivities varying mostly between 1×10^{-2} m/s and 1×10^{-6} m/s (Figure 1). The remaining measured conductivities located in the same part of the system are within the same range. The MADE site is significantly more heterogeneous than the aquifers at the Borden ($\sigma^2_{\ln K}$ = 0.29 [*Mackay et al.*, 1986]), Cape Cod ($\sigma^2_{\ln K}$ = 0.26 [*LeBlanc et al.*, 1991]), and Twin Lakes ($\sigma^2_{\ln K}$ = 0.31 [*Killey and Moltyaner*, 1988]) sites, and this greater heterogeneity was one of the reasons it was chosen for study in the MADE experiments [*Boggs et al.*, 1992].

[17] Porosity as determined from 84 soil cores shows a mean of 0.31 and a range of 0.21 to 0.57 [*Boggs et al.*, 1990, 1992], or −37% to +83% of the mean value. The only spatial pattern apparent in the porosity data is a very slight decrease with depth [*Adams and Gelhar*, 1992], but both here and in that work a uniform value is used. For transport, the most likely result of this approximation is that the

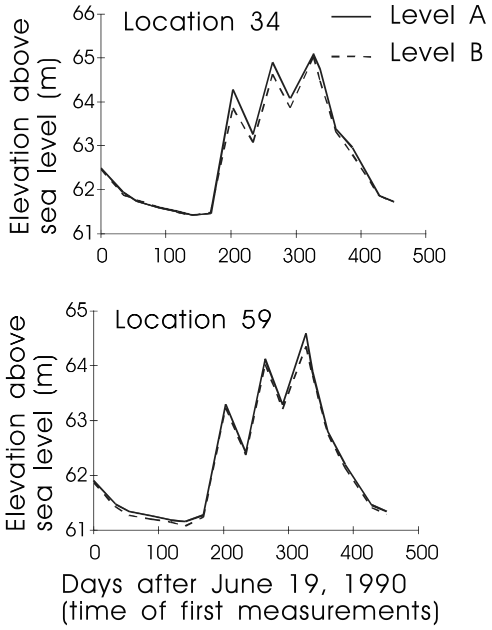


Figure 3. Trends in hydraulic head observations at locations 34 and 59. The locations are shown in Figure 4. The bottom of the simulated groundwater system is at elevations 55 and 51 m, respectively.

simulated fluid velocities are less variable than in reality; the effect would be a slight increase in estimated numerical dispersion. If large-scale patterns exist in the porosity distribution, the effect would be bias in the estimated hydraulic conductivities and recharge rates. These biases would be expected to be as within the range of the measured porosity values, or −37% to +83%. The bias would be expected to be less if, as is likely, these values include some experimental error as well as reflecting variations in porosity.

[18] Hydraulic heads were measured at 21 locations during the MADE 2 experiment, approximately monthly over a 16-month period. At most times and locations, hydraulic heads were measured at two elevations above mean sea level: 61.1 m and 56.3 m [*Boggs et al.*, 1993]. These are referred to in this paper as levels A and B, respectively. In the process of analyzing the head data, 13 clearly erroneous measurements, as determined from time trends and hydraulic head contour maps, were corrected and five missing observations at level B were interpolated from observations at level A. The locations and dates are listed in Appendix A. No trends in time or space were evident in the erroneous data.

[19] Seasonal fluctuations of the water table during MADE 2 were significant. Water level changes ranged from 3 to 4 m, about 30 to 40% of the average thickness. Temporal trends in water table elevations at two locations are shown in Figure 3; these are considered typical of the site. The magnitude of hydraulic head gradients along the plume centerline varied from the time-averaged gradient by a factor of 0.32 to 1.86 for level A, and 0.19 to 2.29 for level B.

[20] Although temporal water level changes are significant, the northward gradient and the existence and orientation of the trough (depicted as the axis toward which the hydraulic gradients on both sides slope in Figure 4a) were consistent throughout the year. This contradicts findings of *Stauffer et al.* [1994], *Harvey* [1996], and *Harvey and Gorelick* [2000], who report radical temporal changes in gradient direction. The different conclusions reached in this work may result from the data modification described above because *Stauffer et al.* [1994] imposed a planar trend on an irregular surface to determine hydraulic gradients or because *Harvey* [1996] and *Harvey and Gorelick* [2000] show only part of the area considered here.

[21] Despite the significant temporal changes in the magnitude of the gradient, steady state conditions are simulated here as they have been in all other studies of this site to date. Our reasons are (1) the direction of the hydraulic head gradients appears to be consistent over time, (2) this work focuses on reproducing major hydraulic head trends and characteristics of a plume that evolved over an 11-month period, and (3) transient simulations would have required several hours for a single solution instead of the half hour required for steady state and the moderately improved accuracy was not worth the less thorough calibration and evaluation effort attainable with the increased execution time.

[22] The steady state hydraulic heads used in the optimization are calculated as time-averaged values. The resulting time-averaged hydraulic head maps and the 21 hydraulic head measurement locations are shown in Figure 4. Major features from monthly hydraulic head maps are preserved in the time-averaged map. The overall horizontal hydraulic gradient, calculated as the difference in head at the most distant model boundaries divided by the distance between them (Figure 4), is approximately 0.003. At several measurement locations the vertical hydraulic gradient is as large as, or larger (up to 0.08) than, the overall hydraulic gradient. This suggests that vertical flow and therefore a three-dimensional model are important.

[23] The net infiltration at the site was calculated as 650 mm/year (T. Stauffer, Tyndall Air Force Base, written communication, 1995) but this value seems high for the area. Average annual streamflow divided by the area of the region is about 500 mm/year [*U.S. Geological Survey*, 1966]. Average annual streamflow divided by the contributing area approximates average annual infiltration plus surface runoff. Net infiltration is thus likely to be less than 500 mm/yr. In this area where actual evapotranspiration is expected to approach potential evapotranspiration, infiltration also can be approximated as precipitation minus potential evaporation and surface runoff. The map of precipitation minus potential evaporation in North America by *Winter* [1989] shows a value of about 300 mm/year at the MADE site; again net infiltration may be less. In this work, the validity of optimized recharge values is evaluated using these field values.

[24] In the MADE 2 tritium tracer experiment, approximately 9.7 m^3 of solution with a mean concentration of 55,610 pCi/ml was injected over 48.5 hours between elevations 57.5 and 58.1 m in five wells placed 1 m apart [*Stauffer et al.*, 1994]. Four snapshots of the full plume were measured 27, 132, 224, and 328 days after the injection giving a total of 6344 measured tritium concentrations. Horizontal and vertical profiles of the plume at 328 days,

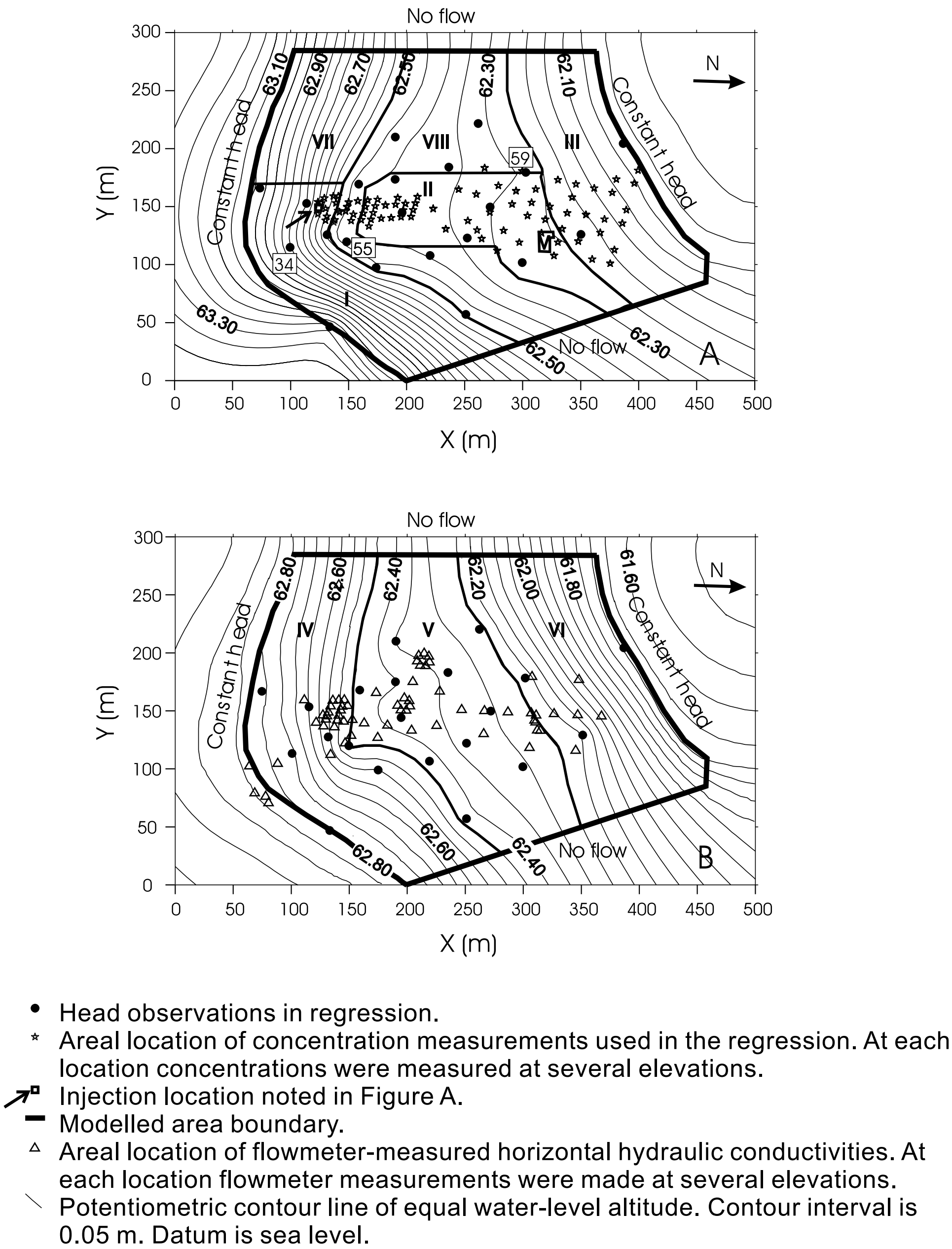


Figure 4. Time-averaged hydraulic head maps in levels (a) A (elevation 61.1 m) and (b) B (elevation 56.3 m). Hydraulic head observations are located in both levels A and B. Areal locations of multilevel concentration measurements are shown in Figure 4a; concentrations were measured at many depths at each location. The zones used to define the final hydraulic conductivity distribution are shown and labeled I, II, and so on.

including the location of the middle injection well, are shown in Figure 2. The background tritium concentration is about 2 pCi/ml.

3. Flow and Transport Inverse Model and Application to the Made Site

[25] Here inverse modeling is used to evaluate modeled processes and field data in a manner similar to that of *Barth et al.* [2001]. The three-dimensional groundwater flow and transport model includes nonlinear regression capabilities, as described by *Barlebo et al.* [1998]. The methods used are documented in that work, so are described only briefly here.

3.1. Flow and Transport Model

[26] The finite element, nonreactive, single-species, single-porosity flow and transport code used was developed by E. O. Frind and J. W. Molson (written communication, University of Waterloo, 1988), and is an early version of WATFLOW/WTC [*Molson and Frind*, 2002]. This code has a moving water table that is coincident with the upper boundary of the top layer of elements and three-dimensional implementation of dispersivities [*Burnett and Frind*, 1987].

Both capabilities are used in the modeling. The model grid size and transport step size were adjusted to ensure that the Peclet and Courant numbers did not exceed 5 and 1, respectively. Advective-transport models based on particle tracking, such as the method of characteristics, were not used because previous work had shown that oscillation common in these methods produce inaccurate sensitivities.

3.2. Objective Function and Weighting of Observations

[27] The statistical inverse method used is based on nonlinear regression [*Hill*, 1998], as implemented by *Barlebo et al.* [1998]. Observations of hydraulic head and concentration are included in the regression. With only head data the inverse problem is poorly posed because the estimated parameters are all extremely correlated; concentration data are needed for there to be any possibility of obtaining unique parameters estimates.

[28] Error for observation i is represented by ε_i, which is assumed to be a random error with zero mean. Representing the ith observed hydraulic head, $h_{i,obs}$, or concentration, $c_{i,obs}$, as the general variable, $a_{i,obs}$, the errors are conceptualized as

$$a_{i,obs} = a_{i,true}\left(x_i, t_i, \underline{\beta}\right) + \varepsilon_i \tag{1a}$$

Where $a_{i,true}$ is the true, unknown system, $\mathbf{x}_i$ is spatial location (l); t_i is time (t); and β is a vector of true, unknown parameter values. In this work a numerical model is constructed to duplicate the important processes and characteristics of the true system, and the observations are related to simulated values as

$$a_{i,obs} = a_{i,sim}(x_i, t_i, \underline{\theta}) + e_i \tag{1b}$$

where $\underline{\theta}$ is a vector of unknown parameter values and e_i is the residual for the ith observation. Model fit to heads and concentrations is quantified as:

$$f_h(\underline{\theta}) = \sum_{i=1}^{n_h} \left[h_{i,obs} - h_{i,sim}(\underline{\theta})\right]^2$$
$$f_c(\underline{\theta}) = \sum_{j=1}^{n_c} \left[\frac{c_{j,obs} - c_{j,sim}(\underline{\theta})}{c_{j,sim}(\underline{\theta})}\right]^2 \tag{2}$$

where n_h is the number of hydraulic head measurements and n_c is the number of concentration measurements. The errors in concentrations are thought to be proportional to the concentrations [*Wagner and Gorelick*, 1986], which ensures a good fit to both small and large concentrations. In equation (2) this is accounted for by dividing the concentration residual by the simulated concentration. In this work the quantity $c_{j,sim}(\underline{\theta})$ is never zero because the simulated background concentration is 2 pCi/ml.

[29] Observation errors are considered to be independent, so that the error covariance matrix, **V**, can be divided into two diagonal submatrices associated with hydraulic head, $\mathbf{V}_h$, and concentration, $\mathbf{V}_c$, errors, respectively. They are defined as:

$$\mathbf{V}_h = \mathrm{Cov}\left(\varepsilon_{i,h}, \varepsilon_{j,h}\right) = \sigma_h^2 \mathbf{U}_h$$
$$\mathbf{V}_c = \mathrm{Cov}\left(\varepsilon_{ic}, \varepsilon_{j,c}\right) = \left(CV_c^2\right)\mathbf{U}_c \tag{3}$$

where σ_h^2 is the variance for errors of hydraulic heads [L^2] and CV_c^2 is the coefficient of variation for errors of concentrations (dimensionless). The hydraulic head observation errors are all thought to have the same variance, σ_h^2, so $\mathbf{U}_h$ is a dimensionless unit matrix.

[30] By definition, the coefficient of variation, CV_c, is related to the variance of the errors in the concentrations, σ_c^2, as $CV_c = \sigma_c/c$, where here the concentration c is approximated by c_{sim}. The coefficient of variation is used for concentrations in equation (3) because in equation (2) the differences in concentrations already are divided by the simulated value. *Anderman and Hill* [1999] show that simulated instead of observed concentrations are needed to obtain unbiased parameter estimates. The concentration observation errors are all thought to have the same coefficient of variation, so $\mathbf{U}_c$ is a dimensionless unit matrix.

[31] Weighted-residuals for heads and concentrations are calculated as $\sigma_h^{-1}(h_{i,obs} - h_{i,sim}(\underline{\theta}))$ and CV_c^{-1} $(c_{i,obs} - c_{i,sim}(\underline{\theta}))/c_{i,sim}(\underline{\theta})$. The latter also can be expressed as $CV_c^{-1}c_{i,sim}(\underline{\theta})^{-1}$ $(c_{i,obs} - c_{i,sim}(\underline{\theta})) = \sigma_c^{-1}(c_{i,obs} - c_{i,sim}(\underline{\theta}))$. *Hill* [1998] suggests that σ_h and CV_c be determined based on an analysis of contributing errors. Here we determine them using an alternative approach, and evaluate the results from the perspective of plausible contributing errors.

[32] In this work, the least squares objective function is defined as:

$$f(\underline{\theta}) = f_h(\underline{\theta}) + \lambda_c f_c(\underline{\theta}) \tag{4a}$$

where λ_c is equivalent to the penalty function of *Carrera and Neuman* [1986] and is calculated as $\lambda_c = \sigma_h^2/CV_c^2$. Model parameters are estimated by minimizing the objective function with respect to the parameter values, $\underline{\theta}$, using an iterative Levenberg-Marquardt algorithm [*IMSL Inc.*, 1987; *Seber and Wild*, 1989, pp. 624–627]. Upper and lower limits are imposed to assure that each optimized parameter stays within a defined range, but wide ranges are applied so that unrealistic estimates can be used to diagnose model errors, as discussed by *Poeter and Hill* [1996] and *Hill* [1998].

[33] Using an automated version of the approach described by *Gailey et al.* [1991] (the equivalence is demonstrated in Appendix B), the value of λ_c is iteratively updated to achieve a solution for which the weighted-residuals all have the same variance, on average. Initially, $\lambda_c = 1.0$, which is equivalent, for example, to $\sigma_h = 0.3$ m and $CV_c = 0.3$. After each optimization iteration, r, new values of σ_h^2 and CV_c^2 are calculated as

$$\sigma_h^2 = f_h(\underline{\theta}^r)/n_h \text{ and } CV_c^2 = f_c(\underline{\theta}^r)/n_c, \tag{4b}$$

where $\underline{\theta}^r$ are the parameter values at iteration r. If the absolute difference between the new and the old value of λ_c is larger than a tolerance factor η (1×10^{-3} is used), λ_c is assigned the new value. For the final results presented in this work, $\lambda_c = 2.13 \times 10^{-3}$ m^2, which results from $\sigma_h = 0.0597$ m = 5.97 cm and $CV_c = 1.29$, as discussed below. Results reported by *Gailey et al.* [1991] produce a value of $\lambda_c = 1/(375 \text{ m}^{-2}) = 2.67 \times 10^{-3}$ m^2. In many respects the two data sets and groundwater system are similar, so some agreement of these values is to be expected. The smaller value obtained in this work indicates that the heads were more closely matched relative to the concentrations.

3.3. Parameter Uncertainty, Correlation, and Uniqueness

[34] The parameter variance-covariance matrix is used to calculate parameter estimate standard deviations,

Table 1. Labels, Optimized Values, Coefficients of Variation, and Composite Scaled Sensitivities for the Final Estimated Parameters[a]

Parameter Label	Optimized Parameter Estimate	Vertical Anisotropy	CV for the Estimate[b]	CSS for the Estimate[c]
r_1, mm/yr	210	–	1.62	0.035
r_2, mm/yr	317	–	2.28	0.19
α_l, m	8.3	–	0.08	0.40
α_{th}, m	1.3	–	0.05	0.13
α_{tv}, m	0.015	–	0.28	0.26
$k_{h,I}$,[d] m/s	2.66×10^{-5}	–	1.00	0.14
$k_{v,I}$, m/s	2.42×10^{-6}	10	16.70	0.017
$k_{h,II}$, m/s	8.28×10^{-3}	–	3.80	0.22
$k_{v,II}$, m/s	2.88×10^{-5}	287	>50	0.019
$k_{h,III}$, m/s	3.06×10^{-4}	–	>50	0.11
$k_{v,III}$, m/s	2.72×10^{-5}	11	>50	0.0015
$k_{h,IV}$,[d] m/s	2.03×10^{-4}	–	1.15	0.55
$k_{v,IV}$,[d] m/s	1.84×10^{-7}	1103	2.85	0.14
$k_{h,V}$,[d] m/s	5.72×10^{-5}	–	1.82	0.36
$k_{v,V}$,[d] m/s	4.82×10^{-6}	12	1.94	0.27
$k_{h,VI}$,[d] m/s	1.53×10^{-4}	–	5.48	0.45
$k_{v,VI}$, m/s	2.96×10^{-7}	517	>50	0.031
$k_{h,VII}$, m/s	5.86×10^{-5}	–	0.52	0.23
$k_{v,VII}$, m/s	2.73×10^{-4}	0.21	>50	0.019
$k_{h,VIII}$,[d] m/s	1.58×10^{-4}	–	2.66	0.06
$k_{v,VIII}$, m/s	9.85×10^{-8}	1604	>50	0.0035

[a]Here r_1 and r_2 are areal recharge in the southern and northern parts of the model, respectively; α_l, α_{th}, and α_{tv} are dispersivities for the longitudinal, transverse horizontal, and transverse vertical directions, respectively; $k_{h,j}$ and $k_{v,j}$ are horizontal and vertical hydraulic conductivities, respectively, where j indicates one of the zones shown in Figure 4.

[b]CV is coefficient of variation, the standard deviation of the estimated parameter (s_{kj}) divided by the estimated value (b_j). The CVs refer to native, untransformed parameters. Hydraulic conductivities are log transformed before estimation; their standard deviations are transformed back as $s_{kj} = [e^{2 \log k_j + cov(j,j)}(e^{cov(j,j)} - 1)]^{1/2}$ before they are used to calculate the coefficient of variation.

[c]CSS is composite scaled sensitivity, calculated as suggested by *Barlebo et al.* [1998, equations (9) and (10)], as modified from *Hill* [1998, equation (10)]. Calculated at the final parameter values.

[d]Parameter correlation coefficients are $k_{h,I}$ and $k_{h,IV}$, 0.97; $k_{v,IV}$ and $k_{h,I}$, $k_{v,IV}$ and $k_{h,IV}$, $k_{v,V}$ and $k_{h,V}$, $k_{h,VIII}$ and $k_{h,I}$, $k_{h,VIII}$ and $k_{h,IV}$, and $k_{h,VIII}$ and $k_{v,IV}$, 0.95; all others are less than 0.77.

coefficients of variation, linear confidence intervals, and correlation coefficients. The matrix is calculated as [*Graybill*, 1976, pp. 207–208; *Seber and Wild*, 1989, p. 25]

$$\mathrm{Cov}\left\{\underline{\theta}^*\right\} = \left(\underline{J}^T \underline{V}^{-1} \underline{J}\right)^{-1} \quad (5)$$

where $\underline{\theta}^*$ is a vector of optimized parameter values with jth element b^*_j; $\underline{J}$ is the Jacobian matrix with elements $\partial a_{i,sim}/\partial b_j$; and T indicates the transpose of the matrix.

[35] The Jacobian matrix is evaluated at the optimal parameter estimates and is calculated using central differences with a perturbation of 1×10^{-4} times the parameter estimate. The parameter standard deviations equal the square roots of the diagonals of $\mathrm{Cov}\{\underline{\theta}^*\}_{ii}$ or, for the log-transformed hydraulic conductivity parameters, using the equation noted in Table 1. The coefficients of variation (CV) are defined as the parameter standard deviations divided by the estimated values. The confidence intervals are linear and therefore approximate for the nonlinear groundwater model [*Seber and Wild*, 1989, p. 571; *Hill*, 1992, p. 69].

[36] Parameter correlation can be measured using parameter correlation coefficients calculated as $\mathrm{Cov}\{\underline{\theta}^*\}_{ij}/[\mathrm{Cov}\{\underline{\theta}^*\}_{ii}\ \mathrm{Cov}\{\underline{\theta}^*\}_{jj}]$ or using eigenanalysis of $\mathrm{Cov}\{\theta^*\}$. As shown by *Hill and Østerby* [2003], the two methods give similar results. Parameter correlation coefficients are easy to interpret: absolute values close to 1.00 suggest nonunique parameter values. Thus they are used here. Commonly parameter correlation coefficients are not used because they only identify extreme correlation between pairs of parameters. However, if more parameters are involved in the correlation, all pairs will have correlation coefficients with absolute values close to 1.00, and the limitation is rarely problematic.

[37] Parameter uniqueness is difficult to prove. In this work uniqueness is investigated by restarting the regression from several different sets of parameter values. This method is effective if the objective function is well-posed with the exception of extreme correlation between two or more parameters or extreme insensitivity. It may not be effective if multiple, disconnected minima are present, as can occur because of nonlinear relations between parameters and the simulated equivalents of the observations, and is exacerbated as the problem becomes more ill posed. The approach to parameterization we take in this work attempts to maintain a well-posed regression problem, which increases the chance that the method used to investigate uniqueness is effective.

3.4. Defined Parameters

[38] Assuming horizontal isotropy for the hydraulic conductivity in the model, unknown flow parameters are the horizontal and vertical hydraulic conductivity ($k_x = k_y$, k_z) and recharge rates. Horizontal anisotropy was considered in early simulations but this approach did not help explain the observed flow and transport. The hydraulic conductivity distribution was developed as discussed below, and is consistent with what is known about the depositional processes that created the deposit. The transport parameters are the porosity, n_e, and the longitudinal (α_l), transverse-horizontal (α_{th}), and transverse-vertical (α_{tv}), dispersivity coefficients. These parameters are assumed constant throughout the model domain, except as noted below. Estimating all hydraulic conductivity, dispersivity, recharge, and porosity values simultaneously would result in extreme parameter correlation, and of these it was thought that the porosity was determined most precisely and accurately from field data. Thus porosity is set to the average measured value of 0.31.

4. Model Construction

[39] Grid design and flow boundary conditions, tracer source, head and concentration observations, hydraulic conductivity field, and areal recharge are described below.

4.1. Grid Design and Flow Boundary Conditions

[40] The model domain is 410 m long, 280 m wide, and up to 13 m thick. Elements are 10×10 m^2 and 1 m thick, but at the injection location the elements are about $1 \times 1 \times 1$ m^3. The east and west boundaries are no-flux along approximate flow lines; the north and south boundaries are constant head along approximate head-contour lines (Figure 4). The constant head changes linearly between levels A and B. The limited hydraulic head measurements away from the plume makes determination of these boundaries uncertain, but it was expected that conditions within

the model area would be dominated by the internal hydraulic conductivity distribution (an assumption questioned later in this work). The impermeable bottom is defined as shown in Figure 1. The tritium concentration of areal recharge over the top of the model and the background subsurface concentration are simulated as 2 pCi/ml.

4.2. Tracer Source

[41] The tracer was injected at 3.3 L per minute over a period of 48.5 hours; five injection wells located as shown in Figure 2 were used. The tracer source injection is not directly simulated in this work; the approximate volume of the injected tracer is used as an initial condition in the model and its subsequent transport is simulated.

[42] Representation of the source was problematic. The first concentration measurements, 27 days after injection, show a vertical spreading of almost 8 m from the injection interval of 0.6 m. Continued vertical spreading is not observed, implying that the spreading took place during injection [*Boggs et al.*, 1992]. To take into account the initial spreading, the simulated source extends over a vertical interval of about 4 m, by assigning five nodes from z = 56 m to z = 60 m an initial concentration. The five injection wells are represented from y = 168 m to y = 170 m, and 2 m in the x-direction, centered at x = 125 m. Thus a total of 15 nodes were used to represent the injection. The total tracer mass introduced in the model is equal to the total mass injected in the field experiment; that is, 0.5387 Ci. This is obtained by assigning each node representing the source an initial concentration of 116,002 pCi/ml. The location of the modeled injection is shown in Figures 1, 2, and 5.

[43] Preliminary model results showed significant spreading of the simulated plume upstream of the injection and minor spreading in the east-west direction that cannot be explained by the flow field. The problem was lessened but not solved by using smaller dispersivity values near the source, suggesting that it possibly results from the Leismann-scheme solution [*Leismann and Frind*, 1989]. Further study of the problem was outside the scope of this work. To minimize the incorrect spreading of the plume, a zone approximately 40 × 40 × 7 m^3 in size is defined around the injection wells with fixed, small dispersivity coefficients. In this region, the longitudinal, transverse-horizontal, and transverse-vertical dispersivity coefficients are set to 0.9 m, 0.009 m, and 0.001 m, respectively, which are about one-tenth of the final values. Results indicated that the concentrations near the source were increased slightly and that downstream plume migration was not significantly affected by introduction of the local dispersivity zone. Results reported by *Pinder* [2002, pp. 220–222] suggest that this numerical difficulty may significantly reduce concentrations at the source and slightly increase spreading of the plume.

4.3. Head and Concentration Observations

[44] Time-averaged heads at 21 locations, two elevations each, were used as hydraulic head observations. These locations generally did not coincide with model grid nodes, so values were interpolated using the finite element basis functions.

[45] Computer limitations prohibited using all 6344 tritium observations in the regression, nor were all observations

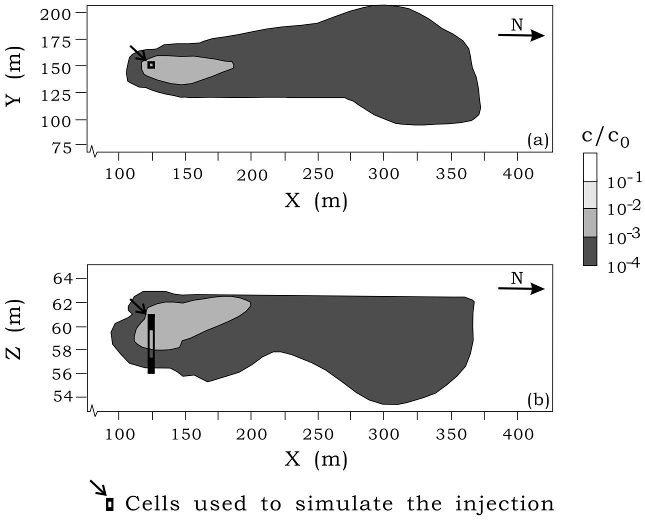


Figure 5. Simulated tritium plume after 330 days. (a) Horizontal section at elevation 59 m. (b) Vertical section along center of plume (y = 168 m).

needed to accomplish the goals of the present work. Instead, 487 measurements that represented the dominant characteristics of how the plume evolved in time and space were included in the regression. The measurement locations used are shown in Figure 4. The simulation starts with the injection and proceeds for 330 days, which is just after the last data used in the regression were collected.

4.4. Hydraulic Conductivity Field

[46] Given the model described thus far, modeling the tritium plume was first attempted using the measured horizontal hydraulic conductivities shown in Figure 1 directly in the model. This failed to successfully reproduce major characteristics of the system. For example, the variations in hydraulic conductivity were too eratic to reproduce the abrupt spatial variation in hydraulic gradients or maintain high concentrations near the source. Because direct use of the measured hydraulic conductivities has been consistently problematic, as shown by Koch and Stauffer (Tyndall Air Force Base, written communication, 1995), *Eggleston and Rojstaczer* [1998], *Zheng and Jiao* [1998], *Harvey and Gorelick* [2000], and *Feehley et al.* [2000], this approach was not pursued further. Instead, this work investigates the possibility that noise and bias of the measured hydraulic conductivities may be problematic.

[47] Error in the measured hydraulic conductivities can only be investigated if the simulated hydraulic conductivity distribution is determined independently of the measured values. This requires a different approach than that considered by most of the above mentioned investigations, and is accomplished by using measured heads and concentrations to determine an appropriate hydraulic conductivity distribution and values, using the processes of a classical advection-dispersion model. While this approach is not likely to produce a unique hydraulic conductivity distribution because different reasonable assumptions about the system will lead to similar matches to the head and concentration data, we consider only one of the possible alternatives here. It is thought that investigation of a single plausible model

is illustrative because any plausible model will need to satisfy the same set of constraints. The relatively extensive data set for this site provides considerable constraints, and it is likely that any plausible model would have much in common with the model developed in this work.

[48] We did not attempt to characterize small lenses of high and low hydraulic conductivity within the system. The irregular distribution of concentrations shown in Figure 2, the hydraulic conductivity data, and the depositional environment strongly suggest that such lenses exist. However, the overall patterns evident in the plume of Figure 2 and the abrupt changes in hydraulic gradient displayed in the hydraulic head data of Figure 4 suggest that the lenses are not big enough and long enough relative to the length of the system to produce transport throughout the system that is dominated by just a few lenses. The idea that the lenses are probably short relative to the length of the system is also supported by the depositional environment because the stream deposit crosses the modeled region and the dominant direction of the hydraulic gradient instead of being parallel to it. This work seeks to identify the dynamics that produce the more dominant patterns of the plume, and combining the lenses in a larger-scale hydraulic conductivity distribution serves this goal very well.

[49] The hydraulic conductivity structure was developed by starting from a simple structure and adding complexity gradually as warranted by lack of fit and constrained by geologic concerns such as depositional processes. While smooth distributions, such as those produced by interpolation, are applicable in many systems, the abrupt changes in hydraulic gradient evident in the hydraulic head contour maps (Figure 4) indicate that preserving sharp contrasts is important in this system. Thus zones of constant value are likely to better represent the basic features of the deposits at this site. This also is consistent with what is known about the depositional processes that produced the media of concern [*Rehfeldt et al.*, 1992].

[50] Hydraulic conductivity zones were first developed using the contour maps of time-averaged hydraulic heads (Figure 4). The model was divided into six zones representing the three areas in level A and B with distinctly different hydraulic gradients. The boundary between levels A and B was set at elevation 57 m, as suggested by *Rehfeldt et al.* [1992] based on particle size characteristics [*Boggs et al.*, 1992]. Inverse modeling using both hydraulic head and concentration observations achieved a reasonable fit to the hydraulic head measurements, but the simulated plume moved toward the northwest instead of straight north and low concentrations did not spread far enough. To address these problems, the hydraulic head maps were used to identify additional regions with more subtle but still distinct hydraulic gradients that were used to further refine the zonation. With a total of six zones in the upper part of the model and three zones in the lower part (zone V is present in both levels), the parameters were optimized. The resulting simulations produced a better fit to the hydraulic heads, and a considerably better fit to the concentrations, but the vertical spreading of the plume was not reproduced. Between x = 150 and x = 300 m in Figure 2b, the simulated plume was too deep, whereas further downstream it was not deep enough. Better reproduction of the measured transport was achieved by using the vertical cross section of the measured plume (Figure 2b) to redefine the elevation between levels A and B. The zonation patterns of Figures 4a, 4b, and 6 were used in the final model.

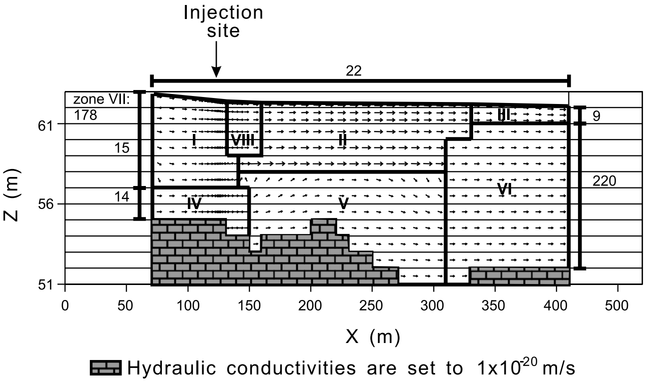


Figure 6. North-south vertical section at y = 168 m showing the simulated velocity field in the vertical section and the mass balance values ($\times 10^3$ m^3/year) for flow for the entire model. Zone VII occurs behind zone I (see Figure 4).

[51] The final hydraulic conductivity zonation depended strongly on the detailed head and concentration measurements available. Less detailed data would produce a less constrained process of model calibration.

4.5. Areal Recharge

[52] Preliminary model results indicated that reproducing the observed hydraulic gradients and maintaining high concentrations near the source were not possible given a spatially constant recharge rate for any plausible values of hydraulic conductivity. A literature review revealed a number of field studies at sites much more homogeneous than the MADE site where significant spatial variation in recharge has been documented (for example, see *Robertson and Cherry* [1989, p. 1101]; *Delin et al.* [2000] present and review more recent work). Thus spatial variations in simulated areal recharge were considered. It was thought likely that the southern high gradient region (zones I and VII of Figure 4) and the northern flat gradient region might experience different recharge rates because lower hydraulic conductivity values are likely to be associated with the high gradients, and higher hydraulic conductivity values are likely to be associated with the lower gradients. Starting recharge values of 220 mm/year in the south and 350 mm/year in the north were updated using regression.

5. Inversion Results

[53] The resulting model had 21 parameters to estimate using 42 head and 487 concentration observations. Inverse results were obtained after 21 iterations. Model validity was tested by considering (1) parameter estimate uncertainty and correlation, (2) how estimated and measured parameter values compare, and (3) the match to observed heads and concentrations. Optimized parameter values for the final model are listed in Table 1; the plume simulated at 330 days using the calibrated model is shown in Figure 5. The three issues of concern are discussed in the following four

sections, except that the estimated horizontal hydraulic conductivities are discussed subsequently.

5.1. Parameter Uncertainty and Correlation

[54] Many of the CV values shown in Table 1 exceed 1.0 and some are huge, indicating large uncertainties in the estimated values. Some parameters are very insensitive as indicated by composite scaled sensitivities which are less than 0.01 times the largest composite scaled sensitivity value of 0.55 [*Hill*, 1998].

[55] Parameter correlation is calculated from the variance-covariance matrix (equation (5)). The largest parameter correlation coefficient of 0.97 is between $k_{h,I}$ and $k_{h,IV}$ but this correlation did not appear to cause uniqueness problems in the estimation: the regression converged to essentially the same set of values for several sets of starting values. Because concentration observations are used and the porosity is set, the calculated correlation values are small; using only hydraulic head observations resulted in most parameters being extremely correlated.

5.2. Plausibility of Optimized Recharge, Dispersivity, and Vertical Hydraulic Conductivity

[56] The optimized recharge rate of 210 mm/year (Table 1) for the southern part of the model area, where the shallow subsurface material is less permeable, is smaller than that of 317 mm/year for the rest of the area, as expected. Both values are smaller than the 650 mm recharge rate suggested by T. Stauffer (Tyndall Air Force Base, written communication, 1995) and the 500 mm/yr rate indicated by average annual runoff and in general agreement with the 300 mm/year rate indicated by subtracting lake evaporation derived from a large regional map [*Winter*, 1989] from precipitation. Uncertainty in the 300 mm/yr value as a regional average and certainly as applied to a specific area probably exceeds 30%, so the 210 mm/yr estimate does not contradict that field estimate. The simulated spatial variation is consistent with the results of *Delin et al.* [2000, and references therein].

[57] The three optimized dispersivities have the smallest coefficients of variation (Table 1), indicating that they are the most precisely estimated. The optimized values are consistent with dispersivities found for other sites with the same plume size [*Gelhar et al.*, 1992]. *Adams and Gelhar* [1992] used moments analysis together with a nonuniform flow advection-dispersion model to suggest that at the MADE site, a longitudinal dispersivity in the range of 5 to 10 m is to be expected. The optimized value of 8.3 m is within this range. These values are larger than the longitudinal dispersivity of about 1.5 m calculated based on stochastic theory but the theory is based on Gaussian assumptions that may not be valid for the heterogeneous conditions of the site [*Rehfeldt et al.*, 1992]. The estimated dispersivities are about an order of magnitude larger than determined for the more homogeneous systems at Borden and Cape Cod.

[58] There are no measurements of vertical hydraulic conductivity, but given the type of deposits considered, vertical anisotropy (the ratio of horizontal to vertical hydraulic conductivity) is expected to range from about 10 to 1000. The simulated values shown in Table 1 display the following difficulties. (1) Vertical anisotropies of 1103 and 1604 in zones IV and VIII, respectively, may be large for these deposits, and (2) in zone VII the vertical hydraulic conductivity exceeds the horizontal hydraulic conductivity, which is thought to be unreasonable. In light of the large CV values for the parameters involved, items 2 and 3 are similar to a situation encountered by *Barlebo et al.* [1998, p. 167], in that reasonable values are included in linear confidence intervals on the parameter values. The difficulties therefore do not necessarily indicate that the model is seriously in error.

5.3. Evaluate Simulated Hydraulic Heads, Gradients, and Flows

[59] Simulated hydraulic head maps, not shown here, closely reproduce the observed hydraulic heads and the hydraulic gradients shown in Figure 4. The variance and standard deviation of the regression, calculated using equation (4b), are $\sigma_h^2 = 3.56 \times 10^{-3}$ m^2 and $\sigma_h = 5.97 \times 10^{-2}$ m = 5.97 cm. This standard deviation is about 5% of the 1 m head loss along the length of the simulated system, and is thought to represent an good fit. Maps of weighted-residuals (not shown) displayed no patterns in level A or B or relative to any zone, so no model bias was indicated. The V-shape is expected to cause groundwater flow to converge and velocities to increase toward a narrow zone with relatively high hydraulic conductivity [*Boggs et al.*, 1992]. In the present study, the zone of convergence is represented by zone II (Figure 4) in which the cross section of Figure 6 shows relatively large velocities.

[60] The simulated flows of Figure 6 show that most of the water enters the simulated system through zone VII. The importance of zone VII horizontal hydraulic conductivity is indicated by the relatively large composite scaled sensitivity and small CV values in Table 1. The presence and location of the boundary between zones I and VII was important to produce the match obtained between measured and simulated concentrations.

[61] Small fluid velocities of about 0.1 m/d are simulated at the injection wells located in zone I (Figure 6), but large velocities of about 2 m/d are simulated nearby in zone VII. As discussed below, large-scale fluid-velocity spatial variability of this type is required for an advection-dispersion model to produce the observed concentration distribution at the MADE site. The existence or absence of such flux rate variations can not be verified with existing data and would require additional tracer tests that are beyond the scope of this work. The absence of such flux rate variations would require a more pronounced role of alternative mechanisms such as dual porosity.

5.4. Evaluate Simulated Concentrations

[62] The match between observed and simulated concentrations achieved by the regression is quantified using the coefficient of variation (CV_c). From equation (4b), $CV_c^2 = 1.67$, so $CV_c = 1.29$. Noting that in this work $CV_c = \sigma_c/c_{sim}$, a coefficient of variation of 1.29 suggests that the absolute value of many concentration residuals (observed minus simulated values) are greater that the absolute value of the related simulated concentration. Maps of the concentration weighted-residuals (not shown) were investigated visually, and no obvious patterns relative to depth or defined zones of hydraulic conductivity were apparent, and no model bias was apparent. Clearly, the model presented here reproduces the measured concentra-

tions more poorly than it reproduces the measured hydraulic heads, but of importance to this work is whether the simulated plume maintains the high concentrations at the source and produces the extensive spreading of low concentrations apparent in the actual plume. This is discussed in the following paragraphs.

[63] Concentrations along sections through the plume simulated using the optimized parameter values at 330 days are shown in Figure 5. The simulated plume is, of course, much smoother than the observations suggest (Figure 2), which is consistent with the goal and construction of the model. The simulated plume matches the main features of the measured plume in that it reproduces the direction of plume migration and the low concentrations far from the center of the plume.

[64] In the model, relatively high concentrations are maintained near the source because the low hydraulic conductivity and velocities of zone I limit mass movement. The highest simulated concentration at the source of 511 pCi/ml (0.4% of the starting simulated concentration), is a factor of eight lower than the highest measured value of 4721 pCi/ml (2.8% of the starting simulated concentration), and the mass is not maintained below the injection wells (zone IV) as indicated in Figure 2b. The difficulties in representing the injected mass at the beginning of the simulation and the numerical difficulty at the source discussed previously could explain, at least in part, the lower maintained simulated concentrations at the source.

[65] The east-west spreading of the simulated plume close to the injection at elevation 59 m (Figure 5a) is not present in the measured plume at elevation 59.5 m (Figure 2a), but at other elevations the simulated plume is as narrow as the measured plume. Thus the simulated plume is not consistently more extensive in the east-west direction at any distance from the plume.

[66] The extensive spreading of the plume is well reproduced (Figures 2 and 5), largely because of the high velocities through zone VII and, to a lesser extent, zone II. Only the simulated plume at 130 days (not shown) displays significant discrepancy with respect to the plume-front location (defined as 5.56 pCi/ml concentration) in that the front of the simulated plume is ahead of the measured plume by 97 m. An obvious possible explanation of this misfit is that the model is steady state and the true system undergoes significant transient effects. A complete transient simulation is beyond the scope of the present work, but attempts to explain the discrepancy using the measured temporal changes in hydraulic gradient between wells 55 and 59 (Figure 4a) indicate that transient changes in gradient could explain much of the discrepancy at 130 days.

[67] The reproduction of the main features of the measured plume is considered to be good, and the model appears to be one plausible representation of the subsurface.

5.5. Evaluation of Simulated Horizontal Hydraulic Conductivities

[68] This section evaluates simulated horizontal hydraulic conductivities by comparing them with measured values. Discrepancies are evaluated using a new conceptual framework. To begin, a few general considerations are discussed.

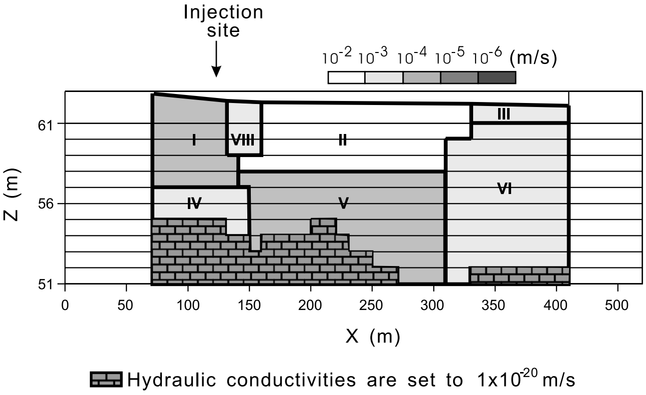


Figure 7. North-south vertical section at y = 168 m (same as in Figure 1) showing the zoned, optimized, horizontal hydraulic conductivity distribution using similar shading as in Figure 1. Zone VII occurs behind zone I (see Figure 4). Horizontal lines mark model layer boundaries.

[69] The zoned, optimized hydraulic conductivity distribution (Figure 7) is in many ways similar to the distribution of measured hydraulic conductivities shown in Figure 1. All horizontal hydraulic conductivity estimates are between 1×10^{-2} m/s and 1×10^{-6} m/s, as are most of the values measured by flowmeter tests. Basic placement of large and small values is similar in Figures 1 and 7. The largest differences appear to be for zones IV and VI. These differences may result from variations in hydraulic conductivity that occur off the section represented by Figure 1.

5.6. Framework for Investigating Differences

[70] To investigate why the measured hydraulic conductivity values, when used predictively in advection-dispersion transport models, so poorly reproduced measured hydraulic heads and concentrations, the 5232 hydraulic conductivities measured by borehole flowmeter are compared to the simulated horizontal zoned hydraulic conductivities, which largely were able to reproduce the measured heads and concentrations.

[71] Differences between the two sets of hydraulic conductivities can result from many causes, so drawing conclusions from the comparisons is difficult. Differences can be classified as systematic or random. The causes considered in this work are listed and briefly described in Table 2 along with the method used to detect and quantify their likely magnitude. The framework is used below to evaluate the simulated and measured horizontal hydraulic conductivities.

[72] Individual flowmeter hydraulic conductivity measurements and geometric and arithmetic means are considered. As with any sample averages, the averages calculated from these measurements are approximate in that, while extensive, the measurements could exclude extreme values or include too many. Also, in the averages presented each measurement is given equal weight, which suggests that each measurement represents an equal material volume. While the flowmeter measurements were each taken from equal well screen lengths, it is unclear what proportion of the material in each zone is represented by each measurement. Lacking data to make such a determination, here we use equal weighting. The geomet-

ric and arithmetic means of the measured values in each zone are shown in Table 3.

5.6.1. Systematic Differences

[73] The geometric mean is an approximate lower bound on the effective value of horizontal hydraulic conductivity for a three-dimensional system if the material is randomly distributed [*Gelhar*, 1993, p. 111], while the arithmetic mean applies to material organized in layers parallel to the flow direction, and is always larger than the geometric mean. The situation at the MADE site is expected to be between these two extremes. Results shown in Table 3 for zones II, IV, VI, and VII violate this expectation, and zone I nearly violates the expectation.

[74] The simulated and measured hydraulic conductivity values for zone VII indicate a large systematic difference, but unlike for the other zones the simulated value is smaller than the geometric mean of the measured values. The difference is substantially larger than can be explained by the uncertainty of the estimate (R3 difference of Table 2), because CV = 0.52 (Table 1). Two circumstances are important: (1) The hydraulic conductivity measurements in zone VII come from a single well (Figure 4), which exacerbates R1 (small sample) differences and can contribute to apparent systematic error; (2) the adjacent constant head and no-flow boundary conditions could be in error due to rather sparse hydraulic head data, and this S1 (model error) difference could contribute to the discrepancy. Thus R1 (small sample) and S1 (model error) differences are expected to dominate the discrepancy between zone VII measured and simulated horizontal hydraulic conductivity, and it is not expected that S2 (measurement bias) differences are as important.

[75] The hydraulic conductivity data are presented in Figure 8, relative to the value simulated for each zone. Taking the difference from K_{gm} instead of K_{sim} would produce graphs in which the bars were distributed approximately symmetrically about zero. Because we expect K_{sim} to be larger than K_{gm}, we expect the bars to tend to be negative. Systematic negative differences between measured and simulated hydraulic conductivity values are indicated only if the magnitude of the negative bars exceed K_{gm}-K_{am} for a large fraction of the measurements. This is the case for the zones for which $K_{sim} > K_{am,obs}$ in Table 3: II, IV, and VI, and almost for zone I.

[76] We would like to determine whether bias in the flowmeter measurements (S2 differences) occur. The substantial negative differences between measured and simulated hydraulic conductivity values for four of the six zones with a substantial number of measurements suggest a substantial contribution from S2 (measurement bias) differences, but it is difficult to distinguish S2 (measurement bias) from S1 (model error) differences. One distinction is that S2 differences would be expected to retain the relative order in terms of where hydraulic conductivity values are large and small, while this is not likely for S1 (model error) differences as long as the parameters are not extremely correlated. Whether the two sets of values reflect the same basic pattern of hydraulic conductivities was investigated by ranking each zone based on mean measured and simulated values of hydraulic conductivity and comparing the ranks. The ranks shown in Table 3 indicate that the ordering is mostly consistent, with zones II and III having the largest values, and zone I having the smallest value. The most obvious deviations occur for zone VII, as expected given the discussion above. Zone IV changes order, but only because both the geometric means of the measured values and the simulated values are very close for zones IV, VI, and VIII so that small differences effect the order among values for these zones. Thus it appears that the ranking indicated by the measurements largely is preserved by the estimated values, as would be expected if bias in hydraulic conductivity (S2 differences) was significant.

5.6.2. Random Differences

[77] Likely random differences are quantified by considering (1) the range of hydraulic conductivity values measured within a zone [possibly exacerbating R1 (small sample) differences for the flowmeter measurements and their means], (2) the error with which hydraulic conductivity is measured as reflected in replicate samples (expected to underestimate the variance of R2 (measurement error) differences), and (3) the imprecision of the hydraulic conductivity estimates, as reflected in the CV values in Table 1 (R3 differences). These three points are addressed in the following three paragraphs.

[78] 1. The variability of natural log of the measured hydraulic conductivities ($\ln(k_{obs})$) within each zone is indicated by the standard deviation calculated as

$$s_{gm,obs} = \left[\sum\nolimits_{nobs} \left(\ln(k_{obs}) - \ln\left(k_{gm,obs}\right)\right)^2 / n_{obs}\right]^{1/2} \qquad (6)$$

where, nobs is the number of measurements in the zone, and $\ln(k_{gm,obs})$ is the natural log of the geometric mean of the measurements within the zone. Ninety-five percent linear confidence intervals for measured values within zones are calculated as the exponentials of $[\ln(k_{gm,obs}) \pm 2 \times s_{gm,obs}]$, where a normal probability distribution has been assumed so that two times the standard deviation is added and subtracted for a 95% interval. The intervals are shown in Figure 9 and cover between about 2.5 and 5 orders of magnitude (zones IV and III, respectively). With this large variability, the limited data in zones III and VII clearly are problematic. The optimized hydraulic conductivity values for each zone, shown in Figure 9, all fall within the 95% linear confidence intervals for the measured values for each zone.

[79] 2. Replicate hydraulic conductivities were measured using multiple flowmeter discharge profiles for 14 of the 67 wells [*Rehfeldt et al.*, 1989]. The analysis suggests that the replicate error for all zones is between 3 and 10 times the local hydraulic conductivity. The larger value is plotted in Figure 9. Estimated values for zones II, III, and IV fall outside the replicate error interval, indicating differences between measured and simulated hydraulic conductivity values that are significant relative to replicate error. Hydraulic conductivity measurement error (R2 differences) generally also will be affected by well construction, so replicate error is expected to underestimate R2 (measurement error) differences. When large, R2 differences exacerbate the R1 (sample size) differences.

[80] 3. The imprecision of some of the estimated values is so large that R3 (imprecise estimate) differences could overwhelm other considerations. However, for the horizontal hydraulic conductivity estimates it is unlikely that R3 (imprecise estimate) differences can explain the prevalence and the magnitude of the negative differences between

Table 2. Causes Considered for the Differences Between Simulated and Measured Hydraulic Conductivities and Methods of Detection and (or) Quantification Used

Label	Cause of Differences Between Simulated and Measured Hydraulic Conductivities[a]	Method of Detection and (or) Quantification
Systematic differences		
S1	Parameter estimates are influenced by **model error**, including parameterization errors, and therefore are not directly comparable to field-measured values.	Model error is expected in the boundary conditions, with the upstream constant-head boundary being most problematic. Hydraulic-conductivity values in zones I and VII are most likely to be affected. Zone definition also is likely to be problematic. The fixed porosity value is likely to play a less important role. Other aspects of model construction have substantial support. Because of the significant number of constraints supplied by the data for this site, other plausible models are likely to be similar to the model presented here.
S2	**Measurement bias** relative to the inferred quantity, which could result from differences in scale, characteristics of measurement method, and so on (this work tries to test for this difference relative to flowmeter measurements).	Measured and estimated hydraulic conductivities are compared using individual measurements and their arithmetic and geometric means. Potential problems with the means are discussed in the text and under R1 differences. Results suggest that flowmeter-measured hydraulic conductivities may be too low by as much as a factor of 5.
Random differences		
R1	Apparent error caused by **small samples**; the mean of a limited number of measurements can differ substantially from the true mean.	Typical when there is a limited number of measurements. Few measurements may poorly reflect the distribution. This affects calculated means through (1) the measurements and (2) the weighting. The weighting should reflect the zone volume represented by the material sampled by each measurement, and this is poorly accomplished by the equal weighting used in this work when there are few measurements. Greatest if measurements are scarce within the hydraulic-conductivity zone, as occurs in zones III and VII. Made worse by large R2 differences.
R2	Random **measurement error**; causes as for S2 errors, but results are random error instead of biased.	Measurement errors in hydraulic heads and concentrations are represented using the weighting of the regression. Replicate hydraulic-conductivity measurements [*Rehfeldt et al.*, 1989] suggest R2 errors of 3–10 times the measured value. Well construction is not tested by replicate measurements, so actual R2 differences are probably greater.
R3	**Imprecise estimates** of the parameter values.	Quantified using the coefficients of variation (CV) in Table 1. The very large CV values for some parameters can dominate all other errors. For a single data set and model, R3 differences can appear to be systematic.

[a]The bold phrases are used in the text where the causes are discussed.

Table 3. Comparison of Estimated and Measured Horizontal Hydraulic Conductivities Within Each Zone[a]

Zone	Number of Wells	Number of Measurements	$k_{gm,obs}$, m/s	$k_{am,obs}$, m/s	k_{sim}, m/s	$Difference_{gm}$,[b] %	$Difference_{am}$,[c] %	Ordered Large to Small $k_{gm\&am,obs}$[d]	Ordered Large to Small k_{sim}[d]
I	17	522	8.41×10^{-6}	2.74×10^{-5}	2.66×10^{-5}	−68	3	**VII**[e,f]	II
II	38	1224	2.57×10^{-4}	$8.05. \times 10^{-4}$	8.28×10^{-3}	−96	−90	II	III
III	3	51	1.05×10^{-4}	7.28×10^{-4}	3.06×10^{-4}	−65	138	III	IV
IV	26	615	1.80×10^{-5}	4.16×10^{-5}	2.03×10^{-4}	−91	−79	VIII	VIII
V	36	1342	2.74×10^{-5}	1.68×10^{-4}	5.72×10^{-5}	−52	193	V[g]	VI
VI	13	865	2.19×10^{-5}	1.09×10^{-4}	1.53×10^{-4}	−85	−28	VI	**VII**[e,f]
VII	1	67	8.22×10^{-4}	1.87×10^{-3}	5.86×10^{-5}	1302[e,f]	3091[e,f]	IV[g]	V[g]
VIII	18	546	4.50×10^{-5}	2.55×10^{-4}	1.58×10^{-4}	−71	61	I	I

[a]Here $k_{gm,obs}$ is geometric mean of horizontal hydraulic conductivities measured by flowmeter; k_{sim} is optimized horizontal hydraulic conductivity of the zone.
[b]$Difference_{gm}$ is calculated as $(k_{gm,obs}-k_{sim})/k_{sim} \times 100$. Expect values to be negative.
[c]$Difference_{am}$ is calculated as $(k_{am,obs}-k_{sim})/k_{sim} \times 100$. Expect values to be positive.
[d]Zones with parameter values that change order significantly are in bold.
[e]Only one well is measured within the zone.
[f]The adjacent constant head boundary may be inaccurately represented.
[g]IV and V change order but are not in bold because the change is not significant.

measured and simulated values. This is discussed further below.

6. Discussion

[81] Overall, the model is considered to represent the system well enough to be used to investigate four issues. (1) The effect of the significant random hydraulic conductivity measurement error on interpretation of subsurface characteristics. (2) Possible bias of measured hydraulic conductivity values. (3) Importance and consequences of the regression approach used. (4) A mass balance problem related to the measured plume.

6.1. Hydraulic Conductivity Variability and Consistency

[82] Measurement errors in hydraulic conductivity are large enough that much of the small-scale heterogeneity at the MADE site depicted in Figure 1 could reflect measurement error. One effect of the measurement error is that it obscures abrupt systematic contrasts in the hydraulic conductivity distribution that are clearly important given the abrupt changes in hydraulic gradients (Figure 4) and are represented in this work using zones of constant value.

[83] Yet, the existence of small-scale pockets and paths of high and low hydraulic conductivity underlie the alternative processes being discussed in the literature. High hydraulic conductivity features can not, of course, be so prevalent that the pattern of hydraulic gradients can not be supported, but presumably the media can still be sufficiently mixed for the variability to play an important role in transport. Thus, though beyond the scope of the current work, the measured hydraulic heads could be used to establish an upper bound on the prevalence of and connections between such features, while the transport dynamics could be used to establish their existence and perhaps place a lower bound on their prevalence.

[84] Ideally, of course, field measurements and geologic arguments will one day be used to characterize such important aspects of subsurface media.

6.2. Are the Measured Hydraulic Conductivities Biased? If So, How Much?

[85] The predominance of often large, negative differences between measured and simulated values in Table 3 and Figure 8 suggest that measured hydraulic conductivities, overall, are too low to produce the observed extensive spreading of the plume in the model constructed. The question remains as to whether the apparent systematic difference between measured and simulated values is from measurement or model error (S2 or S1 differences, respectively). Flowmeter measurements are approximately point hydraulic conductivity measurements while the applied inverse model simulates hydraulic conductivities that are at a much larger scale. The observed discrepancy between measured and simulated hydraulic conductivity values may largely be attributed to this S2 (measurement bias) difference, but various difficulties make it impossible to definitively answer the question. Speculation about how large bias might be, if it exists, is supported by the results.

[86] For zones II, IV, and VI, the ratios of the estimated values to the arithmetic means of the associated measured values are 10, 4.8, and 1.4, respectively. Considering that model error surely is involved to some degree, it seems unlikely that measurement error could be greater than a factor of 5. Clearly this number is not well substantiated by the analysis presented here but provides a rough estimate of maximum likely measurement bias. It is interesting that this bias falls within the range of the random replicate errors, which were a factor of 3 to 10. While the replicate errors were random, however, measurement bias has different consequences.

6.3. Inverse Approach and Consequences

[87] The model presented here is constructed emphasizing the relatively accurate hydraulic head and concentration measurements instead of the relatively inaccurate hydraulic conductivity measurements. Most other MADE studies emphasize the measured hydraulic conductivities which are more directly related to the model input. Comparing the results of this work with previous work shows that the choice is important because, for the MADE site, the two approaches give contradicting results regarding whether conventional advection-dispersion models include the processes important to the measured extensive spreading of the plume. The conclusion that maintaining very high concentrations at the source requires additional processes appears to be robust given the two ways of evaluating the field data. The only

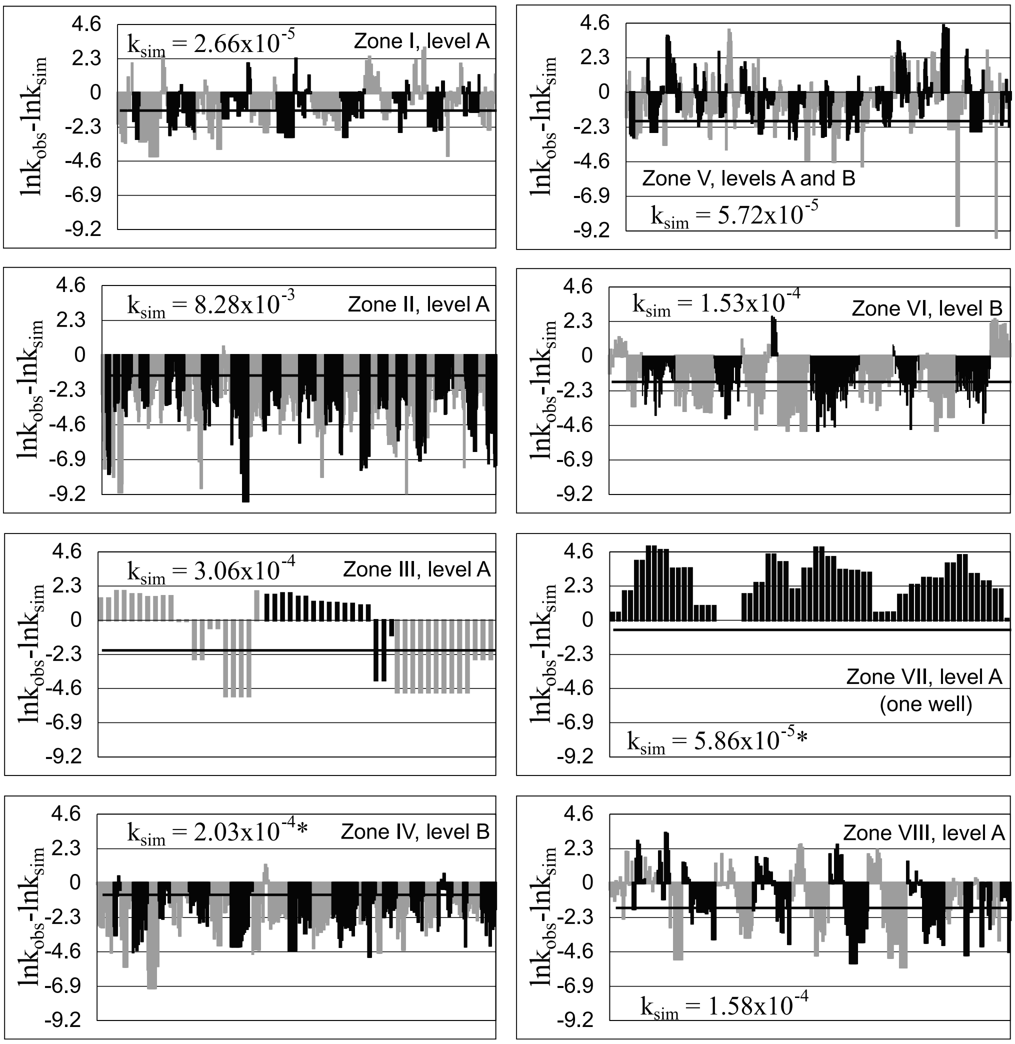


Figure 8. The difference between flowmeter measured and simulated horizontal hydraulic conductivities in the eight zones. The measured values are organized by increasing depth in each well; alternate wells are displayed in different shades of gray; well locations are shown in Figure 4b. Horizontal gridlines mark order of magnitude differences in hydraulic conductivity. ($e^{2.3} \approx 10$ equals one order of magnitude). The added horizontal grid line is placed at $\ln k_{gm,obs}$ - $\ln k_{am,obs}$, and only differences smaller than this have significantly negative values. An asterisk means that the estimated values are out of relative order, as indicated in Table 4. The values have not been cropped.

possible weakness is the previously mentioned numerical difficulty near the source for the convective-dispersive model used in this work.

6.4. Mass Balance Over Time for Tritium

[88] *Stauffer et al.* [1994] calculated mass recovery divided by injected mass for the four snapshots as 1.52, 1.05, 0.98, and 0.77. The 52% surplus at 27 days was attributed to sampling bias toward the tracer concentration of the relatively mobile pore water which, at early time, is expected to have higher concentration than the relatively immobile pore fluids [*Boggs and Adams*, 1992]. The 23% deficit at 328 days is hypothesized to be caused (1) by the reversed mechanisms taking place during later times [*Boggs and Adams*, 1992; *Harvey and Gorelick*, 2000] or, at least in part, (2) by lack of measurements at the front, top, and bottom of the plume (suggested by several authors, including *Adams and Gelhar* [1992, p. 3307] and *Stauffer et al.* [1994]), effectively producing a cropped representation of the plume. The model developed in this work reproduced the spreading of the plume quite well, so it is an appropriate tool with which to evaluate the second of these possibilities.

[89] Values for calculated mass divided by injected mass (M/M_0) are shown in Table 4. At early times large simulated concentration gradients close to the injection resulted in numerical errors that produced simulated values slightly larger than 1.00. For field data such errors are likely to be larger because fewer interpolation points are generally available and actual plumes are likely to be less smooth than the simulated plume. However, it still is hard to believe that such effects could produce a 52% error, which supports the importance of alternative mechanisms.

[90] Cropping of the simulated plume appears to start by day 220, and after 330 days the cropping has caused M/M_0 to decrease 8% to 0.92. This loss of mass is about one-third of the total loss after 330 days of 23%. This suggests that

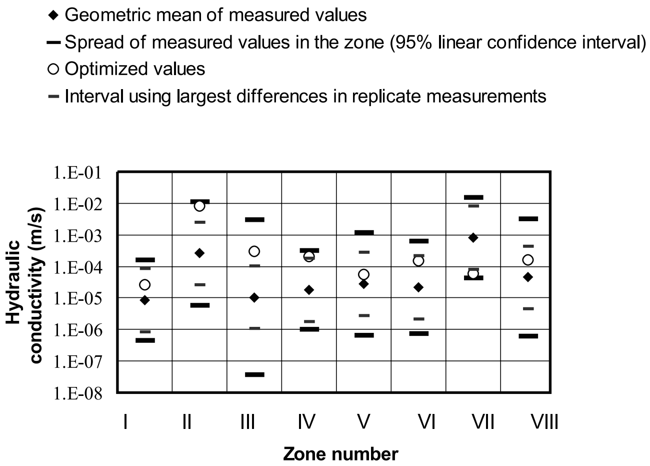


Figure 9. The geometric mean and 95% linear confidence intervals for the measured values within each zone compared to (1) intervals based on replicate borehole flowmeter measurements, as reported by *Rehfeldt et al.* [1989], and (2) optimized hydraulic conductivity values for each zone. Estimated values are expected to be somewhat greater than the geometric means, but the consistently much larger estimated values shown for many zones suggest that bias in the measured values may be significant.

such cropping of the actual plume is a significant contributor to the apparent loss of mass, and is important because it affects the potential significance and effect of alternative proposed mechanisms.

7. Summary and Conclusions

[91] The most important results of this work are as follows.

[92] 1. Obtaining definitive conclusions is hampered by three issues that could be avoided in future field and modeling investigations. First, lateral boundary conditions are poorly supported by measured heads. This difficulty illustrates the importance of measuring hydraulic conditions at some distance from a transport experiment. Second, areal recharge is not well characterized by field data. Although recharge was estimated in this work with the hydraulic head and concentration data, greater field-based knowledge about its amount and distribution would have allowed the model to be more tightly constrained and for hypotheses to be tested more rigorously. Finally, numerical difficulty at the source interfered with determining whether high enough concentrations at the source could be maintained using only advection and dispersion processes. More powerful computers and advances in numerical methods will diminish this problem.

[93] 2. There is some indication that the flowmeter measurements of horizontal hydraulic conductivity could be biased and perhaps are too low by as much as a factor of 5. This suggestion resulted from comparing eight estimated zoned horizontal hydraulic conductivities with 5232 measured values.

[94] 3. Random errors in flowmeter horizontal hydraulic conductivity measurements obscure abrupt lateral variations in hydraulic conductivity evidenced by areas of distinctly different hydraulic gradients. Measured replicate errors ranged from a factor of 3 to 10 times the measured value. For perspective, the measured hydraulic conductivities vary over 4 orders of magnitude. The hydraulic conductivity distribution developed in this work lack the grid-scale variability of other models, but appeared to capture fundamental dynamics because extensive spreading of the plume was simulated with optimized dispersivity values that were not unduly large.

[95] 4. If abrupt hydraulic conductivity variations and associated close juxtaposition of simulated velocities of about 0.1 and 2 m/d actually exist, it appears that classical advection and dispersion processes can reproduce the extensive spreading of the measured plume while maintaining high concentrations at the injection site. Identification of flow field characteristics required for advection-dispersion processes to reproduce the observed concentrations poses a hypothesis that can be tested by future field work at the MADE site and identifies a type of data that may be important in other field experiments.

[96] 5. In both the model and the measurements, the highest remaining concentration occurs at the source, but the maximum simulated value is 0.4% of the starting simulated concentration while the maximum measured concentration is six times that, or 2.4%. How much of the discrepancy is caused by difficulties with simulating the initial concentration distribution and numerical dispersion would determine the role that would need to be played by alternative mechanisms in maintaining high concentrations at the source.

[97] 6. The simulated plume-front location is matched well except at 130 days, when it notably trails that of the measured plume. A simple analysis of transient effects indicates that their omission contributes to, and may largely explain, this discrepancy.

[98] 7. *Stauffer et al.* [1994] reported a mass deficit of 23% at 328 days and partly explained the loss by lack of measurements at the front, top, and bottom of the plume. This work indicates that cropping of the plume can not be discounted as a significant and perhaps dominant contributor. This is important because the apparent deficit has been cited to support the proposed role of alternate transport mechanisms, including dual porosity, at this site.

[99] The results of this work support the possible importance of alternative mechanisms, but also suggest that advection and dispersion are significant and perhaps dominant contributors to system dynamics that have been

Table 4. Relative Mass Balance for Tritium Over Time

Days After Injection	Calculated Mass Divided by Injected Mass (M/M_0): Entire Simulated Plume	Cropped Simulated Plume[a]	From Measured Concentrations[b]
30	1.04[c]	1.04[c]	1.52
130	1.01[c]	1.01[c]	1.05
220	1.00	0.99	0.98
330	0.99	0.92	0.77

[a]Cropped on the front, top, and bottom to the volume sampled by concentration measurements.

[b]From *Stauffer et al.* [1994].

[c]Larger than 1.00 because at early times large concentration gradients close to the injection resulted in small numerical errors.

Table A1. Observation Wells and Dates for Which Measured Hydraulic Heads Were Obviously in Error or Were Missing[a]

Erroneous Head Measurements				Missing Heads		
Well	Date	Original	Adjusted	Well	Date	New Head
24B	5/10/91	63.84	64.97	24B	6/19/90	62.23
25A	5/10/91	64.28	64.76	27B	1/8/91	63.28
27A	8/19/91	61.78	61.45	57B	6/19/90	61.98
42B	7/23/90	61.42	61.47	57B	8/13/90	61.38
43A	8/19/91	58.78	61.57	57B	11/7/90	61.16
46A	8/13/90	61.65	61.49			
46B	7/23/90	62.07	61.82			
46B	8/13/90	61.81	61.62			
46B	12/5/90	61.83	61.45			
56B	12/5/90	60.33	61.27			
58A	10/15/90	61.49	61.18			
62A	7/9/91	61.87	62.31			
62B	5/20/91	64.16	63.89			

[a]Date is month/day/year. Well is well number followed by A for shallow heads and B for deep heads; see Figure 4. Head is in meters above sea level.

difficult to explain. In particular, when large-scale heterogeneity at the MADE site is accounted for, it appears that advection and dispersion can produce the observed extensive spreading of the plume and contribute significantly to maintained high concentrations at the source.

Appendix A: Head Measurement Errors

[100] Table A1 lists the 13 locations and dates for which measured hydraulic heads were clearly in error based on well hydrographs and contour maps of hydraulic heads for each measurement date, and the five locations and dates at which hydraulic head observations were missing.

Appendix B: Equivalence to *Gailey et al.* [1991]

[101] Close evaluation of the five-step iterative procedure described by *Gailey et al.* [1991, p. 311] is used to demonstrate the equivalence of the method used in this work. *Gailey et al.* [1991] apply what *Carrera and Neuman* [1986] call the penalty term to the head part of the objective function, while we apply it to the concentration part of the objective function, but this difference is inconsequential.

[102] Step 3 of *Gailey et al.* [1991] suggests "...fixing λ_c to 1.0 and increasing λ_h by a factor equal to the ratio calculated in step 2." The ratio is defined in their step 2 as [Var C]/[Var H]. At this point in the discussion, it is not quite clear whether [Var H] is calculated with or without the most recent λ_h. Mathematically, using the notation of *Gailey et al.* [1991], 'increasing λ_h by a factor equal to the ratio calculated in step 2' leads to the equation:

$$\lambda_h^{new} = \lambda_h^{old}[\mathrm{Var\ C}]/[\mathrm{Var\ H}] = \lambda_h^{old}\left[\sum_{j=1}^{35}(W_c(c_{obs}-c_{sim})/c_{sim})\right] \Bigg/ \left[a\sum_{i=1}^{35}(W_h(h_{obs}-h_{sim})\right] \quad \text{(B1)}$$

where the factor a is as yet undetermined.

[103] Step 5 states that the ratio [Var C]/[Var H] is expected to approach unity. This can only occur if a = λ_h^{old}. Thus, on the right-hand side of equation (B1), the two occurrences of λ_h^{old} cancel, and we are left with

$$\lambda_h^{new} = \left[\sum_{j=1}^{35}(W_c(c_{obs}-c_{sim})/c_{sim})\right] \Bigg/ \left[\sum_{i=1}^{35}(W_h(h_{obs}-h_{sim})\right] \quad \text{(B2)}$$

which is equivalent to λ_c as defined after equation (4a), considering that in this work the inverse is used.

References

Adams, E. E., and L. W. Gelhar (1992), Field study of dispersion in a heterogeneous aquifer: 2. Spatial moments analysis, *Water Resour. Res.*, *28*(12), 3293–3307.

Anderman, E. R., and M. C. Hill (1999), A new multistage groundwater transport inverse method: Presentation, evaluation, and implications, *Water Resour. Res.*, *35*(4), 1053–1063.

Barlebo, H. C., M. C. Hill, D. Rosbjerg, and K. H. Jensen (1998), Concentration data and dimensionality in groundwater models: Evaluation using inverse modelling, *Nord. Hydrol.*, *29*(3), 149–178.

Barth, G. R., M. C. Hill, T. H. Illangasekare, and H. Rajaram (2001), Predictive modeling of flow and transport in a two-dimensional intermediate-scale, heterogeneous porous media, *Water Resour. Res.*, *37*(10), 2503–2512.

Berkowitz, B., and H. Scher (1998), Theory and anomalous chemical transport in random fracture networks, *Phys. Rev. E*, *57*(5), 5858–5869.

Boggs, J. M., and E. E. Adams (1992), Field study of dispersion in a heterogeneous aquifer: 4. Investigation of adsorption and sampling bias, *Water Resour. Res.*, *28*(12), 3325–3336.

Boggs, J. M., C. C. Toung, D. J. Benton, and Y. C. Chung (1990), Hydrogeologic characterization of the MADE site, *Interim Rep. EPRI EN-6915*, 175 pp., Electr. Power Res. Inst., Palo Alto, Calif.

Boggs, J. M., S. C. Young, L. M. Beard, L. W. Gelhar, K. R. Rehfeldt, and E. E. Adams (1992), Field study of dispersion in a heterogeneous aquifer: 1. Overview and site description, *Water Resour. Res.*, *28*(12), 3281–3291.

Boggs, J. M., L. M. Beard, S. E. Long, M. P. McGee, W. G. MacIntyre, C. P. Antworth, and T. B. Stauffer (1993), Database for the Second Macrodispersion Experiment (MADE-2), *Proj. 2485-05*, interim report, Electr. Power Res. Inst., Palo Alto, Calif.

Burnett, R. D., and E. O. Frind (1987), Simulation of contaminant transport in three dimensions: 2. Dimensionality effects, *Water Resour. Res.*, *23*(4), 695–705.

Carrera, J. (1987), State of the art of the inverse problem applied to the flow and solute equations, in *Groundwater Flow and Quality Modelling*, *NATO ASI Ser., Ser. C*, vol. 224, 549–584, D. Reidel, Norwell, Mass.

Carrera, J., and S. P. Neuman (1986), Estimation of aquifer parameters under transient and steady state conditions: 1. Maximum likelihood method incorporating prior information, *Water Resour. Res.*, *22*(2), 199–210.

Delin, G. N., R. W. Healy, M. K. Landon, and J. K. Böhlke (2000), Effects of topography and soil properties on recharge at two sites in an agricultural field, *J. Am. Water Resour. Assoc.*, *36*(6), 1401–1416.

Eggleston, J., and S. Rojstaczer (1998), Identification of large-scale hydraulic conductivity trends and the influence of trends on contaminant transport, *Water Resour. Res.*, *34*(9), 2155–2168.

Feehley, C. E., C. Zheng, and F. J. Molz (2000), A dual-domain mass transfer approach for modeling solute transport in heterogeneous aquifers: Application to the macrodispersion experiment (MADE) site, *Water Resour. Res.*, *36*(9), 2501–2515.

Gailey, R. M., S. M. Gorelick, and A. S. Crowe (1991), Coupled process parameter estimation and prediction uncertainty using hydraulic head and concentration data, *Adv. Water Resour.*, *14*(5), 301–314.

Gelhar, L. W. (1993), *Stochastic Subsurface Hydrology*, Prentice-Hall, Old Tappan, N. J.

Gelhar, L. W., C. Welty, and K. R. Rehfeldt (1992), A critical review of data on field-scale dispersion in aquifers, *Water Resour. Res.*, *28*(7), 1955–1974.

Graybill, F. A. (1976), *Theory and Application of the Linear Model*, Duxbury, North Scituate, Mass.

Harvey, C. F. (1996), Solute transport in spatially heterogeneous aquifers. Mapping large-scale structures and modelling small-scale effects, Ph.D. dissertation, Stanford Univ., Stanford, California.

Harvey, C. F., and S. M. Gorelick (2000), Rate-limited mass transfer or macrodispersion: Which dominates plume evolution at the Macrodispersion Experiment (MADE) site?, *Water Resour. Res.*, *36*(3), 637–650.

Hill, M. C. (1992), A computer program (MODFLOWP) for estimating parameters of a transient, three-dimensional, ground-water flow model using nonlinear regression, *U.S. Geol. Surv. Open File Rep., 91-484*.

Hill, M. C. (1998), Methods and guidelines for effective model calibration, *U.S. Geol. Surv. Water Resour. Invest. Rep., 98-4005*.

Hill, M. C., and O. Østerby (2003), Determining extreme parameter correlation in ground-water models, *Ground Water*, *41*(4), 420–430.

IMSL Inc. (1987), IMSL FORTRAN subroutines for mathematical applications, users manual, version 1.0, vol. 3, pp. 847–852, Houston, Tex.

Killey, R. W. D., and G. L. Moltyaner (1988), Twin Lake tracer tests: Setting, methodology, and hydraulic conductivity distribution, *Water Resour. Res.*, *24*(10), 1585–1612.

LeBlanc, D. R., S. P. Garabedian, K. M. Hess, L. W. Gelhar, R. D. Quadri, K. G. Stollenwerk, and W. W. Wood (1991), Large-scale natural gradient tracer test in sand and gravel, Cape Cod, Massachusetts: 1. Experimental design and observed tracer movement, *Water Resour. Res.*, *27*(5), 895–910.

Leismann, H. M., and E. O. Frind (1989), A symmetric-matrix time integration scheme for the efficient solution of advection-dispersion problems, *Water Resour. Res.*, *25*(6), 1133–1139.

Mackay, D. M., D. L. Freyberg, P. V. Roberts, and J. A. Cherry (1986), A natural gradient experiment on solute transport in a sand aquifer: 1. Approach and overview of plume movement, *Water Resour. Res.*, *22*(13), 2017–2029.

Mayer, A. S., and C. Huang (1999), Development and application of a coupled process parameter-inversion model based on the maximum likelihood estimation method, *Adv. Water Resour.*, *22*(8), 841–853.

Molson, J. W., and E. O. Frind (2002), WATFLOW/WTC user guide and documentation, version 3, 75 pp., Dep. of Earth Sci., Univ. of Waterloo, Waterloo, Ontario, Canada.

Pinder, G. F. (2002), *Groundwater Modeling Using Geographical Information Systems*, 233 pp., John Wiley, Hoboken, N. J.

Poeter, E. P., and M. C. Hill (1996), Unrealistic parameter values in inverse modeling: A problem of benefit for model calibration, in *Calibration and Reliability in Groundwater Modeling*, *Proceedings of the 1996 ModelCARE Conference*, *IAHS Publ.*, *237*, 277–285.

Rehfeldt, K. R., P. Hufschmied, L. W. Gelhar, and M. E. Schaefer (1989), Measuring hydraulic conductivity with the borehole flowmeter, *Rep. EN-6511, Res. Proj. 2485-5*, Electr. Power Res. Inst., Palo Alto, Calif.

Rehfeldt, K. R., J. M. Boggs, and L. W. Gelhar (1992), Field study of dispersion in a heterogeneous aquifer: 3. Geostatistical analysis of hydraulic conductivity, *Water Resour. Res.*, *28*(12), 3309–3324.

Robertson, W. D., and J. A. Cherry (1989), Tritium as an indicator of recharge and dispersion in a groundwater system in central Ontario, *Water Resour. Res.*, *25*(6), 1097–1109.

Seber, G. A. F., and C. J. Wild (1989), *Nonlinear Regression*, John Wiley, Hoboken, N. J.

Stauffer, T. B., C. P. Antworth, R. G. Young, W. G. MacIntyre, J. M. Boggs, and L. M. Beard (1994), Degradation of aromatic hydrocarbons in an aquifer during a field experiment demonstrating the feasibility of remediation by natural attenuation, *Rep. AL/EQ TR 1993-0007*, Armstrong Lab., Tyndall Air Force Base, Fla.

U.S. Geological Survey (1966), *The National Atlas of the United States*, Reston, Va.

Wagner, B. J., and S. M. Gorelick (1986), A statistical methodology for estimating transport parameters: Theory and applications to one-dimensional advective-dispersive systems, *Water Resour. Res.*, *22*(8), 1303–1315.

Winter, T. C. (1989), Distribution of the difference between precipitation and open-water evaporation in North America, in *The Geology of North America*, vol. O-1, *Surface Water Hydrology*, plate 2, Geol. Soc. of Am., Boulder, Colo.

Yeh, W. W.-G. (1986), Review of parameter identification procedures in groundwater hydrology: The inverse problem, *Water Resour. Res.*, *22*(2), 95–108.

Zheng, C., and J. J. Jiao (1998), Numerical simulation of tracer tests in heterogeneous aquifer, *J. Environ. Eng.*, *124*(6), 510–516.

H. C. Barlebo, Geological Survey of Denmark and Greenland, DK-1350 Copenhagen, Denmark. (hcb@geus.dk)

M. C. Hill, U.S. Geological Survey, 3215 Marine Street, Boulder, CO 80303, USA. (mchill@usgs.gov)

D. Rosbjerg, Environment and Resources DTU, Technical University of Denmark, Building 115, DK 2800 Kongens Lyngby, Denmark. (dr@er.dtu.dk)

WATER RESOURCES RESEARCH, VOL. 42, W06603, doi:10.1029/2005WR004265, 2006

Comment on "Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model" by Heidi Christiansen Barlebo, Mary C. Hill, and Dan Rosbjerg

Fred J. Molz,[1] Chunmiao Zheng,[2] Steven M. Gorelick,[3] and Charles F. Harvey[4]

Received 18 May 2005; revised 19 January 2006; accepted 14 March 2006; published 14 June 2006.

Citation: Molz, F. J., C. Zheng, S. M. Gorelick, and C. F. Harvey (2006), Comment on ''Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model'' by Heidi Christiansen Barlebo, Mary C. Hill, and Dan Rosbjerg, *Water Resour. Res.*, *42*, W06603, doi:10.1029/2005WR004265.

[1] Of the several natural gradient, field tracer studies performed during the 1980s, the tracer tests conducted at the Columbus Air Force Base in northeastern Mississippi, commonly called the Macro-Dispersion Experiment (MADE) site, have stimulated the most continuing interest [*Boggs et al.*, 1992; *Adams and Gelhar*, 1992; *Rehfeldt et al.*, 1992; *Boggs and Adams*, 1992]. This is because the aquifer at the MADE site consists of highly heterogeneous fluvial sediments (the variance of natural log conductivity is about 4.5) and is thus more representative of natural sedimentary aquifers with pervasive heterogeneity. The heterogeneity was documented by core studies, trench studies and a series of smaller scale hydraulic conductivity (*K*) measurements using borehole flowmeters [*Rehfeldt et al.*, 1992]. Because of the greater than anticipated influence of aquifer heterogeneity on tracer transport behavior at the site, and also the close supervision by the Electric Power Research Institute (EPRI), which provided the initial project funding, there was a lot of study and discussion during and after the performance of the tracer tests. Flow and transport appeared to be dominated by larger-scale *K* trends, and a large and dilute leading plume edge developed in front of a much more concentrated and slowly moving center of mass. Also interestingly, the mass budget resulting from the multilevel concentration measurements was significantly unbalanced in a positive sense early in the experiment (too much mass recovered) and in a negative sense later in the experiment (too little mass recovered).

[2] After the initial unsuccessful attempts to simulate the concentration distributions using macrodispersion concepts [*Adams and Gelhar*, 1992], numerous additional studies were performed, including a second tracer test in which tritium was used as an ideal tracer [*Boggs et al.*, 1993; *MacIntyre et al.*, 1993], and a third test that emplaced jet fuel along with a conservative tracer (bromide) in a source trench [*Boggs et al.*, 1995; *Julian et al.*, 2001]. Gradual understanding of the MADE results were built on the realization that neither macrodispersion, nor hydrodynamic dispersion in general, was playing a dominant role at the MADE site [e.g., *Berkowitz and Scher*, 1998; *Zheng and Jiao*, 1998; *Feehley et al.*, 2000; *Harvey and Gorelick*, 2000; *Benson et al.*, 2001; *Zheng and Gorelick*, 2003; *Zinn and Harvey*, 2003; *Liu et al.*, 2004]. Instead, a dual-domain concept (mobile/immobile zones in close contact) led to conceptually simple, successful simulations that incorporated the measured hydraulic conductivity field [*Feehley et al.*, 2000; *Harvey and Gorelick*, 2000; *Julian et al.*, 2001].

[3] However, a recent paper published by *Barlebo et al.* [2004] suggests that phenomena occurring during the MADE experiment can be understood using traditional advection-dispersion concepts. They stated in the abstract: ''If variations in subsurface fluid velocities like those simulated in this work (0.1 and 2.0 m per day along parallel and reasonably close flow paths) exist, it is likely that classical advection-dispersion processes can explain the measured plume characteristics…'' They concluded (paragraph [99]) that ''In particular, when large-scale heterogeneity at the MADE site is accounted for, it appears that advection and dispersion can produce the observed extensive spreading of the plume and contribute significantly to maintained high concentrations at the source.'' Thus the purpose of this comment is to discuss the article by *Barlebo et al.* [2004] with the aim of clarifying differences of opinion and putting the results within the existing context of the many MADE studies, several of which were reviewed briefly by *Barlebo et al.* [2004].

[4] *Barlebo et al.* [2004] present a three-dimensional flow and transport model with 21 free parameters that include two recharge rates, 16 horizontal and vertical hydraulic conductivities within eight homogeneous zones, and three dispersivities. The values of these parameters are selected by a nonlinear optimization routine to best fit model results to the head and concentration data in the measured tritium plume at 328 days after injection during the second MADE tracer study [*Boggs et al.*, 1993]. Barlebo et al. conceived of an initial *K* structure based on the measured head data, and then modified this structure and reapplied optimization in

[1]Department of Environmental Engineering and Science, Clemson University, Anderson, South Carolina, USA.
[2]Department of Geological Sciences, University of Alabama, Tuscaloosa, Alabama, USA.
[3]Department of Geological and Environmental Sciences, Stanford University, Stanford, California, USA.
[4]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

0043-1397/06/2005WR004265$09.00

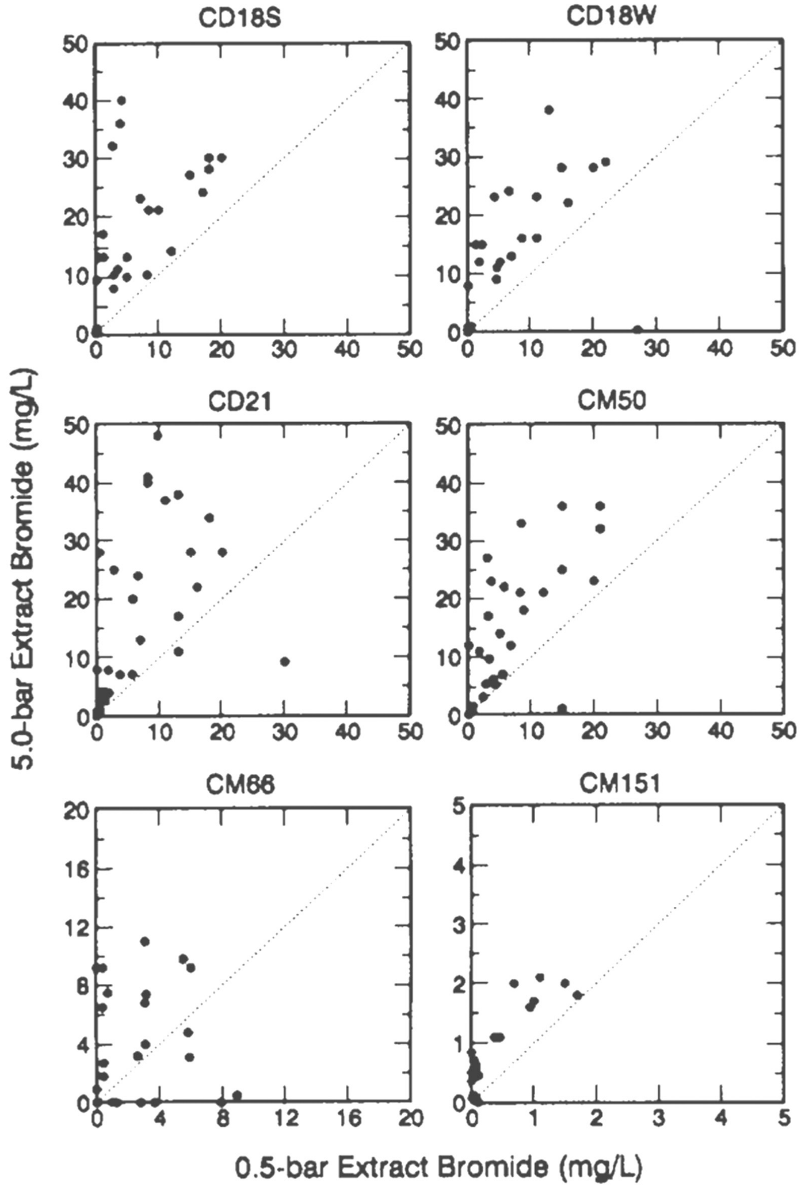


Figure 1. Bromide measurements for 0.5-bar and 5.0-bar vacuum extracts from soil cores [after *Boggs and Adams*, 1992].

order to move model results toward agreeing with the experiment for the 328-day snapshot. Barlebo et al. suggest, among other things, that their results indicate the borehole flowmeter measurements are biased, with random errors obscuring their (assumed) zonal variations in *K*. Most significantly, they contend that classical advection and dispersion processes can reproduce the measured concentration distributions at the MADE site, and the dual-domain effects may not be real or necessary. Below we present our reasons for disagreeing with their suggestions, based mainly on the failure of the *Barlebo et al.* [2004] model to match data and measurements associated with the three MADE tracer tests. We also collected some new data at the MADE site that falls within ("homogeneous") zones II and V of the domain constructed by Barlebo et al. for their simulation.

[5] Recent studies [*Feehley et al.*, 2000; *Harvey and Gorelick*, 2000; *Julian et al.*, 2001] converged on a dual-domain concept as an approximate but somewhat physically realistic model for non-Gaussian plume spreading during the tracer tests at the MADE site. Where did this idea originate? The concept itself goes back many decades, but the observed variable mass balance during the MADE tracer tests (too much mass early, too little late) motivated *Boggs and Adams* [1992] to perform a set of post–tracer test experiments, showing that tracers were not distributed uniformly in the local pore space of the MADE sediments, even after a long residence time. Among a series of well-conceived tests, they conducted vacuum extractions at 0.5 bar and 5 bar vacuums on portions of initially saturated core samples collected in the vicinity of selected multilevel samplers (see Figure 1). These samples were located within the plume that existed about 503 days after the first injection. The 0.5 bar extraction drained the larger, high *K* voids, which released about 12% of the total pore water; the

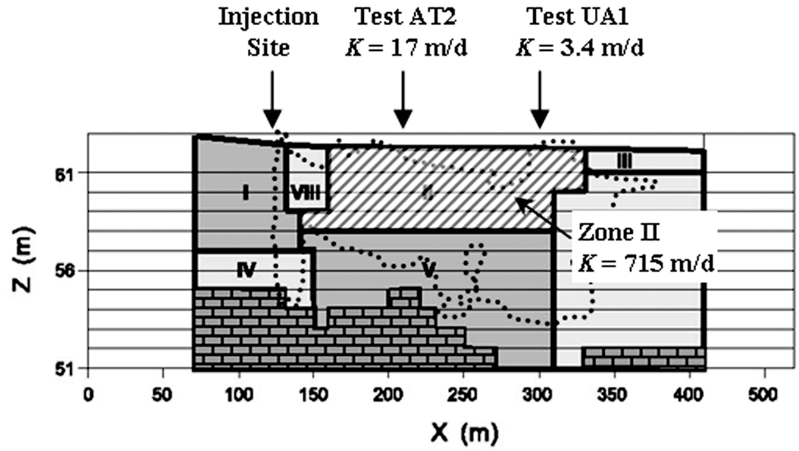


Figure 2. Zonation of hydraulic conductivity used by *Barlebo et al.* [2004] and approximate location of two pumping tests. Zone II is highlighted in diagonal line pattern. The dashed line is the outer extent of the tritium plume on day 328 along plume centerline.

following 5 bar extraction removed an additional 20% of the pore water. Bromide concentration measurements showed on average that the 5 bar extracts contained about three times the bromide concentration of the 0.5 bar extracts, which provided at least a partial explanation for the observed mass balance discrepancy, as explained in detail by *Boggs and Adams* [1992].

[6] On the basis of the laboratory and field experimental data, we conclude that there is direct evidence for delayed solute storage and release from relatively immobile and mobile pore domains in the MADE sediments. This mass transfer process is neglected in Barlebo et al.'s conceptual model. The mass transfer phenomenon manifests itself as spreading in which the slowly advecting solute keeps falling further behind the rapidly migrating solute even though solute exchange occurs between mobile and immobile domains during transport. Consequently, the net spread is proportional to time rather than the square root of time. Thus Fickian dispersive spreading is not a good model to represent multiple domain mass storage and release effects.

[7] On the basis of pioneering analysis and insights of *Boggs and Adams* [1992], *Harvey and Gorelick* [2000] offer an explanation for the mass imbalance from the dual-domain perspective. At early times, water with high concentrations was preferentially sampled from the high-conductivity mobile domain at the centimeter to decimeter scale. This measurement bias led to an overestimation of the plume mass because the same high concentrations were assumed to exist in low-conductivity immobile regions. At late times, this measurement bias continued at the front of the plume, as solute invaded regions of locally high conductivity, but the bias reversed itself at the back of the plume; extracted water samples form local high-conductivity regions did not reveal the higher concentrations of solute that had diffused into low-conductivity immobile regions. The overestimation at the front of the plume and underestimation at the back of the plume cancel, so consequentially the estimated mass approaches the true plume mass over the timescale of diffusion through centimeter-scale low-conductivity regions. *Harvey and Gorelick* [2000] explain a portion of the late time loss of mass as the result of pore-scale processes: diffusion into dead-end pores and intragranular porosity and adsorption. These processes occur quickly but are only evident in the total mass estimate after the Darcy-scale processes have reached equilibrium.

[8] One significant problem with the Barlebo et al. analysis was the huge horizontal K value that was calibrated for the zone II sediments (see Figure 2). The value that resulted was about 715 m/d, which is characteristic of a clean medium gravel. On the basis of core observations, pumping tests and flowmeter tests, such a sediment body does not exist. Its presence in their model probably plays a key role in getting the plume front out to a reasonable location for comparison to the 328-day concentration distribution. Note that zone II as defined by Barlebo et al. measures approximately 150 m long, 65 m wide, and 4 m deep, overlapping a large extent of the tritium plume at 328 days in the shallow portion of the aquifer (Figure 2). Prior to the first MADE tracer experiment, a pumping test was performed near the center of zones II and V [*Boggs et al.*, 1992]. The result was 17 m/d: lower by about a factor of 42 when compared to the value of Barlebo et al. If one assumed that the test well was screened only in the 4-m-thick zone II, and all the pumping (208 L/min for 192 hours) came from that zone, then the K value would be 43 m/d, still lower than the value of Barlebo et al. by a factor of 17. The K value determined from our new pumping test (9.5 L/min for 140 min) also in zones II and V (Figure 2) was even lower at 3.4 m/d, likely the result of being adjacent to a lower K zone north of the test well. Again, if one assumed all the pumped water came from the 4-m-thick zone II, then the K value would still be only 25.6 m/d. On the basis of examinations of cores and trench walls, it is evident that very high K values exist at the MADE site, but they are in relatively small meandering patterns that certainly do not act as homogeneous bodies of relatively large extent, such as zone II of Barlebo et al. Ignoring these facts might have led Barlebo et al. to misunderstand the results of the MADE experiments.

[9] It is noteworthy that *Barlebo et al.* [2004] report a large coefficient of variation for the K value for zone II of 3.8 (estimated standard deviation divided by the mean). The estimated K value in the Barlebo et al. model contains such uncertainty that it is not informative of the zone II conduc-

tivity. Given the reported large standard deviation (3.8 × 715 = 2717 m/d), the K value of the important zone II could be zero or could be over 5000 m/d (two standard deviations), a range that on face value calls into question whether the model itself rests on sound hydrogeologic grounds. One may argue that the unrealistically high estimated K value of 715 m/d could be lowered to a more reasonable value and that it could still lead to as good a fit to the head and concentration data. However, this argument would only be believable if the model of Barlebo et al. is run with a lower K value in zone II and matches the concentration data. As pointed out by *Hill* [1998, p. 36], "Unreasonable estimated parameter values could indicate model error." Indeed, the unreasonably large estimated K value for zone II suggests that the advection-dispersion model used by Barlebo et al. was not appropriate for the MADE site.

[10] Another aspect of the Barlebo et al. analysis that needs to be considered is the actual quality of the match to concentration data that is achieved at 328 days. As reported by *Barlebo et al.* [2004], the highest calculated concentration at 328 days was 551 pCi/mL for the tritium tracer. The observed peak concentration was 4721 pCi/mL, a factor of more than 8 times larger than the calculated value of Barlebo et al. As a matter of fact, one of the major deficiencies of the advection-dispersion model applied to the MADE site was its inability to simultaneously reproduce the high concentrations trapped near the source area as well as the extensive spreading toward the far-field at low concentrations. Matching just one of these features, on the other hand, is of course less difficult. Using an unrealistically high K value for zone II might have allowed the model of Barlebo et al. to match the low-concentration plume edge, but the mismatch to the near-source high-concentration data suggests that there is a problem with the applicability of their advection-dispersion conceptual model to this site. The dual-domain model described by *Feehley et al.* [2000] successfully matched both the near-source peak and the downstream front.

[11] In summary, numerous theoretical, laboratory, and field studies have demonstrated that the classical advection-dispersion model failed to capture the key characteristics of solute transport behavior at the MADE site. The analysis of *Barlebo et al.* [2004] was purported to answer the question of whether the advection-dispersion model could reproduce the field-observed tracer plumes if the hydraulic conductivity field measured by the flowmeter tests were systematically in error. We believe the answer is clearly no, and that they obtained a negative result. If anything, the results of Barlebo et al. point to the inadequacy of their own conceptual model and the failure of advection-dispersion processes alone to reproduce well-documented field observations. The limited success of their zonal model in reproducing rapid transport of dilute solute depends on inserting an extensive region of unrealistic hydraulic conductivity (715 m/d) directly in the plume's path (zone II). Their result is likely an artifact of invoking the implausible model of the key solute spreading mechanism, use of a calibration and fitting procedure that ignores measured conductivities at the MADE site, and not reproducing the measured peak concentration value by a factor of 8. Analysis of multiple core samples and several pump tests confirm that such a large region of highly conductive gravel or other media with a conductivity of 715 m/d simply does not exist. Even if it did, the agreement is still very poor between the observed plume and the calculated plume based on their advection-dispersion model. In contrast, the dual-domain model was able to achieve a significantly better match to the observed plumes for all three natural gradient tracer tests using similar dual-domain model parameters [*Feehley et al.*, 2000; *Harvey and Gorelick*, 2000; *Julian et al.*, 2001]. The dual-domain model provides a physically based, albeit still highly approximate mechanism for accommodating both the rapid solute transport along small-scale preferential flow paths and the mass storage and release effects of relatively immobile solutes in the low-K materials. Also provided is an understanding of the mass balance anomaly observed in the MADE tests and tied further to measurements by *Boggs and Adams* [1992].

[12] Finally, we note that obtaining an excellent mass balance in a numerical model [*Barlebo et al.*, 2004, Table 4]) merely indicates that the numerical approximation being used actually solves the partial differential equation being posed. Obtaining such a mass balance is not evidence that the correct conceptual model is being solved in the first place. In fact, maintaining constant mobile mass is a negative aspect of their conceptual model: the experimental results indicate that the total mass contained in the mobile, sampled portion of the plume changed over time. Years of work at the MADE site repeatedly suggest that much of the migrating solute mass is temporarily trapped in the relatively low conductivity media matrix. The mass balance of Barlebo et al., based on the advective-dispersive model, fails to account for the relatively immobile solute mass. The problem is that their conceptual model ignores a key transport process and a key second coupled partial differential equation that is needed to describe mobile-immobile domain solute mass transfer. Contrary to their claims, the results of Barlebo et al. indeed point to the failure of their advective-dispersive model to describe solute concentrations at the MADE site.

[13] **Acknowledgments.** We are grateful to Gaisheng Liu and Geoff Tick for their assistance with the new pumping test conducted for this study. Partial funding for this work was provided by the National Science Foundation under grants EAR-0537668 and EAR-0538011. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

Adams, E. E., and L. W. Gelhar (1992), Field study of dispersion in a heterogeneous aquifer: 2. Spatial moments analysis, *Water Resour. Res.*, *28*(12), 3293–3307.
Barlebo, H. C., M. C. Hill, and D. Rosbjerg (2004), Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model, *Water Resour. Res.*, *40*, W04211, doi:10.1029/2002WR001935.
Benson, D. A., R. Schumer, M. M. Meerschaert, and S. W. Wheatcraft (2001), Fractional dispersion, Levy motion and the MADE tracer tests, *Transp. Porous Media*, *42*, 211–240.
Berkowitz, B., and H. Scher (1998), Theory of anomalous chemical transport in random fracture network, *Phys. Rev. E*, *57*(5), 5858–5869.
Boggs, J. M., and E. E. Adams (1992), Field study of dispersion in a heterogeneous aquifer: 4. Investigation of adsorption and sampling bias, *Water Resour. Res.*, *28*(12), 3325–3336.
Boggs, J. M., S. C. Young, and L. M. Beard (1992), Field study of dispersion in a heterogeneous aquifer, 1, Overview and site description, *Water Resour. Res.*, *28*(12), 3281–3291.

Boggs, J. M., L. M. Beard, S. E. Long, M. P. McGee, W. G. MacIntyre, C. P. Antworth, and T. B. Stauffer (1993), Database for the Second Macrodispersion Experiment (MADE-2), *Tech. Rep. TR-102072*, Electr. Power Res. Inst., Palo Alto, Calif.

Boggs, J. M., J. A. Schroeder, and S. C. Young (1995), Data to support model development for natural attenuation study, *Report WR28-2-520-197*, TVA Eng. Lab., Tenn. Valley Auth., Norris.

Feehley, C. E., C. Zheng, and F. J. Molz (2000), A dual-domain mass transfer approach for modeling solute transport in heterogeneous porous media, application to the MADE site, *Water Resour. Res.*, *36*(9), 2051–2515.

Harvey, C. F., and S. M. Gorelick (2000), Rate-limited mass transfer or macrodispersion: Which dominates plume evolution at the Macrodispersion Experiment (MADE) site?, *Water Resour. Res.*, *36*(3), 637–650.

Hill, M.C. (1998), Methods and guidelines for effective model calibration, *U.S. Geol. Surv. Water Resour. Invest. Rep., 98-4005*.

Julian, H. E., J. M. Boggs, C. Zheng, and C. E. Feehley (2001), Numerical simulation of a natural gradient tracer experiment for the natural attenuation study: Flow and physical transport, *Ground Water*, *39*(4), 534–545.

Liu, G., C. Zheng, and S. M. Gorelick (2004), Limits of applicability of the advection-dispersion model in aquifers containing connected high-conductivity channels, *Water Resour. Res.*, *40*, W08308, doi:10.1029/2003WR002735.

MacIntyre, W. G., J. M. Boggs, C. P. Antworth, and T. B. Stauffer (1993), Degradation kinetics of aromatic organic solutes introduced into a heterogeneous aquifer, *Water Resour. Res.*, *29*(12), 4045–4051.

Rehfeldt, K. R., J. M. Boggs, and L. W. Gelhar (1992), Field study of dispersion in a heterogeneous aquifer: 3. Geostatistical analysis of hydraulic conductivity, *Water Resour. Res.*, *28*(12), 3309–3324.

Zheng, C., and S. M. Gorelick (2003), Analysis of solute transport in flow fields influenced by preferential flow paths at the decimeter scale, *Ground Water*, *41*(2), 142–155.

Zheng, C., and J. J. Jiao (1998), Numerical simulation of tracer tests in a heterogeneous aquifer, *J. Environ. Eng.*, *124*(6), 510–516.

Zinn, B., and C. F. Harvey (2003), When good statistical models of aquifer heterogeneity go bad: A comparison of flow, dispersion, and mass transfer in connected, and multivariate Gaussian hydraulic conductivity fields, *Water Resour. Res.*, *39*(3), 1051, doi:10.1029/2001WR001146.

S. M. Gorelick, Department of Geological and Environmental Sciences, Stanford University, Bldg 320, Room 118, Stanford, CA 94305, USA.

C. F. Harvey, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Ralph M. Parsons Laboratory 48-321, Cambridge, MA 02139, USA.

F. J. Molz, Department of Environmental Engineering and Science, Clemson University, 342 Computer Court, Anderson, SC 29625, USA.

C. Zheng, Department of Geological Sciences, University of Alabama, 202 Bevill Building, Box 870338, Tuscaloosa, AL 35487-0338, USA. (czheng@ua.edu)

Reply to comment by F. Molz et al. on "Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model"

Mary C. Hill,[1] Heidi Christiansen Barlebo,[2] and Dan Rosbjerg[3]

Received 29 September 2005; revised 27 February 2006; accepted 14 March 2006; published 14 June 2006.

Citation: Hill, M. C., H. C. Barlebo, and D. Rosbjerg (2006), Reply to comment by F. Molz et al. on ''Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model,'' *Water Resour. Res.*, *42*, W06604, doi:10.1029/2005WR004624.

[1] We are pleased to have the opportunity to discuss further what we think are important methods and results presented by *Barlebo et al.* [2004]. We are especially pleased to enter into a public discussion with four scientists who we regard with such high esteem concerning an important topic of mutual interest.

[2] The main goal of our paper is to present and demonstrate a novel method of using dependent-variable data (often referred to as observations) and models to investigate the accuracy of data related to input parameters, here, hydraulic conductivity. The idea of using conservation of mass equations to test different types of data against one another rigorously is not new to science in general, but to our knowledge, the only comparable attempt at testing hydraulic conductivity data rigorously using groundwater models was reported by *Barth et al.* [2001] using data from a controlled laboratory experiment. Using data from a complex field system such as that at the MADE site, is, of course, much more difficult. Less rigorous evaluations using groundwater models have been conducted, as discussed by *Ingebritzen and Sanford* [1998, pp. 14–15]. Our results suggest that while the dual-domain processes proposed by *Molz et al.* [2006] may be important, difficulties in the data set considered indicate that it does not demonstrate the dominance of dual-domain processes as vividly as has been presented in the literature. We went on to discuss what site-scale data would be needed to provide more conclusive evidence.

[3] Our reading of *Molz et al.* [2006] yields five issues that we address in the following five sections.

1. Misrepresented Results [*Molz et al.*, 2006, paragraphs 3, 4, and 11]

[4] *Barlebo et al.* [2004, paragraphs 61, 85, and 92 and Table 2] indicate that their results are not as definitive as suggested by Molz et al.. The statements from the abstract and conclusions cited by Molz et al. include qualifiers, and the difficulties are described explicitly in the text of the article. Considering the acknowledged difficulties, it does not seem to us that the article was ''claiming a positive [result]''. Rather, we explored an alternative that is important to understanding measurements and simulation of groundwater transport. The results were not definitive but suggested some possibilities that we tried to present clearly.

2. On the Existence of Dual Domain Processes in Natural Systems in General and the MADE Site in Particular [*Molz et al.*, 2006, paragraph 6]

[5] In this work we consider important questions about the precision and accuracy of the hydraulic conductivity data and about the extent to which imprecise or inaccurate hydraulic conductivity data might affect the support for hypotheses being considered in the literature, such as dual porosity. In our minds, the issue addressed is not whether such mechanisms occur but in what ways this data set conclusively demonstrates their prevalence and what the data set can reveal about conducting more definitive experiments. Neglecting alternative mechanisms was not ''arbitrary.'' It was required for the scientific inquiry conducted.

3. Use of Zones of Constant Value Given the Locally Heterogeneous Texture of the Material [*Molz et al.*, 2006, paragraph 8]

[6] As stated by Molz et al., larger-scale hydraulic conductivity trends appeared to dominate flow and transport at the MADE site. To build a model with which the measured hydraulic conductivity data could be evaluated, the hydraulic conductivity data could not be used directly to construct the hydraulic conductivity distribution, as had been done in other studies [e.g., *Feehley et al.*, 2000; *Julian et al.*, 2001]). The head data clearly show abrupt changes in hydraulic gradient indicating that a hydraulic conductivity distribution represented using zones of constant value might be an approximation with some promise. The paper clearly shows that we were fully aware of the advantages and difficulties of this approximation, and we discussed in some detail what the data implied about the continuity of the hydraulic conductivity field [see *Barlebo et al.*, 2004, paragraphs 48 and 82–84].

[1]U.S. Geological Survey, Boulder, Colorado, USA.
[2]Geological Survey of Denmark and Greenland, Copenhagen, Denmark.
[3]Institute of Environment and Resources, Technical University of Denmark, Kongens Lyngby, Denmark.

0043-1397/06/2005WR004624$09.00

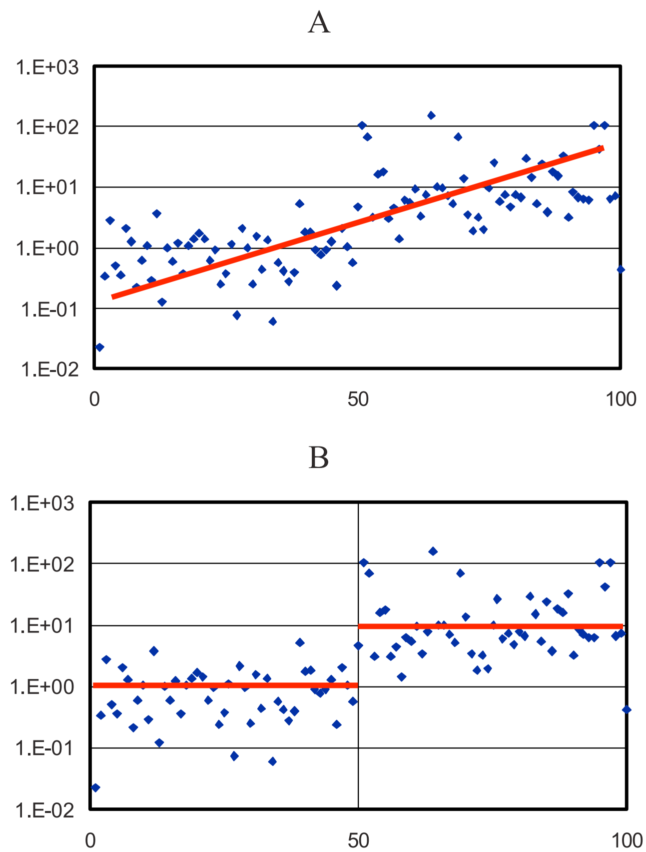


Figure 1. Random numbers demonstrating how noise obscures identification of large-scale trends. The random numbers are lognormally distributed with a standard deviation of half an order of magnitude. (a) The data could easily be interpreted erroneously as coming from a distribution with a linear trend. (b) The true mean values used to generate the numbers are shown.

[7] Defining zones using the hydraulic conductivity data needs to be considered in the context of the replicate data from the MADE site presented by *Rehfeldt et al.* [1989]. The replicate data suggest errors between 3 and 10 times the measured value. To demonstrate the consequences such errors have when trying to identify large-scale trends, consider the example shown in Figure 1. In practice, we have data sets that are far sparser and trends would be more difficult to identify.

[8] One concern we have is that investigations of alternative mechanisms such as dual porosity have not, to our knowledge, tried to explicitly consider the clearly documented replicate errors in the hydraulic conductivity data. We wonder what this means about the efficacy of the alternative mechanisms being proposed. Does it mean that they overwhelm the errors in the hydraulic conductivity data? Does it mean that they produce the right concentration distribution but they are not representative of the actual processes, for which the errors in the hydraulic conductivity data would need to be considered? We believe these questions need to be addressed to truly understand what measured hydraulic conductivity values mean and what mechanisms govern subsurface transport. *Barlebo et al.* [2004] present one attempt to address some of these questions. Clearly, more work is required in this area.

4. Implausibility of the Estimated Hydraulic Conductivity of Zone II [*Molz et al.*, 2006, paragraph 8, 9, and 10]

[9] To investigate the concern about plausibility of the hydraulic conductivity of zone II presented in the paper, all values involved are presented in Table 1. In addition, we have included characteristic values for different types of deposits as needed to address the comment about the type of materials found at the site.

[10] The pump test values are reasonably similar to the geometric mean of the flowmeter measurements for zone II, and this consistency might be thought to lend credence to the flowmeter measurements. However, an important issue is what material is measured by the pump tests. The material represented by zone II is distinct enough to result in hydraulic gradients that are flatter than in neighboring areas [see *Barlebo et al.*, 2004, Figure 4], and on average, the hydraulic conductivities in zone II are expected to be higher than in the surrounding deposits. On the basis of remarks made by Molz et al. and Boggs et al. [1992], it seems likely that the pump test values should be lower than local zone II values of hydraulic conductivity (see notes 3 and 4 of Table 1). The consistency between the pump test and flowmeter values thus supports the idea that the flowmeter measurements may be biased such that they are lower, on average, than the actual values in zone II. Further evaluation of this issue would require an analysis of the pump test data using a numerical model of the system, which is beyond the scope of this reply.

[11] Molz et al. suggest that the materials in zone II are not the clean medium gravels indicated by the model calibrated hydraulic conductivity of 82.8×10^{-4} m/s (715 m/d). We would be very interested in whether the adjusted value of 41.4×10^{-4} m/s (358 m/d), which we used to estimate the maximum possible bias of a factor of 5, is thought to be consistent with the field material. The estimated value was adjusted to account for model error. The adjustment is well within the range of its uncertainty as reflected by its coefficient of variation [*Barlebo et al.*, 2004, Table 1]. If the adjusted value is not considered to be plausible, obtaining a plausible range from Molz et al. would assist us in determining a more accurate estimate of maximum possible bias.

[12] An attempt to create a simulation using the adjusted value of hydraulic conductivity for zone II would require not only changing that parameter value but also consideration of alternative models, and especially alternative ways of representing the questionable boundary conditions. Such an evaluation, though important, was considered to be beyond the scope of the paper. We felt that the model we produced was sufficiently plausible to produce some important insights, and we stopped with those.

[13] Molz et al.'s statement that the large confidence interval on the hydraulic conductivity of zone II "calls into question whether the model itself rests on solid hydrogeologic grounds" is curious. It is easy to create situations using synthetic models in which the model is known to accurately represent a system yet large confidence intervals

Table 1. Hydraulic Conductivity Values Associated With Zone II of *Barlebo et al.* [2004][a]

Source of Estimate	Notes[b]	Hydraulic Conductivity	
		Meters per Second	Meters per Day
Cited by Barlebo et al. [2004]			
Geometric mean of flowmeter measurements	1	2.57×10^{-4}	22.2
Arithmetic mean of flowmeter measurements	1	8.05×10^{-4}	69.5
Model calibration		82.8×10^{-4}	715
Used to conclude that at the very most, K measurements may be biased by a factor of 5	2	41.4×10^{-4}	358
Cited by Molz et al. [2006]			
Old pump test, using full thickness	3	2.0×10^{-4}	17
Old pump test, using limited thickness	3	5.0×10^{-4}	43
New pump test, using full thickness	4	0.39×10^{-4}	3.4
New pump test, using limited thickness	4	2.96×10^{-4}	25.6
Text Book Values for Relevant Materials			
Gravel	5	10×10^{-4} to 1	9 to 90000
Gravel	6	3×10^{-4} to 300×10^{-4}	26 to 2600
Coarse sand	6	9×10^{-7} to 60×10^{-4}	0.1 to 500
Sand	5	10^{-6} to 100×10^{-4}	0.09 to 9
Medium sand	6	9×10^{-7} to 5×10^{-4}	0.1 to 40
Fine sand	6	2×10^{-7} to 2×10^{-4}	0.1 to 18

[a]Values are reported with units of meters per second (m/s) used by *Barlebo et al.* [2004] and units of meters per day (m/d) used by *Molz et al.* [2006].

[b]Notes: 1, "The geometric mean is an approximate lower bound of the effective value of horizontal hydraulic conductivity for a three-dimensional system if the material is randomly distributed, while the arithmetic mean applies to material organized in layers parallel to the flow direction. The situation at the MADE site is expected to be between these two extremes." [*Barlebo et al.*, 2004, paragraph 73]); 2, *Barlebo et al.* [2004, Table 2 and paragraph 86] assume that model error, and especially difficulties with boundary conditions, could easily result in the estimate being off by a factor of 2, so the smaller value was used to derive an estimate of the maximum possible bias; 3, from *Boggs and Adams* [1992, Table 3]; the test is described as a large-scale test carried out over 192 hours at a pumpage rate of 208 L/min; it seems very likely that these values are affected by nearby lower hydraulic conductivity deposits; 4, Molz et al. mention that nearby areas with lower values of hydraulic conductivity affect pump test results; 5, from *Freeze and Cherry* [1979, p. 29]; 6, from *Domenico and Schwartz [1990*, p. 65] and *Zheng and Bennett* [2002, p. 296].

on parameters are produced. The large confidence intervals do indicate a poorly constrained parameter value, and, as noted in the next paragraph, this made it difficult to obtain definitive conclusions.

[14] Molz et al. suggest that a solution with parameter values that more closely match measured values and are more consistent with the texture of the material would be more convincing. Of course we agree with this suggestion. Also, if the coefficients of variation on the parameters had been smaller, then the unreasonable parameter values would have clearly demonstrated the importance of alternative mechanisms, and that definitive result would have been welcome. Our results were between these two definitive possibilities. We used the model we had to learn as much as possible about the simulated flow conditions that were producing what we considered to be a reasonably good fit to the concentrations using advective-dispersive processes.

5. Model Fit to Concentrations [*Molz et al.*, 2006, paragraphs 10 and 11]

[15] *Barlebo et al.* [2004] clearly discuss the ways in which their model fit and did not fit the concentration data. We state clearly that it is the simultaneous fitting of high concentrations near the source and extensive spreading of the plume that is important to consider. The extensive spreading is simulated quite well. The misfit at the source is discussed in section 5 of Barlebo et al. (paragraph 96) as follows: "In both the model and the measurements, the highest remaining concentration occurs at the source, but the maximum simulated value is 0.4% of the starting simulated concentration while the maximum measured concentration is six times that, or 2.4%. How much of the discrepancy is caused by difficulties with simulating the initial concentration distribution and numerical dispersion would determine the role that would need to be played by alternative mechanisms in maintaining high concentrations at the source."

6. Interpretation of Mass Balance Analysis Presented in Table 4 of Barlebo et al. [*Molz et al.*, 2006, paragraph 12]

[16] In Table 4 of *Barlebo et al.* [2004] we presented a mass balance to investigate the possibility that at late times the hypothesized mass deficit might be partly explained by mass having passed beyond the sampling network. Our analysis suggests that this effect may indeed be a significant contributing factor. We agree completely with Molz et al. that a good mass balance measures the accuracy of the numerical approximation, not the validity of a simulation.

7. Another Issue

[17] An interesting issue not raised by Molz et al. is that *Julian et al.* [2001] were able to produce a head distribution that was similar to that considered by *Barlebo et al.* [2004] using a hydraulic conductivity distribution that was more

closely related to the measured values of hydraulic conductivity. *Julian et al.* [2001], however, do not compare simulated and measured hydraulic conductivities, do not discuss the simulated flow field, and do not discuss any effort to consider what might be a trade-off between deviations from measured hydraulic conductivities and the importance of dual porosity processes. In addition, *Julian et al.* [2001] neglect recharge. While the reasons stated might justify that assumption for their model, the effects of neglecting recharge on dual-porosity importance were not evaluated. The results from *Barlebo et al.* [2004] as well as common hydrologic principles suggest that the recharge rate and distribution can be important to transport. Further analysis with the model presented by *Julian et al.* [2001] might help to address some of the questions posed and not definitively resolved by *Barlebo et al.* [2004] as well as help to understand how recharge and dual-porosity processes interact. For example, such an effort could be used to identify aspects of transport that can be equivalently produced by variations in hydraulic conductivity, recharge, or dual porosity, and aspects of transport that are unique to these system characteristics.

[18] Finally, there is one detail that needs to be corrected. Molz et al. suggest that we only considered concentration data from 328 days in our regressions, and this is incorrect. We included selected concentration data from all four of the snapshots, as indicated in paragraphs 24 and 45 of Barlebo et al. [*Molz et al.*, 2006, paragraph 4].

8. Conclusions

[19] We believe that our results in some ways support the importance of dual-porosity processes, especially to maintaining high concentrations at the injection site. However, our results also suggest that dual-porosity processes may not play as dominant a role as sometimes suggested. Understanding the interplay of large-scale heterogeneity and dual-porosity processes is important to accurate predictions of groundwater transport.

[20] At a fundamental level, our goal is that *Barlebo et al.* [2004] and *Molz et al.* [2006] focus attention on measurements and how they can be used in conjunction with conservation principles embodied in quantitative solutions such as process-based numerical models to test hypotheses about groundwater systems. Groundwater systems are perplexing and are likely to remain so for some time. Yet careful, ever vigilant inquiry is slowly providing answers.

[21] We appreciate the interest and effort of Molz et al. and look forward to fruitful discussions in the future.

References

Barlebo, H. C., M. C. Hill, and D. Rosbjerg (2004), Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model, *Water Resour. Res.*, *40*, W04211, doi:10.1029/2002WR001935.
Barth, G. R., M. C. Hill, T. H. Illangasekare, and H. Rajaram (2001), Predictive modeling of flow and transport in a two-dimensional intermediate-scale, heterogeneous porous media:, *Water Resour. Res.*, *37*(10), 2503–2512.
Boggs, J. M., and E. E. Adams (1992), Field study of dispersion in a heterogeneous aquifer: 4. Investigation of adsorption and sampling bias, *Water Resour. Res.*, *28*(12), 3325–3336.
Domenico, P. A., and F. W. Schwartz (1990), *Physical and Chemical Hydrogeology*, 824 pp., John Wiley, Hoboken, N. J.
Feehley, C. E., C. Zheng, and F. J. Molz (2000), A dual-domain mass transfer approach for modeling solute transport in heterogeneous porous media, application to the MADE site, *Water Resour. Res.*, *36*(9), 2051–2515.
Freeze, R. A., and J. A. Cherry (1979), *Groundwater*, 604 pp., Prentice-Hall, Upper Saddle River, N. J.
Ingebritzen, S. E., and W. E. Sanford (1998), *Groundwater in Geologic Processes*, 341 pp., Cambridge Univ. Press, New York.
Julian, H. E., J. M. Boggs, C. Zheng, and C. E. Feehley (2001), Numerical simulation of a natural gradient tracer experiment for the Natural Attenuation Study: Flow and physical transport, *Ground Water*, *39*(4), 534–545.
Molz, F. J., C. Zheng, S. M. Gorelick, and C. F. Harvey (2006), Comment on "Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model" by Heidi Christiansen Barlebo, Mary C. Hill, and Dan Rosbjerg, *Water Resour. Res.*, *42*, W06603, doi:10.1029/2005WR004265.
Rehfeldt, K. R., P. Hufschmied, L. W. Gelhar, and M. E. Schaefer (1989), Measuring hydraulic conductivity with the borehole flowmeter, *Rep. EN-6511*, Res. Proj. 2485-5, Electr. Power Res. Inst., Palo Alto, Calif.
Zheng, C., and G. D. Bennett (2002), *Applied Contaminant Transport Modeling*, 2nd ed., 621 pp., John Wiley, Hoboken, N. J.

H. C. Barlebo, Geological Survey of Denmark and Greenland, DK-1350 Copenhagen, Denmark. (hcb@geus.dk)
M. C. Hill, Water Resources Division, U.S. Geological Survey, 3215 Marine Street, Boulder, CO 80303, USA. (mchill@usgs.gov)
D. Rosbjerg, Environment and Resources DTU, Technical University of Denmark, Building 115, DK-2800 Kongens Lyngby, Denmark. (dr@er.dtu.dk)

Evaluating the MADE Dilemma

1. What is the major thesis of Barlebo et al. (2004)?

2. What data do they have to support this thesis?

3. What role does data error play in their analysis?

4. What is the major thesis of Molz et al. (2006)?

5. What data do they have to support this thesis?

6. What role does data error play in their analysis?

7. What is the major thesis of Hill et al. (2006)?

8. What data do they have to support this thesis?

9. What role does data error play in their analysis?

10. List **three** main areas of disagreement between the two sides. Be specific.

11. Consider the argument. Decide whether you are convinced by one or the other, and what data you would like to have to help answer this question. Debate the importance of this issue. Include a brief summary of each group member's views, and the arguments used to support her/his view. While the goal is not consensus, mention whether or not there was any sort of general agreement reached among your group members.

Arguments supporting Barlebo et al. (2004)/Hill et al. (2006):

Arguments supporting Molz et al. (2006):

Group Opinion(s):

12. Your group may have questions that arise during your discussions, and these may not be covered during the class synopsis. Please add anything that is yet unclear here.

References:

Barlebo, H. C., M. C. Hill, and D. Rosbjerg (2004), Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model, Water Resour. Res., 40, W04211, doi:10.1029/2002WR001935.

Hill, M. C., H. C. Barlebo, and D. Rosbjerg (2006), Reply to comment by F. Molz et al. on "Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model", Water Resour. Res., 42, W06604, doi:10.1029/2005WR004624.

Molz, F. J., C. Zheng, S. M. Gorelick, and C. F. Harvey (2006), Comment on "Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model" by Heidi Christiansen Barlebo, Mary C. Hill, and Dan Rosbjerg, Water Resour. Res., 42, W06603, doi:10.1029/2005WR004265.

Sand Tank Aquifer Experiment 2

Today you'll explore transport within the sand tank aquifers.

When you complete this exercise, you will be able to:

1. calculate the groundwater velocity in an aquifer
2. explore transport behavior within a heterogeneous aquifer

Equipment:

1. sand tank
2. nalgene water bottles with lids
3. syringe
4. funnel
5. food dye
6. ruler
7. calculator
8. stopwatch (or watch with second hand)
9. pencils
10. buckets
11. towels
12. gallons of water

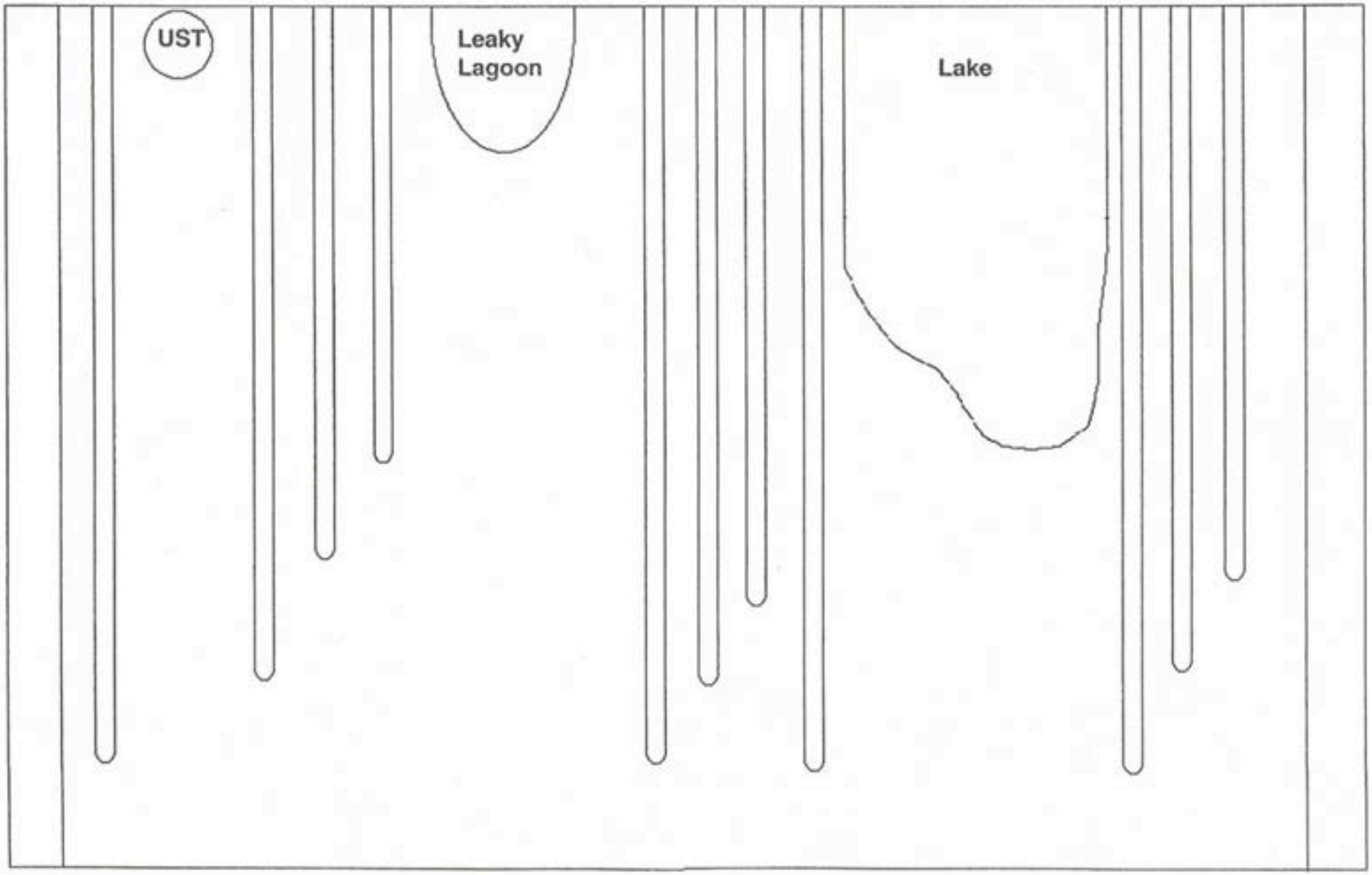
Start by filling the tank. Close all valves and add water as uniformly as possible across the top of the model. Once full, fill the two plastic recharge bottles with water, secure the rubber stopper assemblies, and insert into the two wells on each side of the demonstration (see Figure 1). This will maintain a constant water level just below the two outlet drains at the top of the demonstration. The several empty containers and bucket included with the model can be used to catch any overflow.

1. Add two different contaminants to two different wells using the syringes and mixing a small amount of dye with water. Observe how the different colored dyes travel through different layers of sediment from various wells. Which layer of sediment (sand or gravel) does groundwater travel through faster and why?

2. Leaky underground storage tanks can be sources for contaminating groundwater supplies. Inject dye into the underground storage tank and observe what happens as the storage tank begins to leak. Draw on the sand tank diagram where the "pollutants" traveled. Time "pollution" was added: __________

3. Calculate the velocity of the pollution front.

4. Given a porosity of 0.3, what is the average hydraulic conductivity of the sand tank?



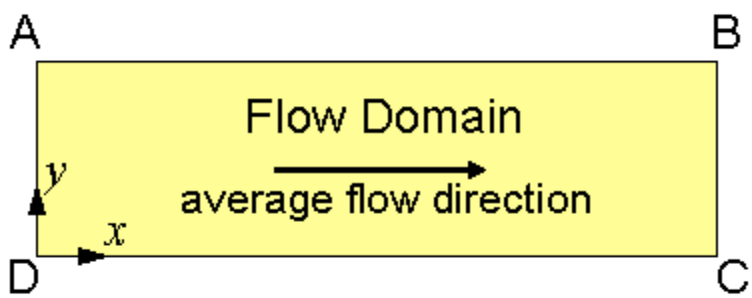
Amy Hobbs, 2001
Department of Geological Science:
University of Texas at Austin

ParticleFlow

ParticleFlow and Introductory Material Credit:
Paul A. Hsieh
U. S. Geological Survey
345 Middlefield Road, Mail Stop 496
Menlo Park, CA 94025
http://water.usgs.gov/nrp/gwsoftware/tdpf/tdpf.html

Introduction to ParticleFlow

The two-dimensional model ParticleFlow simulates flow in a rectangular domain. A key purpose of the ParticleFlow model is to illustrate how heterogeneities in hydraulic properties cause the spatial spreading of fluid particles. This spreading is analogous to macro-scale solute dispersion.



The rectangular flow domain (see above figure) is assumed to be bounded on the left and right sides (AD and BC) by specified head boundaries, and on the top and bottom (AB and DC) by no-flow boundaries. Assuming that the head along AD is higher then the head along BC, the average flow is from left to right.

Governing Equation

The steady-state ground-water flow equation to be solved is

$$\frac{\partial}{\partial x}\left(K\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial h}{\partial y}\right) = 0 \qquad (1)$$

where h is hydraulic head, and K is hydraulic conductivity (assumed isotropic), and x and y are the Cartesian coordinates.

Boundary Conditions

The boundary condition along AD is

$$h = h_1 \qquad (2)$$

where h_1 is a constant. The boundary condition along BC is

$$h = h_2 \qquad (3)$$

where h_2 is also a constant. The boundary condition along AB and DC is

$$\frac{\partial h}{\partial y} = 0 \tag{4}$$

The computer model ParticleFlow solves the above equations by the finite element method. The flow domain is represented by a rectangular mesh composed of square cells, each is divided into two triangular elements. Linear basis functions are used in the finite element formulation. After solving for hydraulic head h, the x and z components of the average interstitial velocity vector are computed by

$$v_x = -\frac{K}{n}\frac{\partial h}{\partial x} \qquad v_y = -\frac{K}{n}\frac{\partial h}{\partial y} \tag{5}$$

where n is porosity. The velocity vectors are used for calculating flow paths and the advective movement of fluid particles.

In a flow field with non-uniform velocity, a cloud of fluid particles will tend to spread. This spreading can be described by the spatial variance (in the x and y directions) of particle positions, defined as:

$$S_{xx} = \frac{1}{N}\sum_{i=0}^{N}(x_i - x_c)^2 \qquad S_{yy} = \frac{1}{N}\sum_{i=0}^{N}(y_i - y_c)^2 \tag{6}$$

where N is the total number of fluid particles, x_i and y_i are the x and y coordinates of the i-th particle, and x_c and y_c denote the x and y positions of the center of mass, defined as

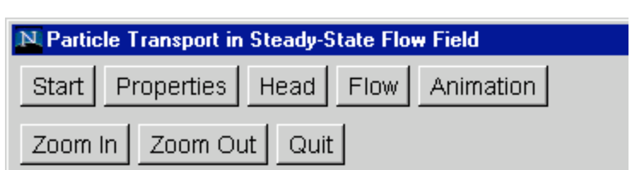
$$x_c = \frac{1}{N}\sum_{i=0}^{N} x_i \qquad y_c = \frac{1}{N}\sum_{i=0}^{N} y_i \tag{7}$$

If each fluid particle is assumed to carry a fixed amount of solute mass, then particle spreading is analogous to macro-scale solute dispersion. In the macro-dispersion approach, the small-scale variation of velocity is not explicitly simulated. Instead, solute spreading is characterized by a dispersion tensor. The dispersion process is called Fickian if the plot of the spatial variances S_{xx} and S_{yy} versus time show straight-line relations. In this case, the components of the dispersion coefficients can be estimated by

$$D_{xx} = \frac{1}{2}\frac{dS_{xx}}{dt} \qquad D_{yy} = \frac{1}{2}\frac{dS_{yy}}{dt} \tag{8}$$

Running the Model

Running the model involves 5 steps. To begin each step, click the corresponding button at the top of the window. A dialog box appears for you to enter the necessary input data. The three buttons on the second row allow you to zoom in, zoom out, and quit the model.



Step 1: Start -- Specify model dimension
Step 2: Properties -- Specify hydraulic conductivity and porosity
Step 3: Head -- Compute hydraulic head

After hydraulic head is computed, two options are available. You may proceed to

Step 4a: Flow (Path) -- Track flow paths from selected points
Step 5a: Animation -- Animate the evolution of flow paths

or

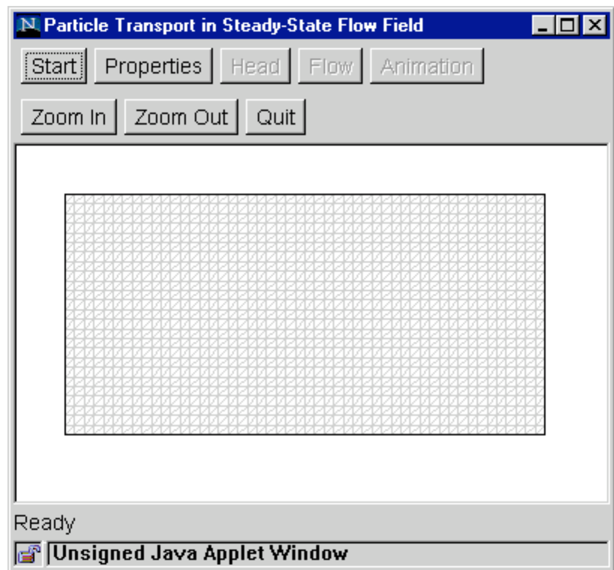
Step 4b: Flow (Particle) -- Set up initial distribution of fluid particles
Step 5b: Animation -- Animate the advective movement of fluid particles

Step 1: Start

This step sets up the flow domain, mesh, and average hydraulic gradient.

- Click the "Start" button to bring up the Start Dialog Box.
- Enter the size of a square element, number of rows and column, and average hydraulic gradient. For example, if the element size is 10 m, and there are 40 columns and 20 rows, the grid will be 400 m by 200 m.
- Click "OK".

The program generates a rectangular mesh and then splits each square element into two triangular elements.

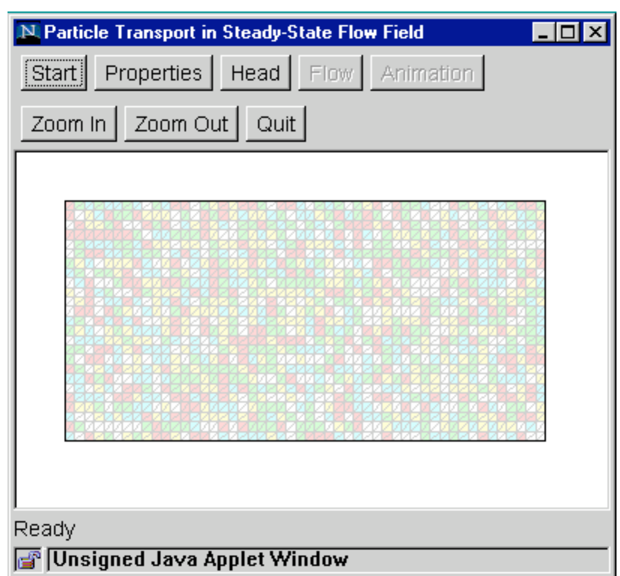


Step 2: Properties

This step assigns hydraulic properties (hydraulic conductivity and porosity) to model elements.

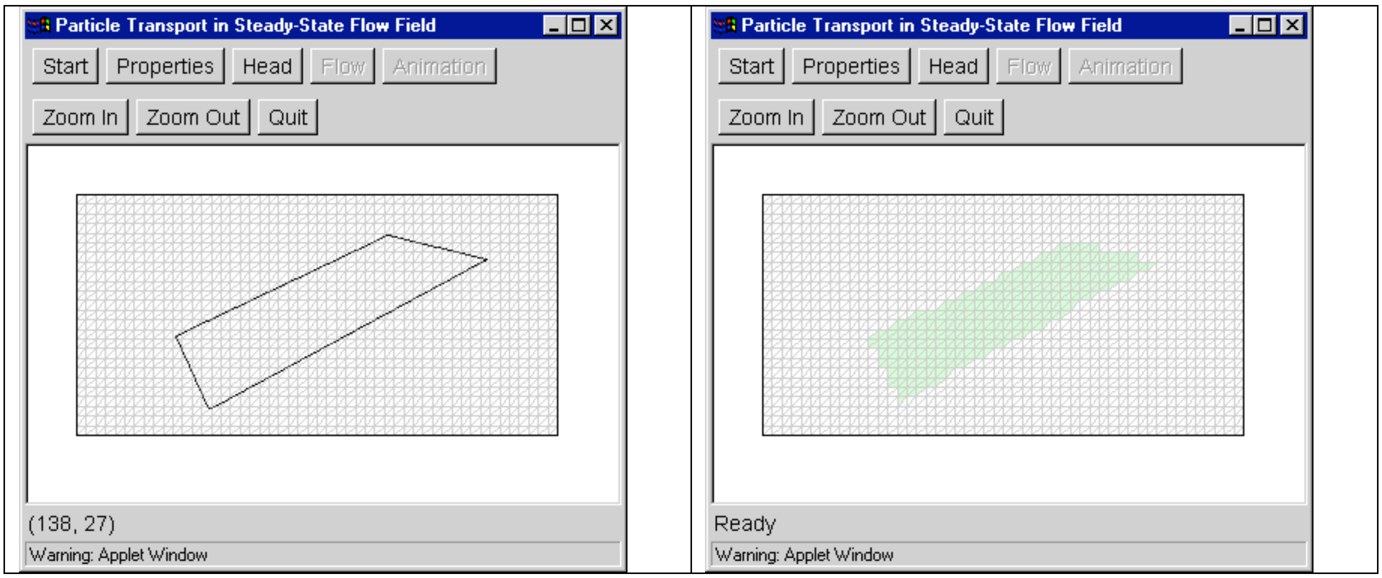
- Click the "Properties" button to bring up the Properties Dialog Box.
- Five sets of hydraulic conductivity (m/s) and porosity (%) values are available for assignment to model elements. Each set is represented by a color. Default values are initially provided, but users may alter any or all of these values in the edit boxes.

Two options are now available. To randomly assign hydraulic conductivity and porosity values to the grid, click the "Randomize" check box and then click "OK". Each pair of triangle elements (forming a square) will be randomly assigned one of five colors corresponding to the properties in the dialog box.



Alternatively, properties can be manually assigned to the grid as follows:

- Select a set of hydraulic conductivity and porosity values by clicking the color icon.
- Click "OK" to close the dialog box.
- Draw a polygon to enclose those elements you want to assign the selected property values. A polygon is drawn by clicking at its vertices. To finish drawing the polygon, double click the last vertex.
- The elements enclosed by the polygon are filled with the color you selected in the dialog box.



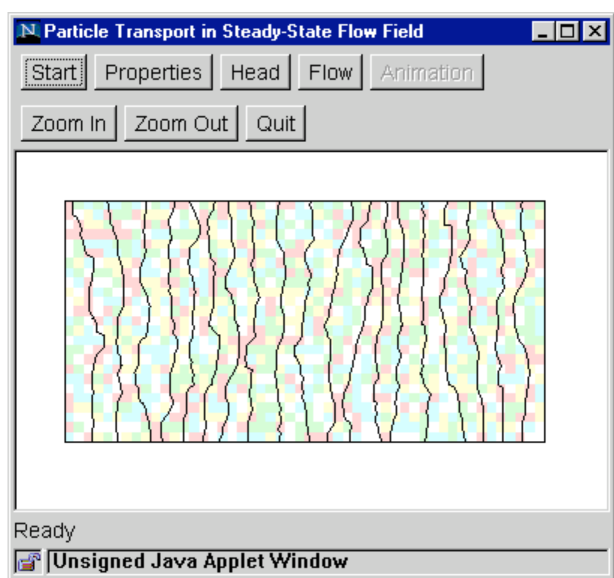
Additional zones with the same properties may be defined by drawing additional polygons. To specify a zone with different property values, click the "Properties" button again to bring up the dialog box and click on a different color icon. Then click "OK," draw a polygon as before. The newly selected elements now are filled with the new color. Drawing mistakes can be rectified by overdrawing with another zone. Any part of the mesh not covered by a polygon will have properties corresponding to the white color.

Step 3: Head

This step computes hydraulic head in the model domain.

- Click the "Head" button to bring up the Head Dialog Box.
- Select the number of contour intervals to be drawn. (Contours are equally spaced between the highest and the lowest head.)
- Click "Compute" to start model computation.

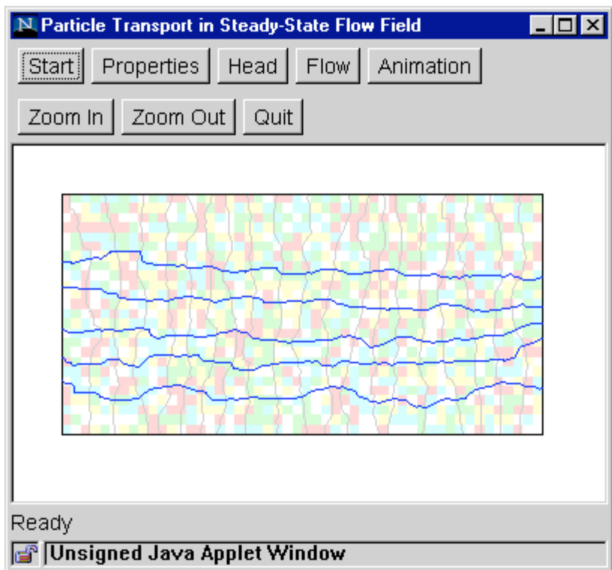
Computational time varies among machines and web browsers. When computation is finished, head contours are displayed.



Step 4a: Flow (Compute Flow Paths)

This step computes ground-water flow paths.

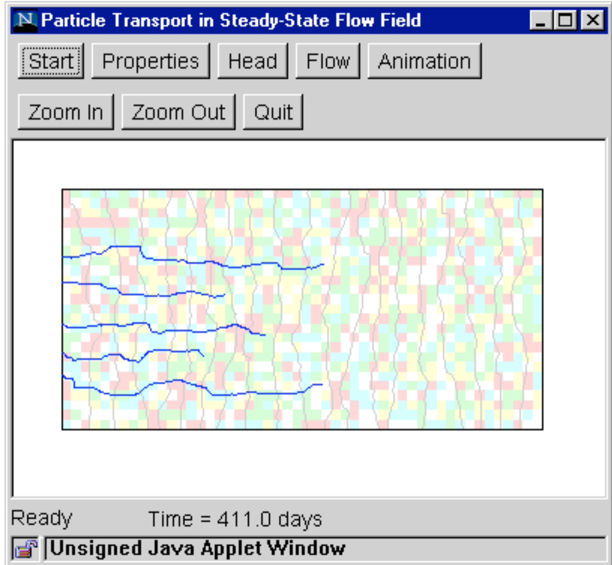
- Click the "Flow" button to bring up the Flow Dialog Box.
- Select the "Flow path tracking" option.
- Select the direction of flow path tracking (forward and backward from the starting point, forward only, or backward only).
- Click "OK.".
- Specify the starting point by clicking on the flow domain. The flow path will be tracked from that point in the manner specified in the dialog box..
- Track additional flow paths by clicking additional starting points in the flow domain.



Step 5a: Animation (Flow Path Evolution)

This step shows the evolution of the flow paths computed in Step 4a.

- Click the "Animation" button to bring up the Animation Dialog Box.
- Set the animation speed by specifying the amount of travel time (in days or years) that is equal to 1 second of animation time. The appropriate speed will depend on the domain length, average hydraulic gradient, and hydraulic properties. For an initial attempt, try setting 1 second of animation time = 10 days. If the resulting animation is too slow, then increase the animation speed (for example, 1 second of animation time = 100 days). If the animation is too fast, decrease the animation speed (for example, 1 second of animation time = 1 day).
- Set the animation smoothness by specifying number of frames per second.
- Click "OK" and wait for the window to be refreshed.
- To start the animation, click anywhere inside the window, below the buttons.
- Additional clicks alternately freeze and unfreeze the animation.
- The elapsed travel time is shown at the bottom of the window.

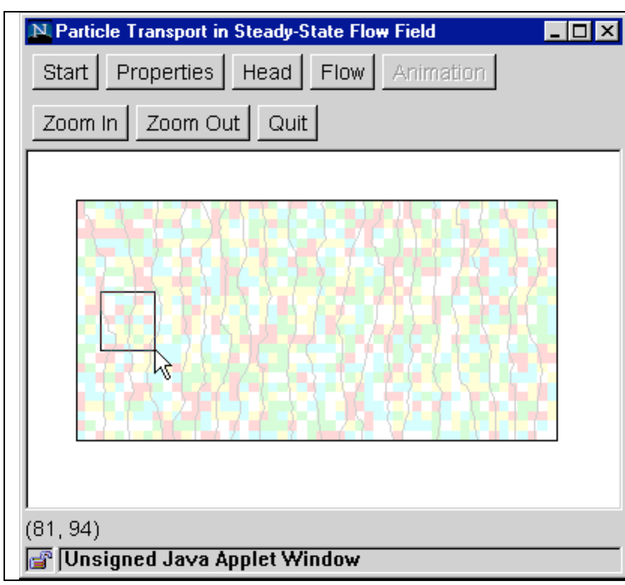


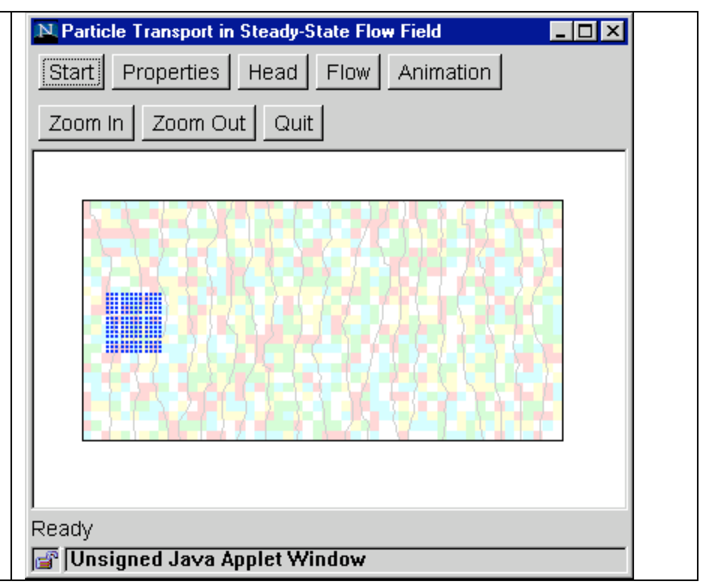
Step 4b: Flow (Particle Transport)

This step sets up the initial position of a cluster of fluid particles.

- Click the "Flow" button to bring up the Flow Dialog Box.
- Select the "Particle movement" option.
- Enter the initial particle spacing (in meters). As a general guide, start with a spacing that about 1/100 of the model domain length. (For example, if the model domain length is 1000 meters, then enter a particle spacing of 10 meters.)
- Click "OK" to close the dialog box.
- Draw a polygon to outline the initial location of a cluster of fluid particles. Keep the polygon relatively small to avoid having too many particles (which will slow down the animation).
- After the polygon is drawn, it will be filled with particles at the prescribed spacing.

To change the particle spacing, repeat the above step.

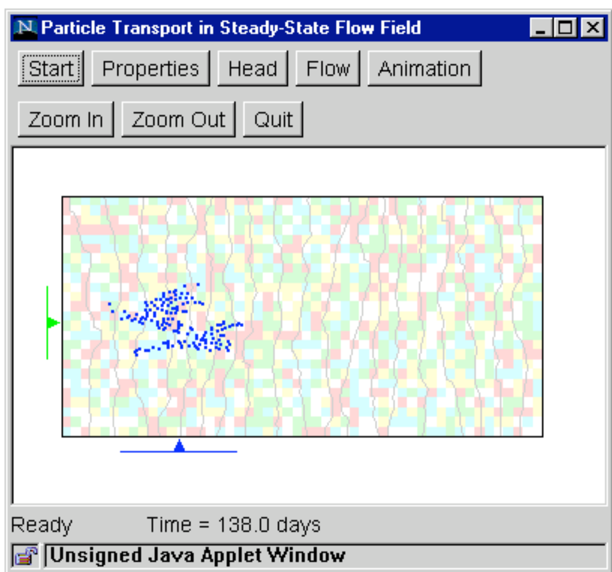




Step 5b: Animation (Particle Movement)

This step shows the movement of fluid particles whose initial positions are specified in Step 4b.

- Click the "Animation" button to bring up the Animation Dialog Box.
- Set the animation speed by specifying the amount of travel time (in days or years) that is equal to 1 second of animation time. The appropriate speed will depend on the domain length, average hydraulic gradient, and hydraulic properties. For an initial attempt, try setting 1 second of animation time = 10 days. If the resulting animation is too slow, then increase the animation speed (for example, 1 second of animation time = 100 days). If the animation is too fast, decrease the animation speed (for example, 1 second of animation time = 1 day).
- Set the animation smoothness by specifying number of frames per second.
- Local dispersion may be added by specifying non-zero values for longitudinal and transverse dispersivity (in m). Local dispersion represents spreading caused by heterogeneities at sub-grid level, and is simulated by adding a small random perturbation to the particle movement at each time step. To turn off local dispersion (that is, to simulate purely advective transport), set the dispersivities to zero.
- Set the options to show the center of mass, standard deviations, or plots of spatial variance versus time by checking or unchecking the option boxes.
- Click "OK" and wait for the window to be refreshed.
- To start the animation, click anywhere inside the window, below the buttons.
- Additional clicks alternately freeze and unfreeze the animation.
- The elapsed travel time is shown at the bottom of the window.



If activated, the center of mass in the *x* and *y* directions are respectively indicated by blue and green arrow heads. The specified number of standard deviations (on both sides of the center of mass) is indicated by blue and green lines. In addition, if the plots of spatial variance versus time are activated, two additional windows appear to display the *x* spatial variance (S_{xx}) versus time and the *y* spatial variance (S_{yy}) versus time. As the simulation progresses, these displays will be updated until 10 percent of the particles have exited the flow domain. The animation terminates when the last fluid particle exits the flow domain.

Animation of fluid particle movement is computationally intensive because particle positions are computed "on the fly," that is, during the animation process. Animating a large number of fluid particles at fast animation speed could result in a "jerky" animation because the computer cannot update the screen at the required rate. If this occurs, stop the animation, reduce the number of particles (draw a smaller polygon and/or increase the particle spacing), and/or use a lower animation speed (reduced the travel time per second of animation time).

<u>Start of the Homework Assignment</u>

TASK 1: Simulate flow in a homogeneous aquifer

You will first model an aquifer with longitudinal and transverse dispersivities equal to zero; thus dispersion will be due *only* to aquifer heterogeneity.

Click START to start the model simulation. In the box, use an element size of 20 m. Use 50 columns (this makes the model length = 1000 m) and 20 rows. Use an average hydraulic gradient of 0.001 (this is applied between the ends of the model domain). Click OK.

Click on PROPERTIES and enter the same hydraulic conductivity and porosity values for all five materials, creating a homogeneous aquifer. Use a hydraulic conductivity value of 1e-4 m/s (0.0001 doesn't work, for some strange reason) and a porosity value of 0.25 (25%).

Solve for head (clicking the HEAD button), using 20 contour intervals. Click COMPUTE.

(1) Describe the spacing and distribution pattern of the hydraulic-head contours. [2 pts]
(2) How should groundwater flow lines appear? Why? [1 pt]

Click on FLOW, and choose the "Flow path tracking" option. Click on several places along the left boundary to initial flow lines.

Create an initial slug of particles by selecting the FLOW button and selecting the "Particle movement" option. Use a particle spacing of 3 m. If the program runs very slowly on your computer, increase this particle spacing. Next, on the model domain, draw an initial slug (i.e. a square of particle). Place the mouse cursor on the screen. Note the coordinates displayed in the lower left corner. Click at the coordinates 50, 100, again at 50, 300, and again at 250, 300, and finally at 250, 100 and click *while pressing the CONTROL key* to set your domain.

Select Animation. Select 1 sec of animation time = 250 days, smoothness = 10 fps, and click the ratio buttons to show center of mass (+/- 2 stdev) and spatial variance versus time. The model domain reappears with green and blue arrows and lines. The arrows represent the vertical and horizontal centers of mass of the particle plume, and the colored lines outside the axes represent two standard deviations (which are square roots of the variances). Note two windows appear. One contains a plot of the horizontal special variance (Sxx) versus time, and the other is vertical spatial variance (Syy).

(3) Calculate (using the appropriate equation, not the model) when the center of mass will reach the 450-m x-coordinate. [1 pt]
(4) Calculate (using the appropriate equation, not the model) when the last particle will leave the end of the model at the 1000-m x-coordinate. [1 pt]

To stop or restart the simulation, simply click the simulation screen. You may do this at any time, and at multiple times, during the simulation. If you wish to abandon the simulation, select START (or any of the other intermediate steps defined by the buttons) and redefine the problem. Note that travel times can be read from the bottom of the domain window.

Use your cursor to find the location of x = 450 m by reading the coordinates at the bottom. Now start the simulation by clicking on the screen, being prepared to stop the simulation when the center of mass arrow reaches xc = 450 m. Record this time, and restart the simulation by clicking on the simulation screen.

(5) Describe the movement of the plume and the spreading of the particles. [2 pts]

(6) Report the times calculated by the model for the travel referred to in questions 3 and 4. Were your predictions accurate? Why or why not? [2 pts]

(7) Estimate the lumped-dispersion coefficients (Dx and Dy), using the information shown on the plots and using Equation 8. Is the spreading process Fickian? [3 pts]

TASK 2: Simulate flow in a heterogeneous aquifer

Run a second model simulation, this time using a more realistic porous medium that has random heterogeneities.

Return to PROPERTIES, and enter variable values of K: 0.001, 5e-4, 1e-4, 5e-5 and 1e-5 m/s. Note K varies over two orders of magnitude. Check the "Randomize" box, which will create a random distribution of K using your values.

(8) What range of materials does this simulation represent? [1 pt]

(9) Describe the head distribution compared with the homogeneous case and discuss reasons for the difference. [2 pts]

(10) Calculate (using the appropriate equation, not the model) when the center of mass will reach the 450-m x-coordinate. (Think: what would be a way to average these K values?) [2 pts]

(11) Calculate (using the appropriate equation, not the model) when the last particle will leave the end of the model at the 1000-m x-coordinate using the same K. [1 pt]

Repeat the earlier steps, solving for heads, and inserting the same slug of particles, without changing any other parameters besides K.

(12) Describe the movement of the plume and the spreading of the particles. [2 pts]

(13) Report the times calculated by the model for the travel referred to in questions 10 and 11. Compare these to the homogeneous simulation. [2 pts]

(14) Estimate values for the horizontal and vertical dispersion coefficients, using Equation 8. Is the spreading process Fickian? [3 pts]

TASK 3: Simulate flow in a homogeneous aquifer with dispersion

Now consider a simulation that includes dispersion coefficients. You will compare homogeneous, lumped-dispersion-coefficient simulations to simulations of actual spreading behavior that is due to velocity variations. Your comparisons should be based on center-of-mass travel times, travel times for the tail of the plume, horizontal and vertical spreading (e.g., the standard deviation bars in the simulation), and the overall shape and behavior of the plume.

(15) Choose/estimate a single value for K based on the five K values used in the heterogeneous aquifer model. Why did you select this value? [1 pt]

(16) Calculate the groundwater average linear velocity using your estimated K value. [1 pt]

(17) Estimate the dispersivities based on your velocity (above) and dispersion coefficients (from 14). Run the model. Is the process Fickian? [2 pts]

(18) Describe the plume migration and the variation of the S^2 plot. How does the spreading compare to that for the heterogeneous simulation? [2 pts]

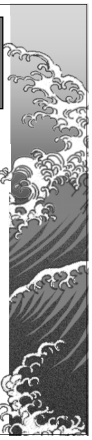
(19) What does the model report for the average travel time to the 450-m x-coordinate? What does the model report for the time that the last particle exited the edge of the model at x = 1000 m? [2 pts]

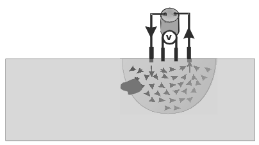
(20) Do you think that dispersion should have been included in the heterogeneous simulation as well? Why or why not? [3 pts]

(21) Briefly discuss limitations and advantages of modeling using the three approaches above to simulate, understand, and predict contaminant plume movement in the real world. [3 pts]

Electrical and Electromagnetic Methods

- Outline: direct-current resistivity, ground-penetrating radar





Geophysical Methods

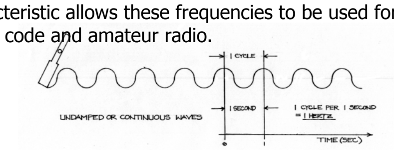
- Two tools for hydrologic characterization:
  - Direct-current resistivity methods: sensitive to electrical resistivity (conductivity)
  - Ground-penetrating radar: sensitive to dielectric permittivity
- What is an electromagnetic method, anyway?
- An EM wave is an energy wave produced from an electrical discharge.

What are EM Waves?

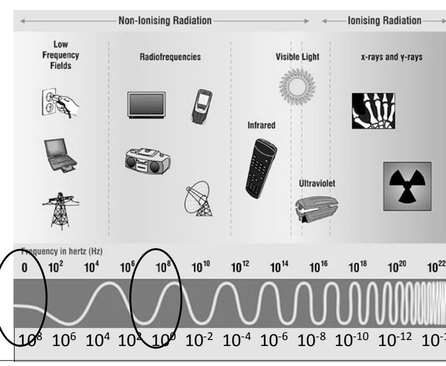
- The number of rise and fall cycles per second is its frequency.
- Frequencies are sinusoidal waves.
- Speed of Light = Frequency x Wavelength

  Example: The wavelength of a signal resonating at 3kHz is:

  $\frac{3 \times 10^8 \text{ m/s}}{3 \times 10^3 \text{ Hz}}$ = 100 kilometers or ~ 62 miles!
- Lower frequencies have longer wavelengths. This characteristic allows these frequencies to be used for Morse code and amateur radio.



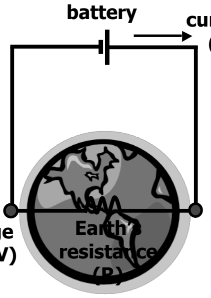
Frequency Bands



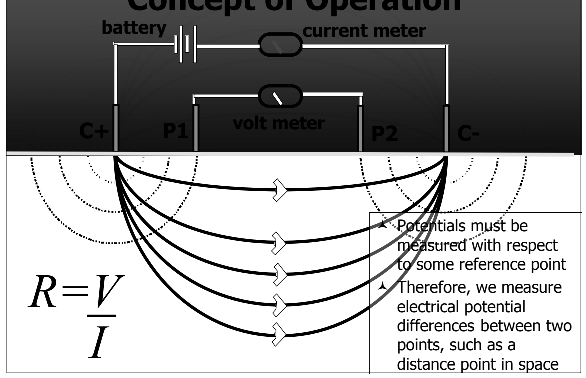
Electrical Resistance Measurements

- The earth is considered a simple circuit
- Use Ohm's Law to find subsurface resistance

$$R = \frac{V}{I}$$



Concept of Operation

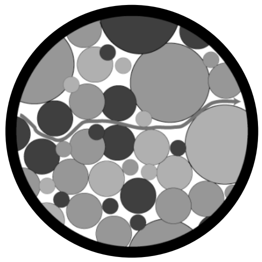


$$R = \frac{V}{I}$$

- Potentials must be measured with respect to some reference point
- Therefore, we measure electrical potential differences between two points, such as a distance point in space

Why resistivity methods?

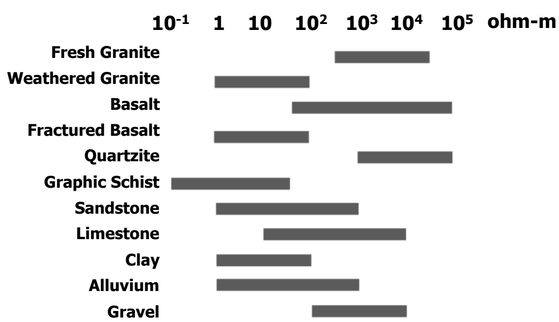
- Measured potentials are sensitive to the bulk electrical properties
  - lithology
  - porosity
  - connectivity of pore fluid
  - pore fluid chemistry



Specific Applications

- Depth to or thickness of:
  - Water table
  - Clay units
  - Bedrock
  - Salt water
  - Conductive contaminant plumes
- Delineating coarse-grained from fine-grained material
- Spatially exhaustive, minimally invasive data

Rock Resistivities

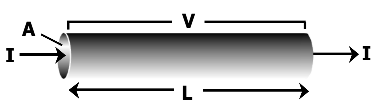


Analogous to Fluid Flow!

VARIABLE	GROUNDWATER	ELECTRICITY	HEAT
Potential	Head, h [cm]	Voltage, V [Volts]	Temperature, T [°C]
Quantity transported	Volume discharge rate [$cm^3\ s^{-1}$]	Electrical charge [Coulomb]	Heat [calorie]
Physical property of medium	Hydraulic conductivity, K [$cm\ s^{-1}$]	Electrical conductivity, σ [$mhos\ m^{-1}$]	Thermal conductivity, K [$cal\ cm^{-1}\ s^{-1}\ °C^{-1}$]
Relation between potential and flow field	Darcy's law $\mathbf{q} = -K\ \mathbf{grad}\ h$ where $\mathbf{q}$ is specific discharge [$cm\ s^{-1}$]	Ohm's law $\mathbf{i} = -\sigma\ \mathbf{grad}\ V$ where $\mathbf{i}$ is electrical current [Amperes]	Fourier's law $\mathbf{q} = -K\ \mathbf{grad}\ T$ where $\mathbf{q}$ is heat flow [$cal\ cm^{-2}\ s^{-1}$]
Storage quantity	Specific storage, S_s [cm^{-1}]	Capacitance, C [microfarad]	Heat capacity, C_v [$cal\ cm^{-3}\ °C^{-1}$]

(Wang and Anderson 1982)

Resistance vs. Resistivity



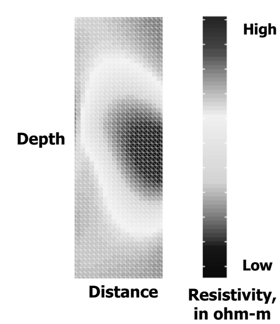
① $$R = \rho \cdot \frac{L}{A}$$

② $$\rho = \frac{1}{\sigma}$$

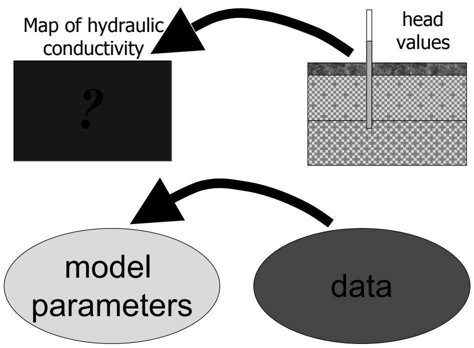
R = resistance (Ω)
L = sample length (m)
A = sample area (m^2)
ρ = resistivity (Ωm)
σ = conductivity $(\Omega m)^{-1}$

How to get resistivity?

Resistance data are reconstructed into a electrical resistivity model consistent with the data through inversion



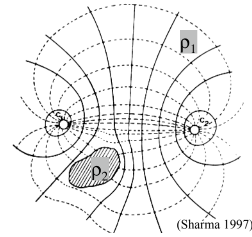
Inverse Modeling



Apparent Resistivity

Can approximate an *Apparent Resistivity* ρ_a based on geometry:

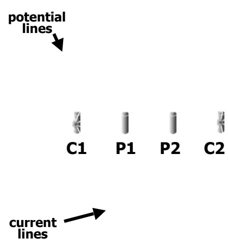
$$\rho_a = K\frac{V}{I}$$



Definition: Resistivity of a fictitious homogenous subsurface that would yield the same voltages as the earth over which measurements were actually made.

1-D Acquisition

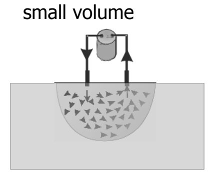
- Not automated
- Four electrodes are used and moved manually in field
- Estimate change in resistivity with depth or distance



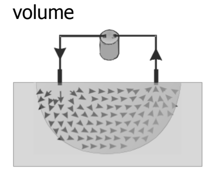
Depth Soundings (1-D)

Volume interrogated depends on spacing of electrodes

closely spaced electrodes = small volume

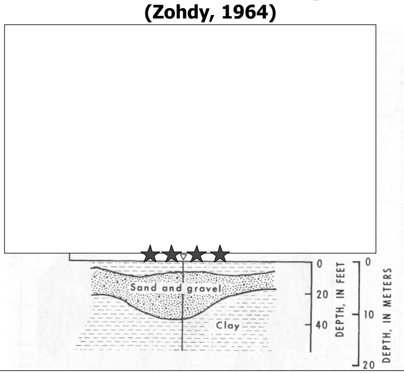


greater electrode spacing = larger volume

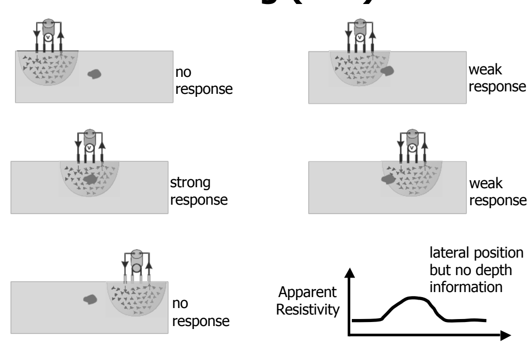


1-D Resistivity

(Zohdy, 1964)

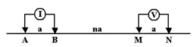


Profiling (1-D)



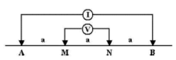
Electrode Arrays

Dipole-dipole



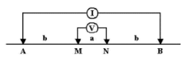
$$\rho_A = \frac{V}{I}\pi a n(n+1)(n+2).$$

Wenner



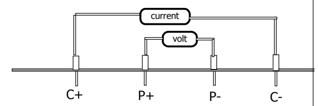
$$\rho_A = 2\pi a \frac{V}{I}$$

Schlumberger



$$\rho_A = \frac{V}{I}\pi\frac{b(b+a)}{a} \approx \frac{V}{I}\pi\frac{b^2}{a} \quad \text{if } a \ll b$$

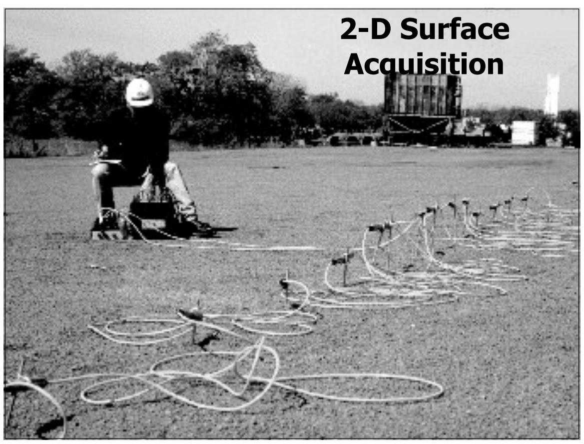
Array Choice



Depends on:
1) type of structure to be mapped
2) sensitivity of the resistivity meter
3) background noise level

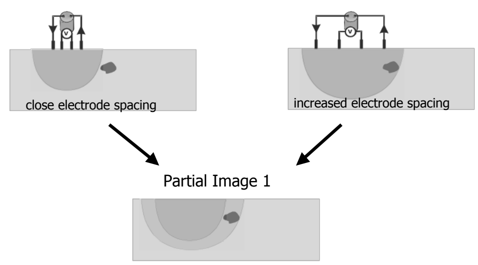
Things to be considered:
1) depth of investigation
2) sensitivity of the array to vertical and horizontal structures
3) data coverage
4) signal strength

2-D Surface Acquisition

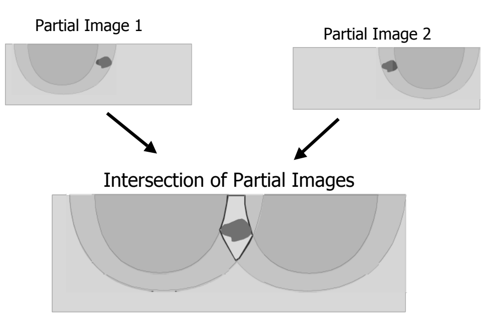


2-D Sounding

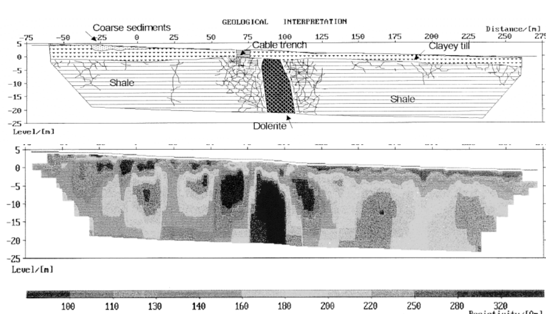
Modern systems allow a large number of electrodes with automated switching



2-D Profiling

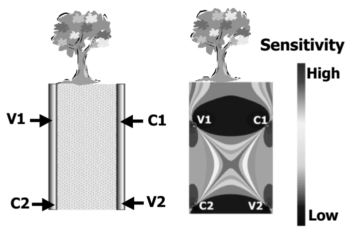


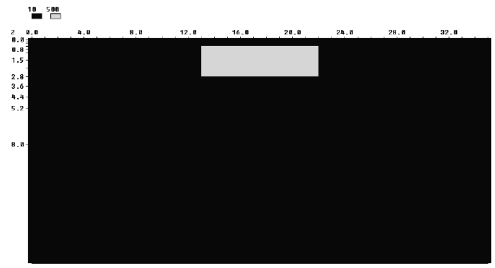
2-D Resistivity Line



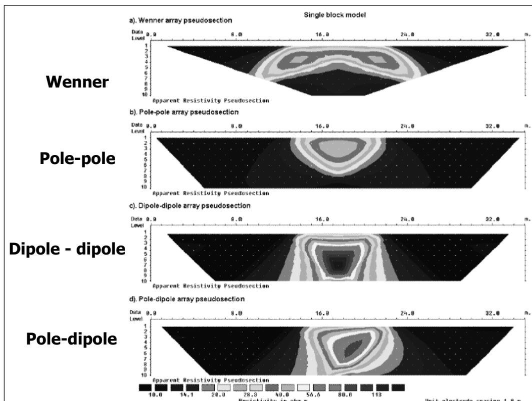
Sensitivity

- Sensitivity varies with distance from electrodes
- Variable target recovery depending on location



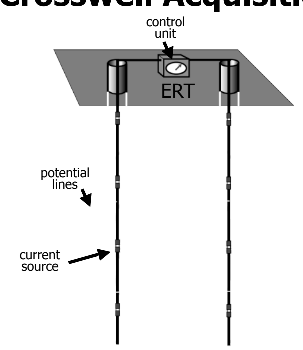


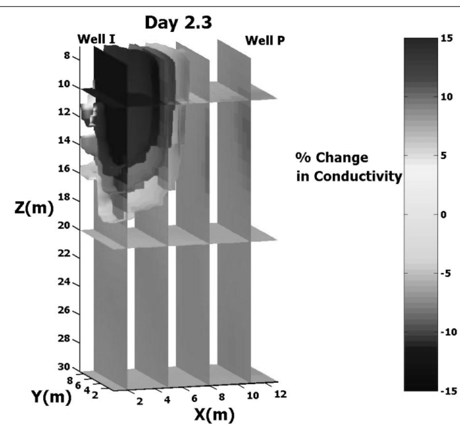
Block model (from Loke, 2002)



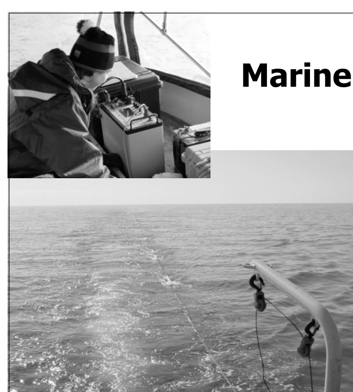
Block model response

Crosswell Acquisition





Marine Resistivity

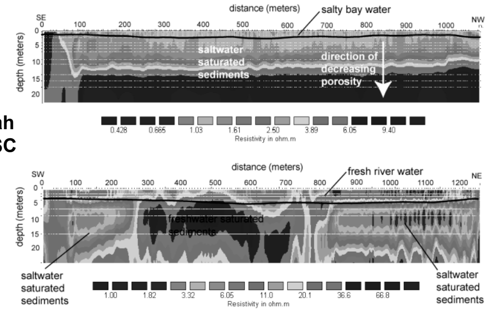


- Electrodes towed on water surface behind moving survey vessel
- Potentials measured at set time intervals
- Real-time GPS integration

Marine Survey

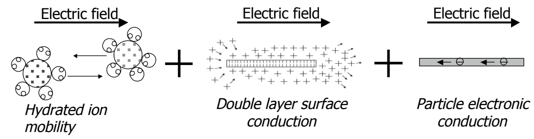
(Belaval, 2003)

Winyah Bay, SC



Electrical Conductivity in Geomaterials

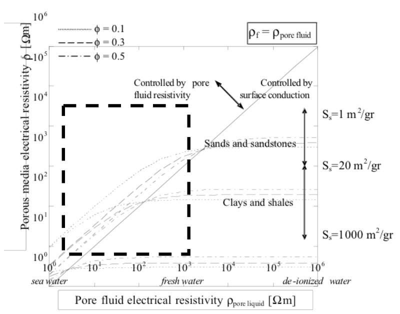
- Non-conductive minerals



	Equation	Comments
Electrolyte	$\sigma_f \left[\frac{mS}{m}\right] = 0.15\,TDS\left[\frac{mg}{L}\right]$	TDS: total dissolved salts
Archie's law	$\sigma_b = a\sigma_f\, S_r^n\, \phi^m$	a≈0.4-2.0; m~1.3-2.5; n~2

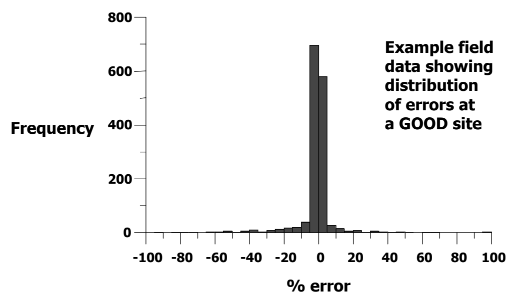
Remember: $\rho = 1/\sigma$

Electrical Conductivity of Geomaterials



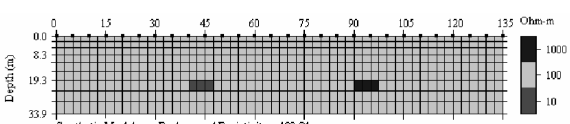
(Attia et al. 2008)

Practical Application



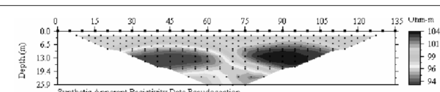
Example field data showing distribution of errors at a GOOD site

Effects of Error & Noise



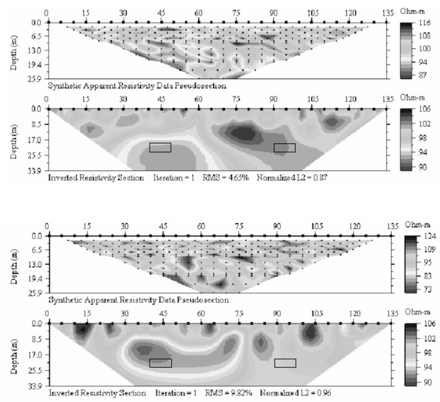
Block Model (from Yang and Lagmanson, 2003)

No noise



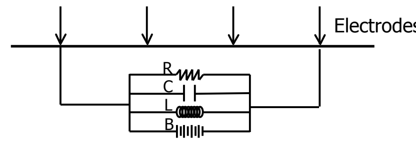
5% Gaussian noise

10% Gaussian noise



Earth as a Circuit

Geological materials can be conceptually modeled as a circuit made of a resistor, capacitor, inductor and battery:



Resistor R: dissipator of applied energy as heat
Capacitor C: storage of energy as separation of charges
Inductor L: self voltage associated to electromagnetic methods
Battery B: electrokinetics and self-potentials

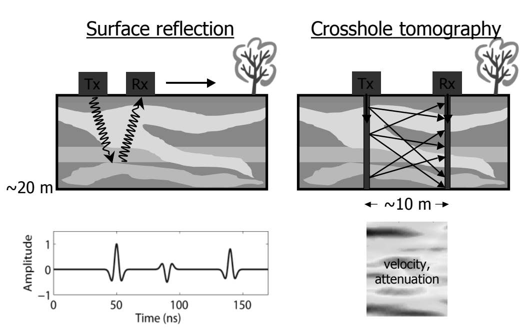
The dielectric "constant"

- a.k.a. "relative permittivity"
- represented by κ or ε_r
- dielectric permittivity normalized by its free-space value (i.e., $\kappa = \varepsilon_r = \varepsilon/\varepsilon_0$)
- Is a measure of capacitance
- Measured with GPR!

What is GPR?

- geophysical method that uses radio (high-frequency EM) waves to (mainly) explore the capacitive part of the subsurface
- frequency range: ~10 to 5000 MHz
- basic idea: short EM pulse is radiated from a transmitter (Tx) antenna, travels through the earth, and is picked up by a receiver (Rx) antenna and recorded
- repeated many times for different Tx-Rx positions

GPR survey configurations

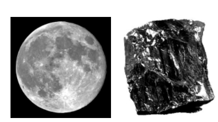


Brief history

1950s:

radio echo sounding (RES) to map glacier thickness

1970s:

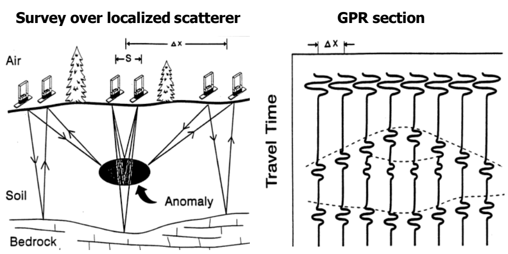


introduction to electrically resistive geological environments

1980s:

many advances in technology, development of digital radar systems

Diffraction hyperbolas



TYPICAL DIELECTRIC CONSTANT, ELECTRICAL CONDUCTIVITY, VELOCITY, AND ATTENUATION OBSERVED IN COMMON GEOLOGICAL MATERIALS

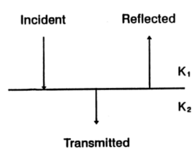
MATERIAL	K	σ (mS/m)	v (m/ns)	α (dB/m)
Air	1	0	0.3	0
Distilled Water	80	0.01	0.033	2×10^{-3}
Fresh Water	80	0.5	0.033	0.1
Sea Water	80	3×10^{3}	0.01	10^{3}
Dry Sand	3-5	0.01	0.15	0.01
Saturated Sand	20-30	0.1-1	0.06	0.03-0.3
Limestone	4-8	0.5-2	0.12	0.4-1
Shales	5-15	1-100	0.09	1-100
Silts	5-30	1-100	0.07	1-100
Clays	5-40	2-1000	0.06	1-300
Granite	4-6	0.01-1	0.13	0.01-1
Dry Salt	5-6	0.01-1	0.13	0.01-1
Ice	3-4	0.01	0.16	0.01

Reflection coefficient

- At a subsurface interface, equal to the ratio of the amplitude of reflected energy to incident energy ($R = E_r/E_i$), typically

$$R = \frac{\sqrt{\kappa_1} - \sqrt{\kappa_2}}{\sqrt{\kappa_1} + \sqrt{\kappa_2}}$$

- i.e., the strength and polarity of a GPR reflection is controlled by the contrast in dielectric permittivity at the interface



VERTICAL INCIDENCE REFLECTION COEFFICIENT FOR SOME TYPICAL GEOLOGICAL CONTACTS

FROM		TO		REFLECTION COEFFICIENT	(dB)
Air	K=1	Dry Soil	K=5	-0.38	-8.4
Dry Soil	K=5	Wet Soil	K=25	-0.38	-8.4
Dry Soil	K=5	Rock	K=8	-0.12	-19
Wet Soil	K=25	Rock	K=8	0.28	-11
Water	K=81	Gyttja	K=50	0.12	-18
Water	K=81	Rock	K=8	0.52	-5.7
Ice	K=3.2	Water	K=81	0.67	-3.5
Frozen Soil	K=6	Wet Soil	K=25	0.34	-93
Soil	K=3-50	Metal	$K \to \infty$	-1	0

Basic theory

EM material properties		
Control all behavior of GPR pulse as it travels through the subsurface.	→	σ = electrical conductivity ε = dielectric permittivity μ = magnetic permeability

Wave propagation regime: $\sigma << \omega\varepsilon$

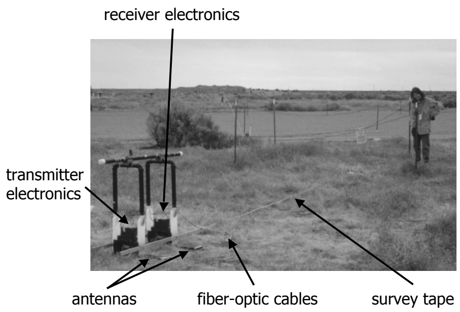
(required for successful GPR operation!!!)

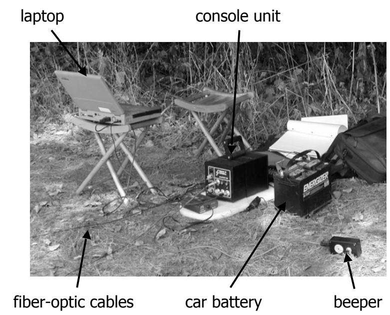
Limitations

- GPR is not suitable in electrically conductive environments (i.e., environments containing significant amounts of clay, or electrically conductive pore fluids). In these cases, diffusion dominates over wave propagation, and the GPR signal attenuates much too quickly to be useful.
- Under low-loss conditions, the velocity and attenuation of the GPR pulse in the subsurface can be approximated by the following simple expressions:

$$v \approx \frac{c}{\sqrt{\kappa}} \qquad \alpha \approx \frac{\sigma}{2}\sqrt{\frac{\mu_0}{\kappa\varepsilon_0}}$$

Field survey setup





Example data set

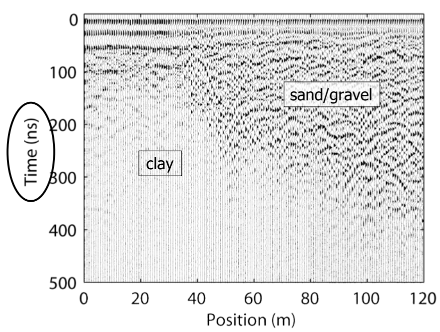
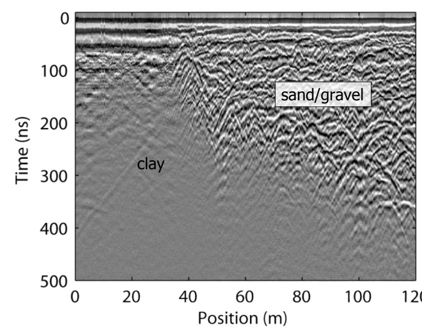
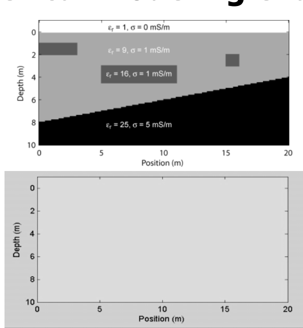


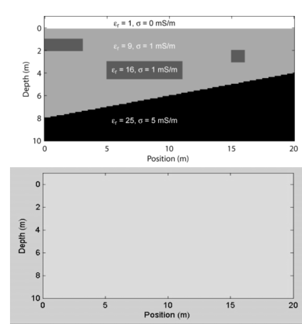
Image plot of data



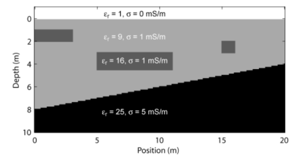
Numerical modeling example

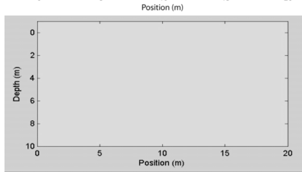


Numerical modeling example

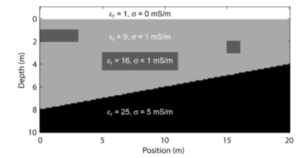


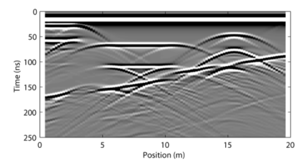
Numerical modeling example





Numerical modeling example





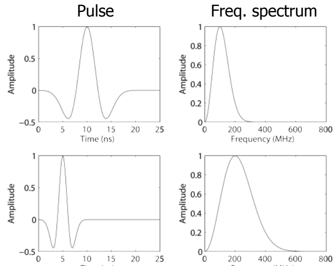
GPR Antennas

- specified by center or dominant frequency of pulse in air
- many different frequencies available (e.g., 25, 50, 100, 200, 500, 1000 MHz)

100 MHz antennas

~1 m

200 MHz antennas



Antenna selection

Higher Frequency Antennas

= shorter pulse width

= better spatial resolution of reflectors

BUT...

less power radiated and received

+ more scattering by small objects (clutter)

= lesser depth of investigation!!!

<u>General rule of thumb:</u> Select highest antenna frequency that will allow us to reach the subsurface depth of interest.

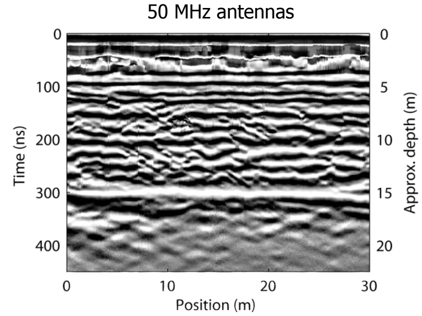
Typical depths of investigation

NOTE: Very rough guide!!! Depends strongly on environment.

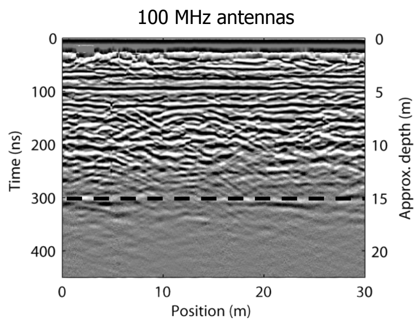
Antenna Frequency (MHz)	Depth (m)
25	30
50	10
100	7
200	2
500	1
1000	0.5

Resolution/depth trade-off

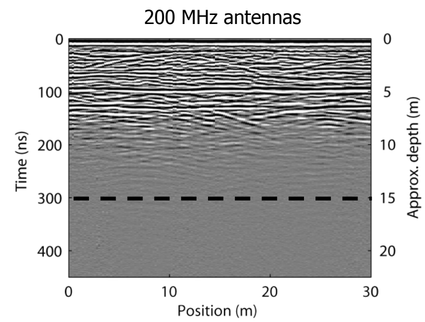
50 MHz antennas



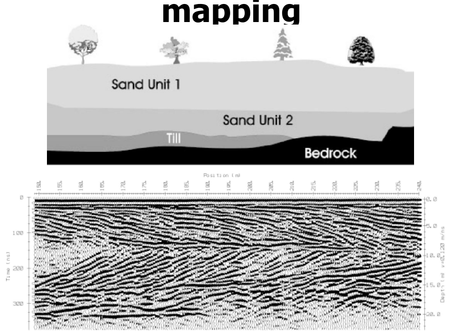
Resolution/depth trade-off



Resolution/depth trade-off

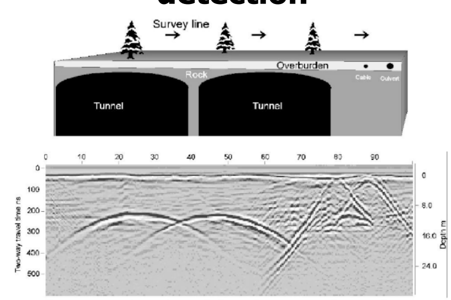


Example: Stratigraphy mapping



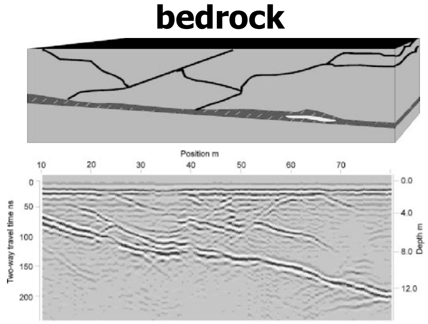
Source: Ground Penetrating Radar Workshop Notes, A.P. Annan, 2001.

Example: Tunnel and utility detection



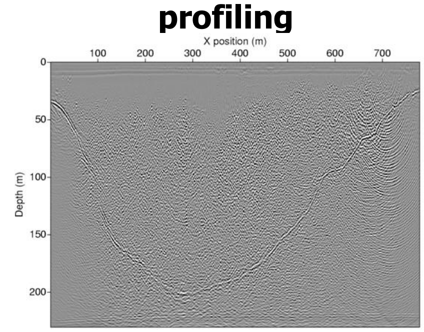
Source: Ground Penetrating Radar Workshop Notes, A.P. Annan, 2001.

Example: Mapping fractures in bedrock



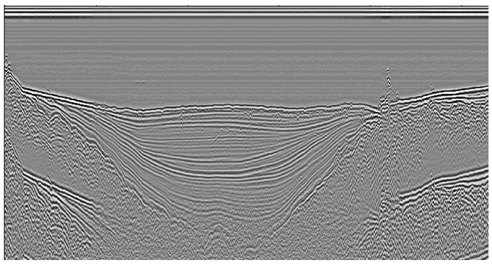
Source: Ground Penetrating Radar Workshop Notes, A.P. Annan, 2001.

Example: Glacier bed profiling



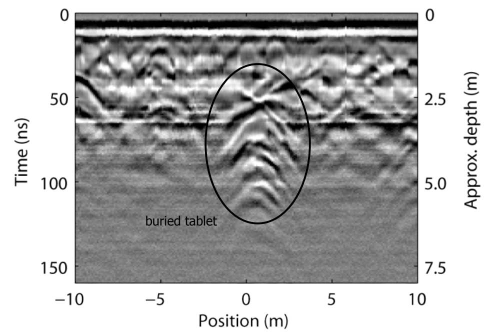
Source: Harper and Bradford, Geophysical Research Letters, 2005.

Example: Lake-bottom profiling



Source: Steve Arcone, U.S. Army Cold Regions Research Laboratory.

Example: Archaeology



Example: 3-D GPR surveying

Source: Alastair McClymont, ETH Zurich.

GPR summary

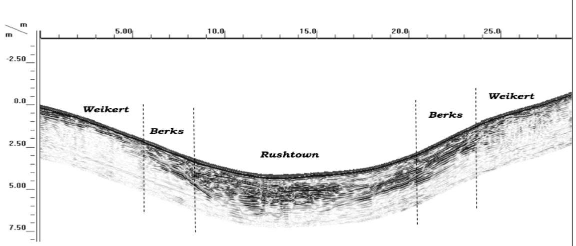
Advantages

- fast (= cost-effective)
- high-resolution (highest of all geophysical methods!)
- less ambiguous interpretation than diffusive geophysical methods

Disadvantages

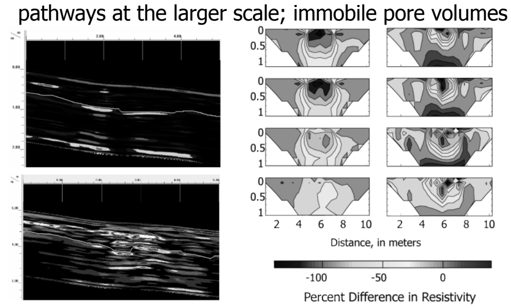
- only applicable in non-conductive geological environments (big limitation!)
- important trade-off between resolution and penetration depth
- reliable images require accurate velocities and sophisticated processing

GPR Data: Shale Hills



Monitoring flow and tranport at the field scale

- Geophysics to explore “hot spots” and preferential pathways at the larger scale; immobile pore volumes



Take Home Messages

- Resistivity methods are good for detecting changes in electrical properties associated with pore connectivity, pore fluid content, and lithology
- Reflection GPR surveying can be an effective tool for high-resolution imaging of shallow subsurface structure, but is not suitable in environments with high electrical conductivity (e.g., clay-rich soils, conductive pore water)
- GPR antenna selection should generally be geared towards selecting the highest antenna frequency that allows us to reach the subsurface depth of interest
- Care must be taken to quantify field errors, and select appropriate field geometries for data collection
- It is important to remember that
  - images represent changes in subsurface electrical properties
  - data require further processing to transform them to depth

Electrical Resistivity

Provided equipment that needs to come back with us:

- Tape measures (2)
- IRIS Resistivity Meter
- 48 surface electrodes
- 4 cable reels
- 3 cable connectors
- cables to connect IRIS to battery, etc.
- Deep-cycle marine batteries (2)
- Surveying flags (lots)
- Sledgehammers (2)
- Shovels (2)
- AC/DC converter
- Fluke voltmeter
- Graph paper

During this part of the field trip, we will (1) measure resistance for both soundings and profiles with a resistivity meter, and (2) build resistivity meters to try to alleviate some of the black-box problems associated with using expensive equipment we can't open up. The learning goals of this exercise are that you:

1. Better understand the relationship between soundings, profiles, and subsurface apparent resistivity (see attached notes).
2. Determine one method of estimating electrical resistance in the field.
3. Strengthen mathematical skills by calculating the geometric factors for the electrode configurations, and consequently estimate apparent resistivities in the field.
4. Make #1-3 more meaningful by having you collect your own field data.
5. Learn to assess error on replicate quadripoles.

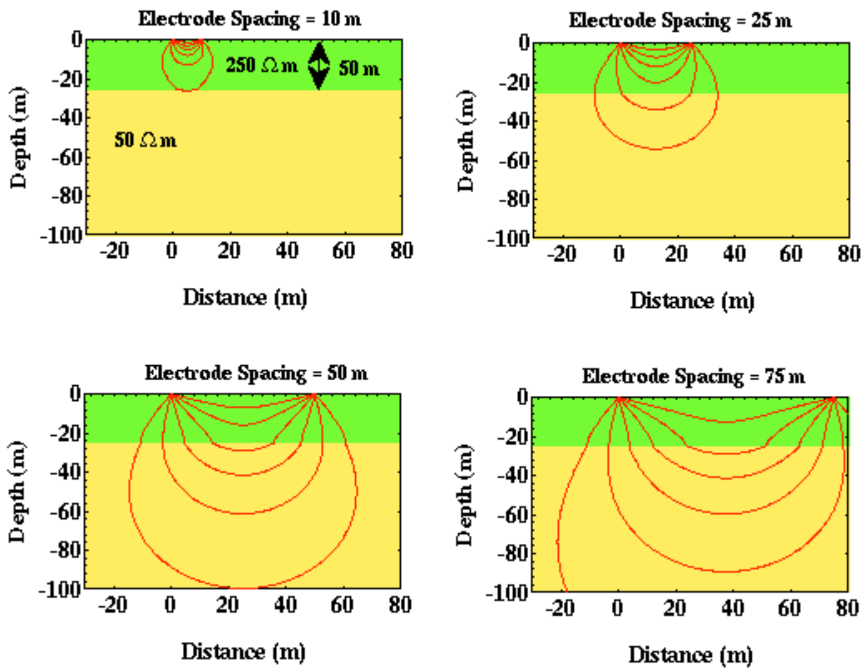
TASK 1: COLLECTING DATA WITH THE RESISTIVITY METER

The resistivity meter we'll be using has 48 electrodes, separated a maximum distance of 5 m apart. This means our lines can be no longer than 240 m, so that's the largest A-B (current separation) distance we can have. The smallest one will be 5 m. This gives us somewhat less than 2 decades (5-50, 50-500 m) to collect data over.

Similar to the conducting-paper lab, we will need to develop a survey plan including

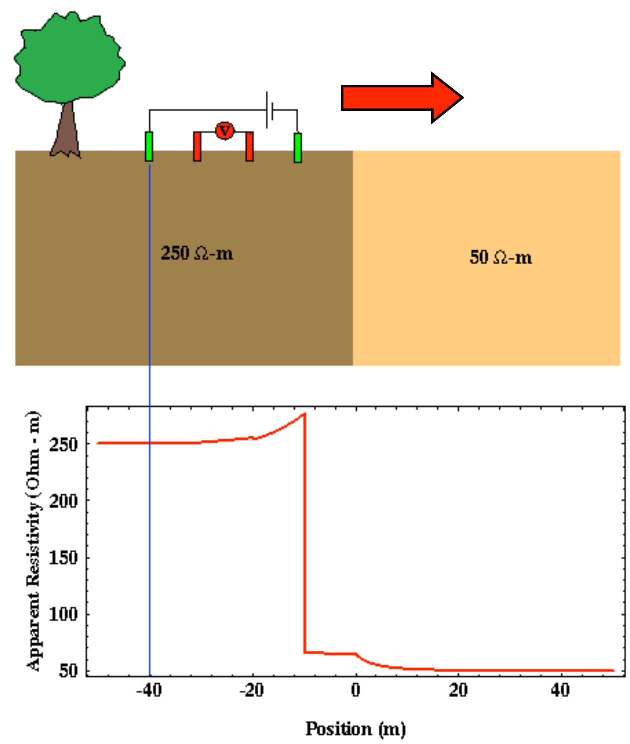
- Number of soundings/profiles to be collected,
- Location and orientation of each sounding or profile,
- Survey geometry to be used,
- Minimum electrode spacing to be used,
- Number of electrode spacings to be collected per decade in electrode distance,
- Number of decades in electrode distance over which to collect data (limited by equipment to 2), and
- Number of readings over which to average for each electrode spacing.

So we'll collect both profiles and soundings, as discussed in class. To review:



Resistivity Soundings - Surveys that are designed to determine resistivity variations with depth above some fixed surface location are referred to as *resistivity soundings.* In these experiments, electrode spacing is varied for each measurement. The four electrodes expand outward from a common center point. The volume of the subsurface that is interrogated depends on spacing of electrodes: closely spaced electrodes = small volume and shallower depth, greater electrode spacing = larger volume and deeper depth. An example of a problem for which one might employ resistivity soundings is the determination of depth to the water table.

Resistivity Profiles - Resistivity surveys can also be employed to detect lateral variations in resistivity. Unlike soundings, profiles employ fixed electrode spacings, and the center of the electrode spread is moved for each reading. These experiments thus provide estimates of the spatial variation in resistivity at some fixed electrode spacing. Surveys that are designed to locate lateral variations in resistivity are referred to as *resistivity profiles.* An example of a problem for which one might employ resistivity profiles is the location of a vertical fault.



We can collect data with any geometry we'd like, but we'll concentrate on the geometries we've spoken about in class: the Wenner, Schlumberger, and (if there's time) dipole-dipole arrays (see Appendix). You will run 4 sequences: 1) a Wenner sounding, 2) a Schlumberger sounding, 3) a Wenner profile, and 4) a Schlumberger profile. After running these 4 sequences, we'll collect full 2-D Wenner and Schlumberger arrays that include both profile- and sounding-type sequences in one array. If there is time and you are interested, we can collect a dipole-dipole geometry as well.

For each measurement, you will calculate the geometric factor (you can do this prior to data collection) so that you can plot, in the field, apparent resistivity with depth and with distance along our lines. What is the geometric factor, again?

$$K = 2\pi\left[\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right]^{-1}$$

where A and B are the current electrodes and M and N are the potential electrodes such that AM is the distance between the A and M electrodes, BM the distance between B and M, etc. So to estimate apparent resistivity in the field, we know the injected current I, measure the voltage between two electrodes V, and calculate K, such that

$$\rho_a = K\frac{V}{I}$$

Simplications for known geometries are shown in Appendix 1.

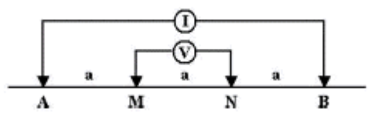
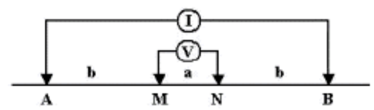
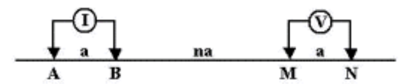
TASK 2: BUILDING A RESISTIVITY METER

Here's where you get to make MacGyver proud. Based on the lab we conducted in class, you'll be trying to build a resistivity meter out here in the field. You have no instructions. All you know is that you have to save the world from destruction, this requires you to build a resistivity meter, and you have only 30 minutes to do it with the supplied materials. Be careful not to camp out to closely to the folks with the resistivity meter so you don't impact their results. What you have:

- A tape measure
- 4 stainless steel electrodes
- A deep-cycle marine battery
- A bunch of wire
- Some alligator clips
- An AC/DC converter
- A toolbox full of miscellaneous parts

Your goal: to conduct a resistivity survey with your gear. You can conduct a sounding or a profile using any geometry you want. You just need to mark down *everything* so that you can make a curve of apparent resistivity with depth or distance. Look at the equations for the previous section.

APPENDIX 1: MEASUREMENTS COLLECTED IN THE FIELD

 $\rho_A = 2\pi a \frac{V}{I}$	 $\rho_A = \frac{V}{I}\pi\frac{b\,(b+a)}{a} \approx \frac{V}{I}\pi\frac{b^2}{a}$ if $a << b$	 $\rho_A = \frac{V}{I}\pi\, a\, n(n+1)(n+2).$
Wenner	**Schlumberger**	**Dipole-dipole**

<u>Wenner Sounding:</u>

Electrodes used (8 quadripoles):

#	A	B	M	N
1	23	26	24	25
2	20	29	23	26
3	17	32	22	27
4	14	35	21	28
5	11	38	20	29
6	8	41	19	30
7	5	44	18	31
8	2	47	17	32

<u>Schlumberger Sounding:</u>

Electrodes used (21 quadripoles):

#	A	B	M	N
1	21	27	22	26
2	20	28	22	26
3	19	29	22	26
4	18	30	22	26
5	17	31	22	26
6	16	32	22	26
7	15	33	22	26
8	14	34	22	26
9	13	35	22	26
10	12	36	22	26
11	11	37	22	26
12	10	38	22	26
13	9	39	22	26
14	8	40	22	26
15	7	41	22	26
16	6	42	22	26
17	5	43	22	26
18	4	44	22	26
19	3	45	22	26
20	2	46	22	26
21	1	47	22	26

Wenner Profile:

Electrodes used (41 quadripoles):

#	A	B	M	N
1	2	4	6	8
2	3	5	7	9
3	4	6	8	10
4	5	7	9	11
5	6	8	10	12
6	7	9	11	13
7	8	10	12	14
8	9	11	13	15
9	10	12	14	16
10	11	13	15	17
11	12	14	16	18
12	13	15	17	19
13	14	16	18	20
14	15	17	19	21
15	16	18	20	22
16	17	19	21	23
17	18	20	22	24
18	19	21	23	25
19	20	22	24	26
20	21	23	25	27
21	22	24	26	28
22	23	25	27	29
23	24	26	28	30
24	25	27	29	31
25	26	28	30	32
26	27	29	31	33
27	28	30	32	34
28	29	31	33	35
29	30	32	34	36
30	31	33	35	37
31	32	34	36	38
32	33	35	37	39
33	34	36	38	40
34	35	37	39	41
35	36	38	40	42
36	37	39	41	43
37	38	40	42	44
38	39	41	43	45
39	40	42	44	46
40	41	43	45	47
41	42	44	46	48

Schlumberger Profile:

Electrodes used (42 quadripoles):

#	A	B	M	N
1	2	4	5	7
2	3	5	6	8
3	4	6	7	9
4	5	7	8	10
5	6	8	9	11
6	7	9	10	12
7	8	10	11	13
8	9	11	12	14
9	10	12	13	15
10	11	13	14	16
11	12	14	15	17
12	13	15	16	18
13	14	16	17	19
14	15	17	18	20
15	16	18	19	21
16	17	19	20	22
17	18	20	21	23
18	19	21	22	24
19	20	22	23	25
20	21	23	24	26
21	22	24	25	27
22	23	25	26	28
23	24	26	27	29
24	25	27	28	30
25	26	28	29	31
26	27	29	30	32
27	28	30	31	33
28	29	31	32	34
29	30	32	33	35
30	31	33	34	36
31	32	34	35	37
32	33	35	36	38
33	34	36	37	39
34	35	37	38	40
35	36	38	39	41
36	37	39	40	42
37	38	40	41	43
38	39	41	42	44
39	40	42	43	45
40	41	43	44	46
41	42	44	45	47
42	43	45	46	48

Full 2-D Wenner:

Electrodes used (360 quadripoles, first 30 shown):

#	A	B	M	N
1	1	46	16	31
2	1	43	15	29
3	1	40	14	27
4	1	37	13	25
5	1	34	12	23
6	1	31	11	21
7	1	28	10	19
8	1	25	9	17
9	1	22	8	15
10	1	19	7	13
11	1	16	6	11
12	1	13	5	9
13	1	10	4	7
14	1	7	3	5
15	1	4	2	3
16	2	47	17	32
17	2	44	16	30
18	2	41	15	28
19	2	38	14	26
20	2	35	13	24
21	2	32	12	22
22	2	29	11	20
23	2	26	10	18
24	2	23	9	16
25	2	20	8	14
26	2	17	7	12
27	2	14	6	10
28	2	11	5	8
29	2	8	4	6
30	2	5	3	4 … etc.

Full 2-D Schlumberger:

Electrodes used (465 quadripoles, first 30 shown):

#	A	B	M	N
1	1	32	16	17
2	1	30	15	16
3	1	28	14	15
4	1	26	13	14
5	1	24	12	13
6	1	22	11	12
7	1	20	10	11
8	1	18	9	10
9	1	16	8	9
10	1	14	7	8
11	1	12	6	7
12	1	10	5	6
13	1	8	4	5
14	1	6	3	4
15	1	4	2	3
16	2	33	17	18
17	2	31	16	17
18	2	29	15	16
19	2	27	14	15
20	2	25	13	14
21	2	23	12	13
22	2	21	11	12
23	2	19	10	11
24	2	17	9	10
25	2	15	8	9
26	2	13	7	8
27	2	11	6	7
28	2	9	5	6
29	2	7	4	5
30	2	5	3	4 … etc.

Equipotentials and Electric Fields

Two kinds of lines can be used to map an electrical field.

1. Electric field lines (flow lines): these lines would show the direction of a positive charge placed at a point. They begin and end on electrodes. They will not cross each other.
2. Equipotential lines: the voltage between any two points on an equipotential line is zero. They will not cross each other.

When equipotential lines and field lines cross, they are perpendicular (sound familiar? You're making a flownet!)

In this lab we will examine the equipotential lines and electric field lines for different configurations in two dimensions. The basic technique is to use a silver ink pen to draw conducting surfaces on conductive paper, hook up a voltage source to the conducting surfaces, and then measure the voltage at various points on the paper.

You'll turn in your potentiometric surfaces, and your answers to the questions below.

Materials

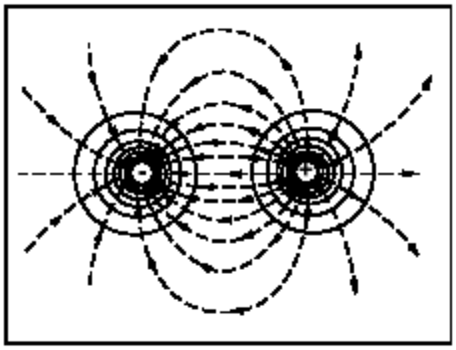
- Carbon impregnated paper. This paper forms the conducting medium or space between the electrodes (5000 ohms/cm)
- Batteries
- Extra wires
- Conductive ink dispensed from a pen. The ink is produced from silver particles in a suspension liquid. As the ink dries, the silver flakes settle on top of each other forming a conductive path, or conductive ink electrodes (4-8 ohms/cm).

The paper is slightly conductive, allowing a small amount of charge so that the voltmeter can make its measurements without disturbing the field. When an electric potential is applied to conductive ink drawn on the carbon impregnated paper an electric field is produced that can be detected by a common voltmeter. You will use the batteries to provide the potential differences for different electrode spreads.

Several theoretical principles:

1. The electric field inside a conductor is everywhere zero. If it were not, free electrons inside the conductor would feel this field and flow in such a way as to reduce it, soon to zero.
2. The potential is the same everywhere inside a conductor. This follows immediately from 1.
3. The electric field outside a conductor very near its surface is perpendicular to the surface of the conductor.
4. A point where the electric field is not zero has a variable potential around it. The potential increases going out in some direction and decreases in others. The boundary between regions of increasing and decreasing potential will be a curve along which the potential neither increases nor decreases. Such a curve is called the equipotential line.

5. Electric field lines are everywhere perpendicular to equipotential lines. This is easy to see since no work is done on moving at constant potential. Hence, there may be no component of the electric field in the direction of equipotential lines. Electric field lines run in the direction of decreasing potential "downhill."
6. The electric field inside an empty cavity of a conductor is zero.



Equipotential and Field Lines

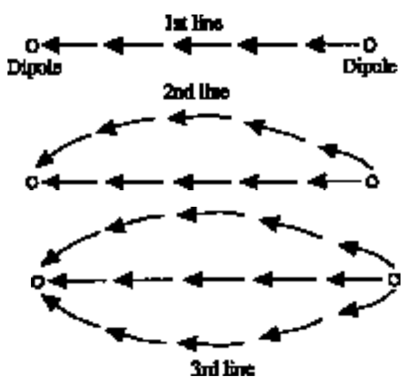
Part I: Mapping the Potential

1. Like potential energy, electric potential is defined as a difference. Therefore, one can always set an arbitrary zero point for the potential. For the purposes of this lab, we will define the zero potential point to be the negative terminal of the power supply.
2. Use the voltmeter to check the battery voltage. The battery should read near 9 volts.
3. Use the alligator clips to connect the terminals of the battery to each of the black/red wires which will be used as "current electrodes" on the paper. Put these electrodes on your paper, some distance away from one another.
4. Connect the leads from the voltmeter to the two current electrodes. This should give very close to the same reading as the potential difference between the two terminals of the power supply itself. If not, there may be some bad connection. (*What does this tell you about measuring voltages at current electrodes?*)
5. You are to plot out equipotential lines for the two fixed current electrodes. Equipotentials are plotted by connecting one lead of the voltmeter (the *ground* or *common*, by convention this is often the black (negative) lead) to the current electrode connected to the negative battery terminal. The other voltmeter lead (the probe) is used to measure the potential at any point on the paper by simply touching the probe to the paper at that point.
6. To map an equipotential, move the probe until the desired potential is indicated on the voltmeter. You are to mark this point on the sheets provided (these sheets have the same grid markings as on the conductive paper). Continue to move the probe, but only in a direction that maintains the meter at the same reading. Continue to mark these points. Connecting the points produces an equipotential line.
7. Draw a handful of equipotential lines, for equal steps in potential difference. For potentials that are close to zero or the full battery potential, this may be difficult and may take some care.
8. Draw another set of equipotentials with your current electrodes either closer together or farther apart.

Q1: What effect does the finite size of the black paper have on the field? (Do the equipotential lines continue as expected when nearing the edges? Describe any distortion.)

Part II: Plotting Field Lines

1. To plot field gradients (field lines), the two leads of the voltmeter will be placed on the conductive paper side-by-side at a set distance of separation. It is best to tape the two leads of the voltmeter together for this procedure. The technique is to use the voltmeter leads to find the direction from an electrode that follows the path of greatest potential difference from point-to-point. Just as the net force on an object resting on a hill is in the direction of the steepest slope, so the electric field at any point is in the direction of greatest change in the potential.
2. To plot the field lines on the conductive paper, place the voltmeter lead connected to ground near one or the dipoles.
3. Place the other voltmeter lead on the paper and note the voltmeter reading.
4. Now pivot the lead to several new positions while keeping the ground lead stationary. Do not press hard enough to make a dent in the paper, or drag the electrodes.
5. Note the voltmeter readings (field gradient) as you touch the lead at each new spot on the paper.
6. When the potential is the highest (maximum field gradient), draw an arrow on the paper from the ground lead to the other lead.
7. Then move the ground lead to the tip (head) of the arrow.
8. Repeat the action of pivoting and touching with the front lead until the potential reading in a given direction is highest.
9. Draw a new arrow.
10. Repeat the action of putting the ground lead at the tip (head) of each new arrow and finding the direction in which the potential difference is highest.

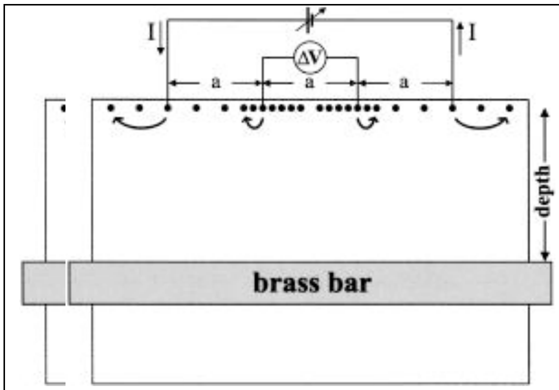


11. Eventually, the arrows drawn in this manner will form a field fine.
12. Return to the dipole and select a new point at which to place the voltmeter's ground lead.
13. Again probe with the other lead until the direction of highest potential difference is found.
14. Draw an arrow from the ground lead to the other lead, and repeat the process until a new field line is drawn.
15. Continue selecting new points and drawing field lines around the original dipole.

Q2: What is the relation between the direction of a maximum value field gradient and equipotential line at the same point? (A geometrical relation is desired.)

Part III: A Resistivity Survey

We'll now model the resistivity of our conductive paper "earth" using the Wenner electrode spread. This electrode spread is commonly employed by geophysicists and is characterized by an equal spacing between adjacent electrodes. The outer two electrodes are connected to a power supply and the current is held constant. The electric potential difference between the inner two electrodes is then measured to determine the resistivity of the ground. To derive the resistivity for a homogeneous subsurface using a Wenner electrode spread, one applies Ohm's law and the definition of the electric field as the gradient of the electric potential to an infinite hemisphere. The result of this derivation is that the electric potential difference (ΔV) between the inner two electrodes is determined by $\Delta V = \rho I/2\pi a$, where a is the spacing between electrodes, ρ is the resistivity, and I is the current. When modeling a Wenner electrode spread on a paper of thickness t, the situation is changed from an infinite hemisphere to an infinite half-circle. The result in this case, $\Delta V = (\rho I/\pi t) ln(4)$, is similar mathematically to a geophysical spread that uses line rather than point electrodes. The important feature of this result is that the electric potential difference between the inner two electrodes is independent of the *a*-spacing, making the analysis more straightforward and thus allowing you to see changes in the electric potential difference that directly reflect the resistivity of the subsurface layers without requiring a correction for the *a*-spacing.



Set up for Wenner array.

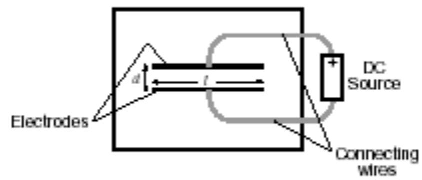
To model a Wenner array, decide where you'd like to inject your currents and measure your potentials. The top of the paper represents the surface of the earth. To simulate a lower resistivity layer at some depth (for example, water saturated sediment), use a strip of aluminum foil that can be moved to any desired position. The foil layer is first placed at the bottom of the paper, a distance of 28 cm from the electrodes, and a Wenner spread is conducted for each of the possible *a*-spacings. The foil layer is then moved upward to depths of 24, 20, 16, 12, 8, 6, 4, and 2 cm and subsequent Wenner spreads are conducted for each new position.

Q3: Plot the electric potential difference (ΔV) between the inner electrodes as a function of *a*-spacing, and describe briefly the results.

If there's time, do one (or both) of these:

Part IV: Equipotential lines of a parallel plate capacitor

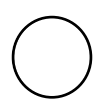
Draw two parallel line segments on the conductive paper with the conductive ink pen, hook up the power supply and the voltmeter, and measure the resulting equipotential lines. You can then draw in the electric field lines, which run perpendicular to the equipotential lines.



1. Use the silver ink pen and a ruler to draw two horizontal parallel lines on the paper at about 7cm and 13cm from the bottom. Draw them symmetrically about the center and make them about 2/3 of the width of the page.
2. Connect the power supply to the parallel lines you just drew.
3. Use the positive lead of the voltmeter to measure the voltage at various points on the conductive paper. Make a map of various equipotential lines on the conductive paper using a pencil. Note: The pattern is symmetric.
4. Draw in the electric field lines using the fact that they are perpendicular to the equipotentials and point in the direction of decreasing potential.
5. Try to get some feel for what the electric field looks like behind the plates by plotting a couple more equipotentials there.

Part V: Field inside a conducting cavity

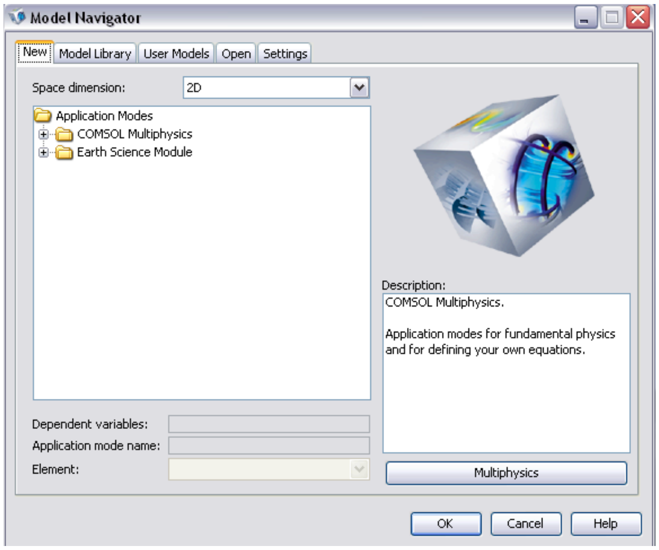
1. Use the silver ink pen and the green template to draw a circle between the plates somewhere to the left of center. (In the region that has not been written on.)



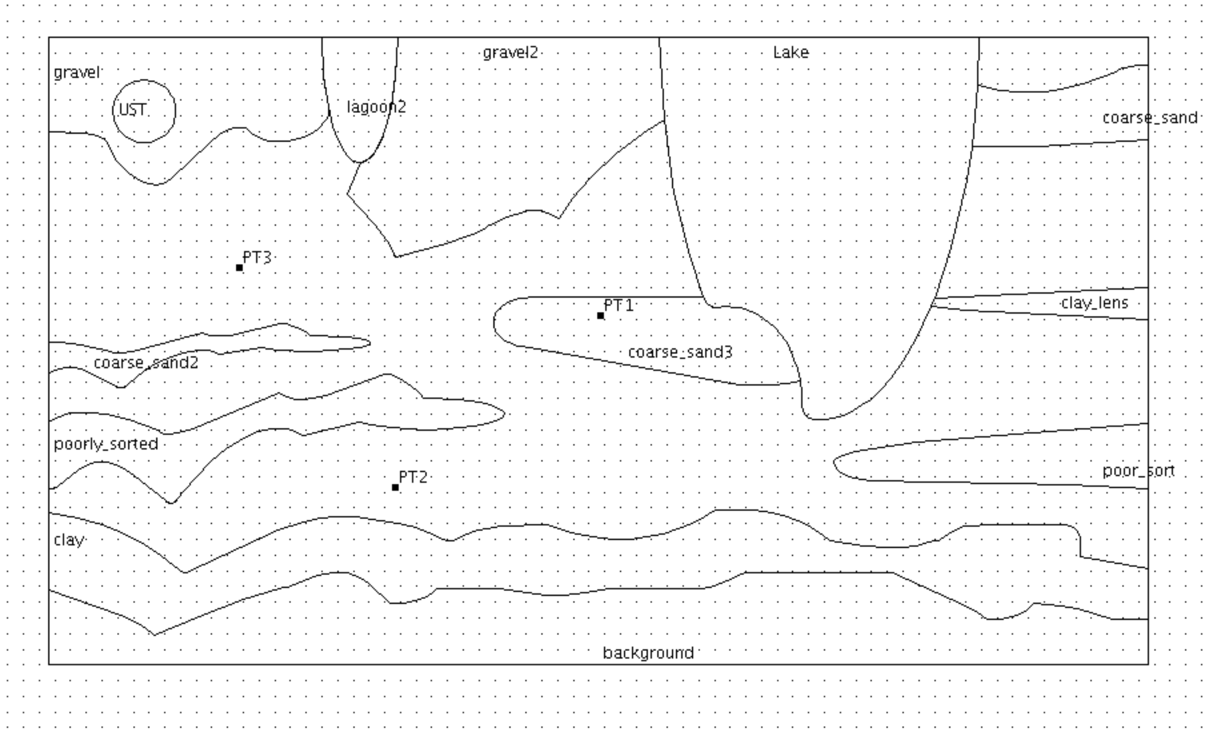
2. When the ink has dried, proceed to measure the equipotentials and draw in the electric field lines in this region.
3. Measure the potential at various points inside the circle. What can you deduce about the electric field inside the circle from your results? Side note: If the top plate represents the clouds at a high potential, the circle represents your car, and the bottom plate represents the ground, where would you be safest during an electrical storm?

Exploring the Sand Tanks with COMSOL

Today we'll explore a model that's already been put together in COMSOL, based on the sand tanks you've been using in class. The goal is to show that numerical models can be used to predict behaviors in real systems. To start, click on the COMSOL Multiphysics shortcut under Start → Programs. The Model Navigator will open:



Go to open and select sandtank_ust_inj.mph. This model should look familiar to you!



Let's explore this model, its parameters and boundary conditions, and see if we can't replicate the behavior we see in the sand tanks we've been using!

EXPLORING THE SAND TANK MODEL

1. Go into the Darcy's Law application. Look at the subdomain settings. What are the important parameters (and their differences) in the subdomains (note: it might be easier to see what's happening if you look under the Groups tab). Do these values make sense? Why or why not?

2. Describe the boundary conditions (note: again, it might be easier to see what's happening under the Groups tab). Do these make sense? What is one problem with this code as set up?

3. Run the flow model using a Stationary solver. Describe the head distribution associated with the heterogeneity in the model.

4. Go to the Solute Transport application. Look at the subdomain settings. What are the important parameters (and their differences) in the subdomains (note: it might be easier to see what's happening if you look under the Groups tab). Do these values make sense? Why or why not?

5. We'll now contaminate our aquifer using the leaky underground storage tank. Explore the subdomain settings of the UST in particular. How is this domain different than the other domains? How is this domain defined differently than the contamination plume we simulated in our simple COMSOL demo? Why is there a difference? What does it mean?

6. Describe the boundary conditions (note: again, it might be easier to see what's happening under the Groups tab). Do these make sense?

7. Run the transport model using a Transient solver. Describe the concentration distribution through time associated with the heterogeneity in the model.

8. Describe the similarities and differences between this numerical model and the physical model we used in class.

Open sandtank_well_inj.mph. This model uses the wells, rather than the underground storage tank to contaminate the aquifer.

9. Go into the Darcy's Law application. Look at the subdomain settings. Write down any differences between this model and the one above. Do these changes make sense? Why or why not?

10. Describe the boundary conditions (note: again, it might be easier to see what's happening under the Groups tab). Do these make sense? Describe how the wells are defined in terms of their fluxes.

11. Run the flow model using a Stationary solver. Describe the head distribution associated with the heterogeneity in the model.

12. Go to the Solute Transport application. Look at the subdomain settings. Write down any differences between this model and the one above. Do these changes make sense? Why or why not?

13. We'll now contaminate our aquifer using the wells. Explore the boundary conditions of the well locations. How do we define the contamination source? What does it mean?

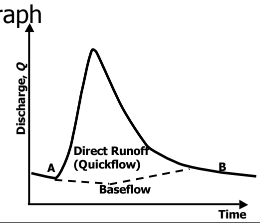
14. Run the transport model using a Transient solver. Describe the concentration distribution through time associated with the heterogeneity in the model.

15. Describe the similarities and differences between this numerical model and the physical model we used in class.

16. Turn on one of the downgradient wells as a pumping well (think about how to do this). How does this change the results of your model?

Surface Water

- Outline:
  - Measuring components of water budget
  - Defining fluxes, discharge, and the hydrograph



So What?

- Surface water is easily accessible for drinking water sources and recreation, but is also the easiest to be impacted by anthropogenic effects
- Needed for:
  - Licensing extractions, e.g., irrigation, dilution
  - Issuing flood warnings
  - Managing pollution incidents
  - Detection of change in land use or climate
  - Availability of potable water supplies
  - Determining flow criteria for ecological health of rivers

Idealized Watershed

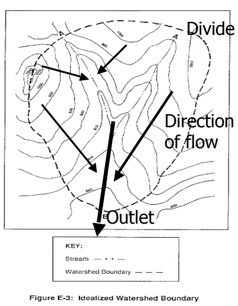
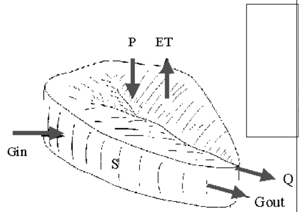
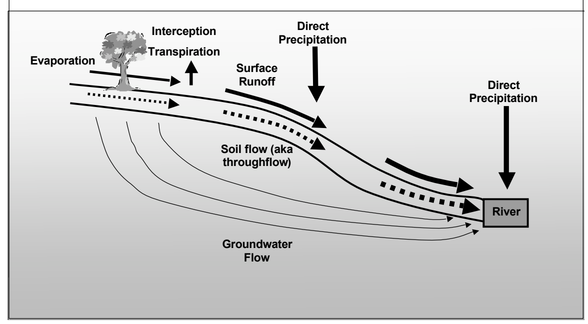


Figure E-3: Idealized Watershed Boundary



Components of Runoff

Pathways

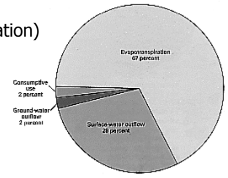


Outputs

Apart from precipitation, the most significant component of the hydrologic budget is evapotranspiration.

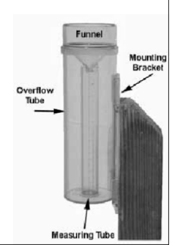
The disposition of this precipitation is illustrated below.

- Evapotranspiration: ~ 67% (majority of loss through transpiration)
- Runoff: 29%
- Groundwater outflow: ~2%
- Consumption: ~2%

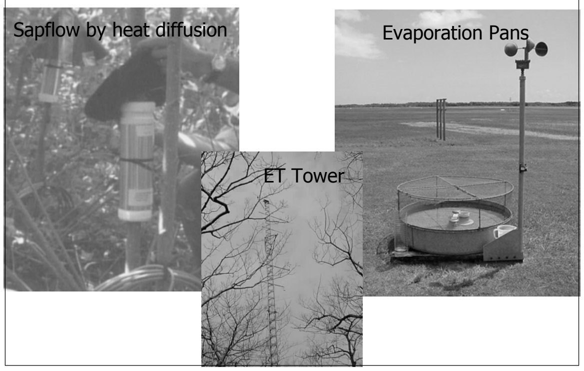


Inputs: Precipitation

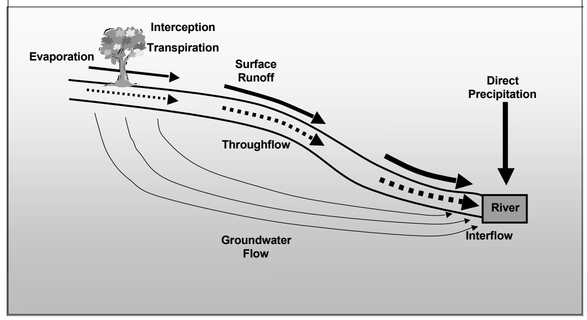
- Measured in open containers
- Location important:
  - Need basin average
  - Measuring discrete points
- Are data
  - Representative?
  - Of long enough record to be useful?
  - Distributed properly?



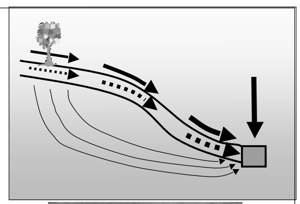
Evap, ET measurements in the field



Components of Runoff
Pathways



Infiltration



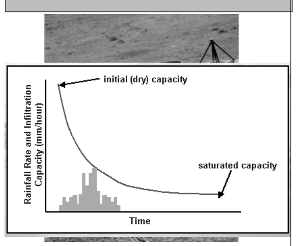
Key Definitions

Infiltration - The process whereby water percolates into the soil

Infiltration rate – Volume per time unit (often mm/hour)

Infiltration capacity – maximum rate soil can absorb (varies with soil wetness)

Surface runoff – water that does not infiltrate

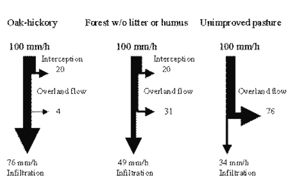


Take 1

- What parameters control infiltration?

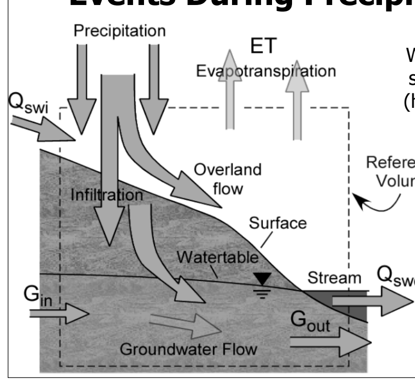
Factors Affecting Infiltration Rate

- 1. Rate at which water arrives.
- 2. Conductivity at the surface
  - a. Vegetation
  - b. Frost
  - c. Soil type
  - d. Pavement
- 3. Water Content
  - a. Saturation
  - b. Antecedent water content (how wet is the soil before the rainfall?)
- 4. Surface slope and "roughness" controls ponding
- 5. Chemistry of soils



The effect of vegetation on infiltration capacity and runoff. After Jones, 1997.

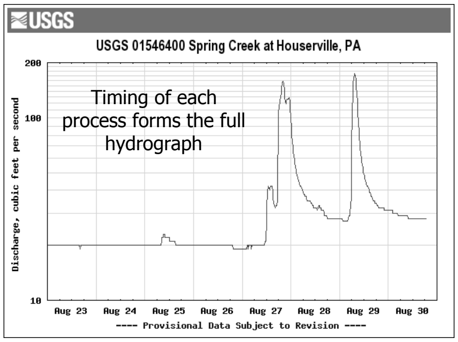
Events During Precipitation



What composes a stream discharge (hydrograph) plot, then?

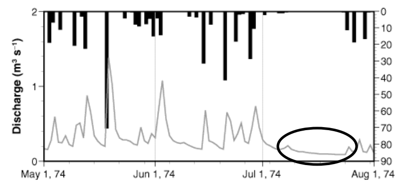
[Hermance, 2003]

The stream hydrograph: a plot of discharge through time at one location



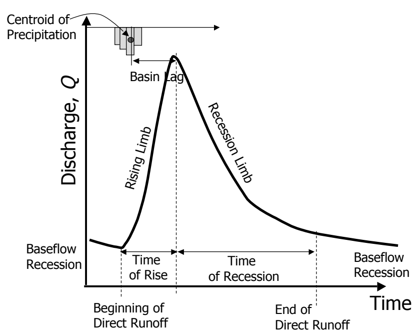
Nature and Cause of Floods

The nature of each hydrograph depends upon watershed and storm characteristics ➔ strong relationship between precipitation and hydrograph:



- Background discharge between floods is called baseflow and is supplied by inflow of groundwater
- Also: there could be interflow: lateral flow in the vadose zone into streams

Streamflow Hydrograph



Components of Runoff

Relative Speed of Pathways

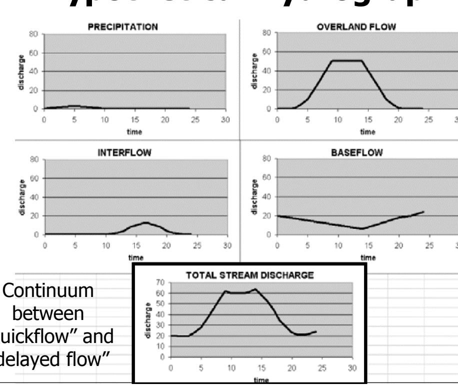
- Direct precipitation
- Overland Flow
- Lateral flow in soil (interflow)
  - macropore and pipe flow
  - matrix flow
- Groundwater flow (baseflow)

Fast

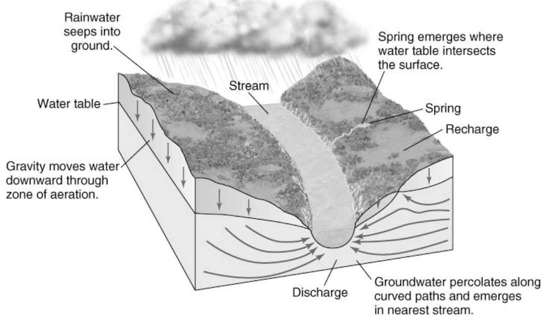
Slow

Time to create a human hydrograph!!!

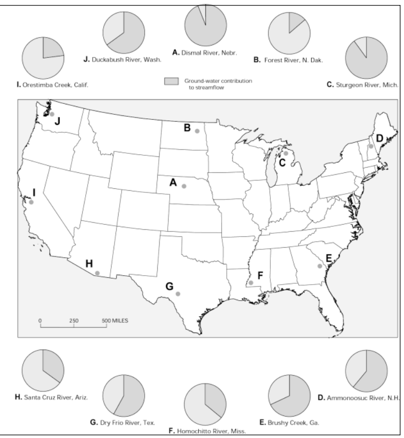
Hypothetical Hydrograph



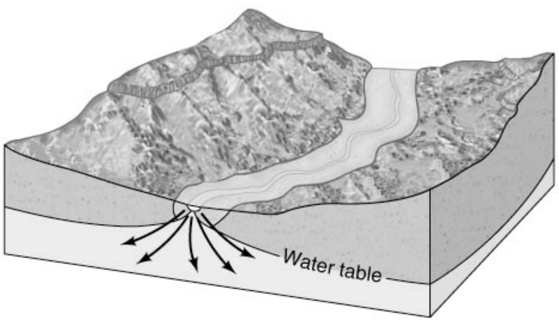
Continuum between "quickflow" and "delayed flow"



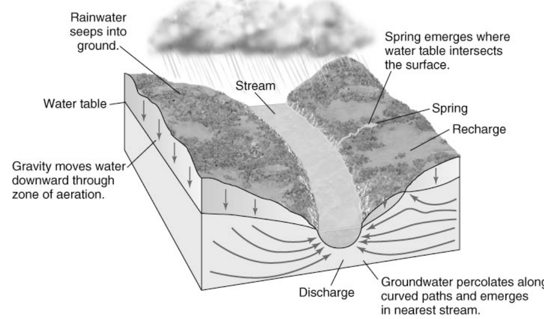
Percent of baseflow is dependent on climate, geology



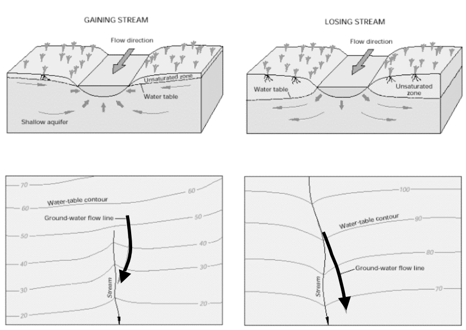
[USGS Circular 1139]



Can you tell if the stream is gaining or losing by looking at it?

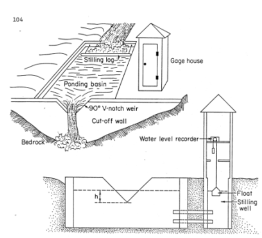


Gaining/losing streams



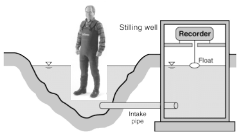
[USGS Circular 1139]

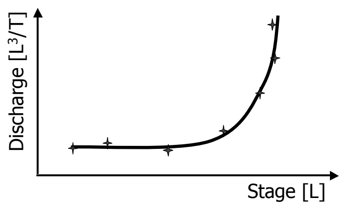
Measuring Stream Stage



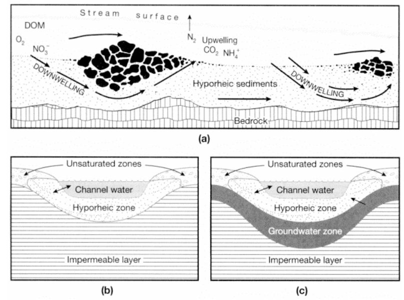
- Use weirs
- Embedded such that no river flow goes under or around (need to capture all flow)
- Height of water (stage) is measured relative to the lowest point of weir

But we don't want stage…





Hyporheic Zones



a)Longitudinal section;

b)cross section, no groundwater

c)cross section, groundwater

HYPORHEIC ZONE: region of alluvial sediment within the stream channel that lies immediately below the bed surface and above bedrock. Can vary in depth from 1" to several feet.

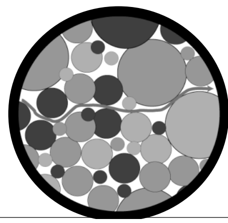
Kalff J (2002) fig. 8-7

Take Home Messages

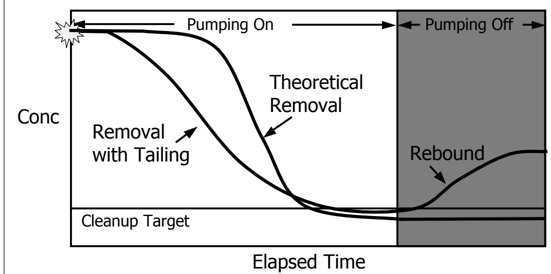
- Storage = Input - Output
- Ground water and surface water are connected
- Principle hydrologic processes are:
  - Precipitation
  - Evaporation & transpiration
  - Infiltration
  - Overland flow
  - Interflow/Throughflow
  - Groundwater flow
  - Streamflow generation

Tracer Tests and Geophysics

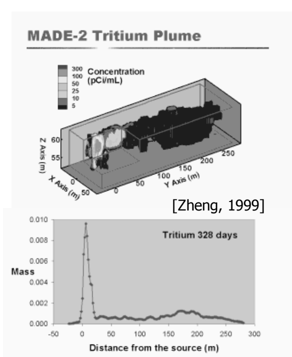
- Outline:
  - Dual-domain mass transfer; Archie's Law; a place where geophysics can help!



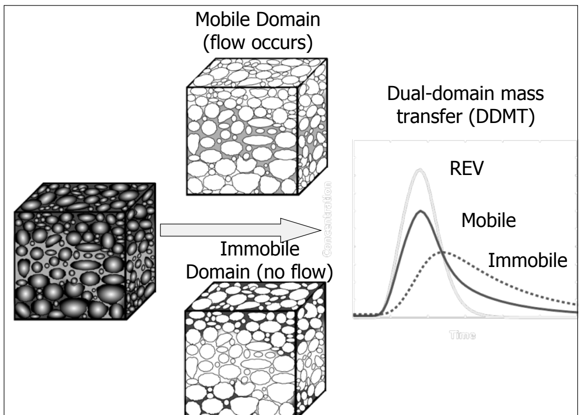
A Common Problem in Pump-and-Treat Remediation



"Anomalous" Transport Behavior

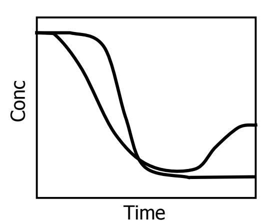


- MAcroDispersion Experiment Site, Mississippi
- Peak concentration stayed close to injection
- Highly asymmetric plume, non-Gaussian pattern
- Observed mass was overestimated early on, underestimated at the end of the test
- Why?



The Problem

- We can't sample the immobile domain, as there's no flow
- DDMT is just a hypothesis
- Standard hydrologic measurements don't provide enough information to determine the magnitude (or existence!) of the post-



Transport Equations

Advective-dispersive transport:

$$\underbrace{\theta_m \frac{\partial c_m}{\partial t}}_{\Delta\ concentration} = \underbrace{\nabla \cdot (\theta_m D \nabla c_m)}_{dispersion} - \underbrace{\theta_m v \cdot \nabla c_m}_{advection}$$

DDMT:

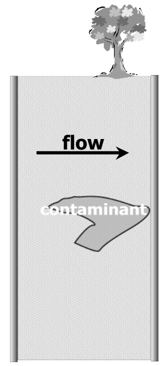
$$\theta_m \frac{\partial c_m}{\partial t} + \boxed{\theta_{im} \frac{\partial c_{im}}{\partial t}} = \nabla \cdot (\theta_m D \nabla c_m) - \theta_m v \cdot \nabla c_m$$

$$\theta_{im} \frac{\partial c_{im}}{\partial t} = \alpha (c_m - c_{im})$$

Problem: more unknown parameters

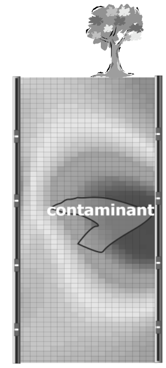
Now what?

- Hydrologic data are frequently sparse or volume averaged, and costly
- Geochemical samples measure fluids in the mobile domain
- How to determine what's in the immobile domain?



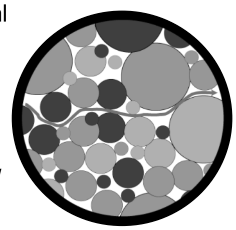
Geophysics!

- Electrical resistivity may be able to provide info on the immobile domain…
- Able to collect spatially exhaustive data



Why electrical resistivity?

- Measured potentials are sensitive to the bulk electrical properties, which are related to:
  - porosity
  - connectivity of pore fluid
  - pore fluid salinity
- Sensitive to changes in *total* dissolved solids
- Doesn't discriminate between mobile and immobile



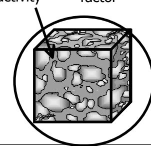
State of the Practice

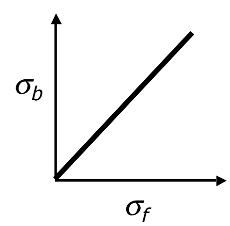
Saline concentration is directly related to fluid conductivity

Archie's Law:

$$\sigma_f = F\sigma_b$$

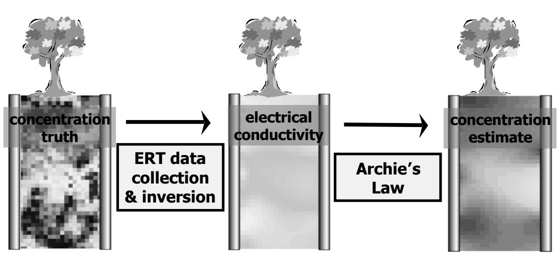
fluid conductivity — formation factor — bulk conductivity (ER)





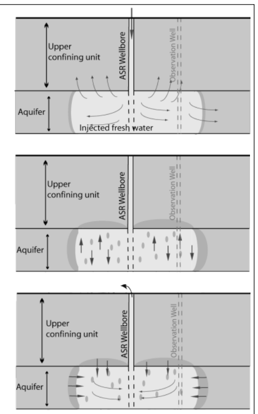
State of The Practice

ER studies often use Archie's law to estimate concentration in the field

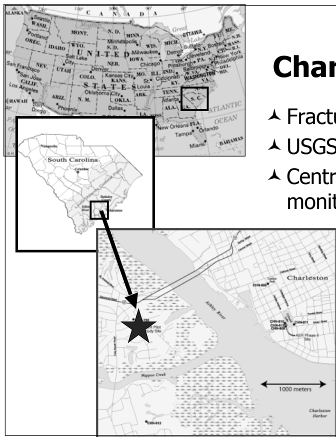


Aquifer-Storage Recovery (ASR)

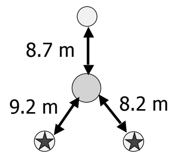
- Inject potable water in times of surplus into subsurface aquifers for later recovery
- What happens to the injected water once it is emplaced?



Field Site: Charleston, SC, USA



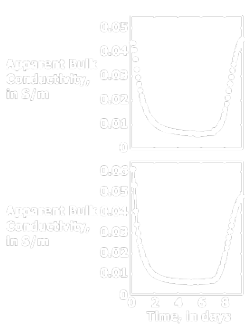
- Fractured limestone aquifer
- USGS research site
- Central ASR well, 3 monitoring wells



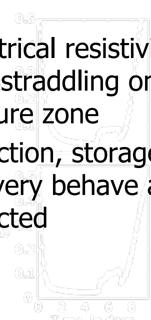
Data Collection

- Injection (5 days): Q = 170 m^3/d; fresh water (σ_f < 0.02 S/m) was injected at into a brackish aquifer (σ_f ~ 0.6 S/m)
- Storage (2 days)
- Recovery (4 days): Q = 480 m^3/d
- Electrical data: 72 electrodes, spaced 1.25-m apart, 24 in each of the three sampling wells

Bulk & Fluid Conductivities in Connected Wells

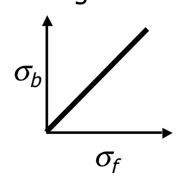


- Electrical resistivity data straddling one fracture zone
- Injection, storage, recovery behave as expected



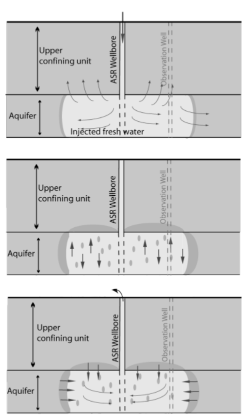
Hysteresis in Behavior

Apparent bulk and fluid conductivity do not fall on a straight line through time

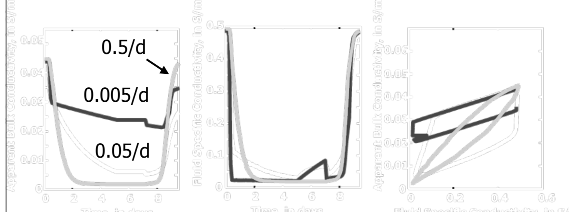


Dual-Domain Mass Transfer?

1. Injection: freshwater fills mobile domain and σ_f decreases; σ_b remains high as immobile domain remains brackish;
2. Storage: local DDMT of salts from immobile to mobile domain → an increase in σ_f but does not impact σ_b; and
3. Recovery: mobile σ_f increases as freshwater is removed; σ_b remains low as immobile domain is now comparatively fresh.

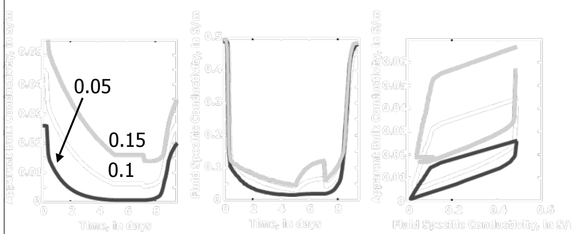


Effect of Variation in Mass Transfer Coefficient (α)



For all models: θ_{im} = 0.1; θ_m = 0.05

Effect of Variation in Immobile Porosity (θ_{im})



For all models: α = 0.05/d; θ_m = 0.05

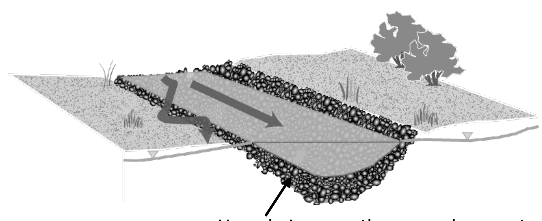
Results of Modeling

- Low mass transfer rates: less communication between domains; system retains high σ_b
- High mass transfer rates: high communication between domains; behaves like a single continuum
- Low immobile porosity: system behaves like a single continuum because less storage is available
- High immobile porosity: more storage is available
- Shape of curves may elucidate parameter magnitudes in situ—but how to estimate directly?

So What?

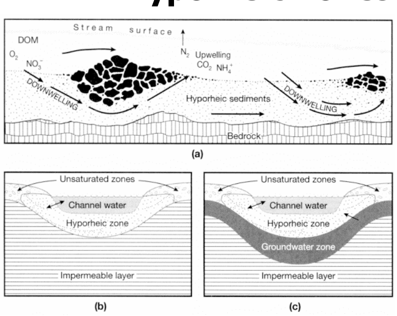
- The disconnect between fluid and bulk conductivity may tell us something about processes!
- Would this work in other settings besides aquifers, where there is a mobile and immobile domain?

Mass transfer in streams?



Hyporheic zone: the area where water leaves the stream, goes into the bed, and returns

Hyporheic Zones



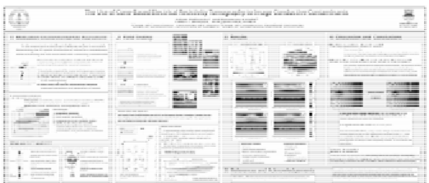
a) Longitudinal section;
b) cross section, no groundwater
c) cross section, groundwater

<u>HYPORHEIC ZONE</u>: region of alluvial sediment within the stream channel that lies immediately below the bed surface and above bedrock. Can vary in depth from 1" to several feet.

Kalff J (2002) fig. 8-7

How to Present Scientific Data

- Outline:
  - Writing abstracts, effective poster/oral presentations, image layout and design, engaging your audience



What is a scientific abstract?

An abstract is a short summary about a project, and should include, in one paragraph, a statement of:

1. the purpose of the project
2. general methods or procedures used
3. principal findings and conclusions.

Rules for an abstract

(reference: Young & Wang, 2004)

- It should be a mini-version of the original paper.
- It should provide balanced coverage of the original.
- It should present the source material in a neutral unbiased fashion.
- It should include nothing that is not in the original (no personal comments).

- Do not try to paraphrase specialized vocabulary or technical terms.
- Include enough support and detail to make it clear.
- Make it flow smoothly.
- Use full sentences.
- Avoid negatives, abbreviations, and jargon.

Procedure for writing an abstract

1. Skim the text, noting the subheadings.
2. Read the text, highlighting important information or taking notes.
3. Write the main points of each section in your own words.
4. Write key supporting points for the main topics.
5. Go through the process again, making changes as needed.
6. Writing the summary in draft form, keeping in mind the required length and the reader.
7. Edit the draft.
8. Rewrite the draft.

Example of composing a 100-word abstract

GLOBAL WARMING: Rain Might Be Leading Carbon Sink Factor
Richard A. Lovett (Science 296, 7 June 2002, p. 1787) (About 540 words)

"Where's all the carbon going?" Atmospheric scientists have been wondering about that for years. The United States spews out more than 5 billion tons of carbon dioxide emissions each year, but mainland U.S. ecosystems are absorbing an unexpectedly large amount of the gas—somewhere between 10% and 30% of the total—and the amount is steadily increasing. Scientists aren't complaining, mind you, because this absorption or sequestration offsets global warming. But they've been at a loss to explain it.

Most of the carbon is being sucked up by plants, which use it to manufacture roots, stems, leaves, and wood. Indeed, over the past several decades, researchers have recorded increased vegetation growth across the country. But why all this vegetation is growing so quickly has remained unclear. Theories abound, but the principal ones involve regrowth of forests on previously logged lands and accelerated forest growth spurred by global warming.

Now, a team is proposing another explanation: rain. A study published online by *Geophysical Research Letters* on 28 May suggests that the increased rainfall and humidity documented in the continental United States might be the single most important factor spurring increased plant growth; this, in turn, is slowing the accumulation of carbon dioxide in the atmosphere.

First, we identify the main points and the supporting points.

- Main Point 1
Mainland U.S. ecosystems are absorbing more CO2 than scientists can explain.

- Main Point 2
Vegetation growth has increased during recent decades.

- Main Point 3
  A recent study suggests that increased rainfall leads to increased plant growth and more CO_2 sequestration.
- Main Point 4
  Carbon sink modelers have concentrated on growth of trees and forests.
- Main Point 5
  A University of Montana study indicates that rainfall is the major influence on plant growth.
- Main Point 6
  Increased moisture encourages growth of all vegetation.
- Main Point 7
  Other scientists support the concept of major influence of moisture.
- Main Point 8
  Researchers are encouraged to revise their Carbon sink models to include all vegetation, not just trees.

- Supporting Point 1
  U.S. ecosystems are absorbing 10% to 30% of the 5 billion tons of CO_2 emissions per year.
- Supporting Point 2
  The reasons for increased vegetation growth are nuclear. The focus has been on forest growth.
- Supporting Point 3
  The GRL paper suggests that increased rainfall and humidity might be the most important factor.
- Supporting Point 4
  Carbon sink modelers have overlooked this factor.

- Supporting Point 5
  The Montana study indicates that 2/3 of the increased growth is due to increased rainfall. Increased moisture during 1950-93 increased plant growth by 14%.
- Supporting Point 6
  Increased moisture provides more moisture to the roots and facilitates photosynthesis.
- Supporting Point 7
  A proponent of temperature change as a major factor admits the need for moisture.
- Supporting Point 8
  It may be naïve to rely only on tree growth during times of changing amounts of moisture.

Draft 1 Abstract

Ecosystems of mainland U.S. have been absorbing CO_2 more rapidly than scientists can explain. New considerations of the effect of rainfall on plant growth are providing a possible explanation. Increased growth during recent decades has been related to increased rainfall. A recent study indicates that 2/3 of the increased plant growth is due to increased moisture. Carbon sink models that have previously focused mainly on tree growth are inadequate to describe the increased absorption. Models that take into account all vegetation might more adequately account for increased growth and increased absorption of CO_2 .

Draft 2 Abstract

Mainland U.S. ecosystems are absorbing more CO_2 than scientists can explain. Also, vegetation growth across the country has increased during recent decades. A recent study suggests that increased rainfall is a major factor in more rapid plant growth, accounting for 2/3 of the increased growth during 1950-1993. Increased moisture not only provides more water to the roots, but also facilitates photosynthesis. Even those scientists who have supported other factors of growth, such as temperature, agree that moisture is essential. This indicates the need to revise growth models, which have emphasized trees and forests, to include all vegetation.

Example of composing a 50-word abstract

Go back to original Main Points. Revise the wording.

1. Mainland U.S. ecosystems are absorbing more CO_2 than scientists can explain with current Carbon sink models.
2. Carbon sink modelers have concentrated on tree and forest growth.
3. Rainfall has increased in recent decades.
4. A recent study suggests a strong effect of rainfall on the growth of all vegetation.
5. Increased vegetation growth increases CO_2 absorption.
6. Models based on rainfall effect on all vegetation might help explain increased CO_2 absorption.

Draft 1

Results of a recent study might offer an explanation of why U.S. ecosystems are absorbing more CO_2 than predicted by current Carbon sink models. Current models focus on trees and forest growth. However, increased rainfall in recent decades has increased the growth of all vegetation and thus increased the absorption of CO_2. Models that take that into account could better estimate the increased CO_2 absorption.

Draft 2

Results of a recent study might explain why current Carbon sink models underestimate CO_2 absorption by green plants. Current models emphasize on trees and forest growth. However, increased rainfall has increased the growth of all vegetation and thus increased the capacity to absorb CO_2. Models should include factors of rainfall and vegetation.

A few things to think about

- The abstract should be very concise and clear
- Describe the purpose of the experiment, the methods (brief) and the results.
- Use short sentences, and don't use references.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. [illegible], NO. 7 (JULY, [illegible]), PP. [illegible], [illegible] FIGS., 1 PLATE

GEOLOGICAL NOTES

A SCRUTINY OF THE ABSTRACT[1]

KENNETH K. LANDES[2]
Ann Arbor, Michigan

ABSTRACT

The behavior of editors is discussed. What should be covered by an abstract is considered. The importance of the abstract is described. Dictionary definitions of "abstract" are quoted. At the conclusion a revised abstract is presented.

Presumably new editors, like new senators and small children, should be seen and not heard. But unfortunately the Association has elected (the electorate had no choice) an editor who is a non-conformist. For many years I have fretted over the inadequate abstract, and now perhaps I can do something about it—but not by keeping quiet.

Many of the abstracts appearing in the publications, including the meeting programs, of the A.A.P.G. can best be described by the use of a homely word that refers to an infestation by certain minute organisms. The abstract appearing at the beginning of this note is in that category. I regret to say that it is not an extreme case. My collection contains several that are worse. Dean Russell of Louisiana State refers to such abstracts as "expanded titles." They could also be looked upon as a table of contents, in paragraph form, with "is discussed" and "is described" added so as to furnish each subject with the verb necessary to complete the sentence. The reader is left completely in the dark not as to what the paper is about but as to what it tells! The information and the interpretation contained therein remain a mystery unless the reader takes the time to read or listen to the entire paper. Such abstracts can be likened to the "teasers" which your local movie manager shows you one week in the hope of bringing you back next week. But the busy geologist is more likely to be vexed than intrigued by the coy abstract.

To many geologists, especially to the tyros in exposition, the writing of the abstract is an unwanted chore required at the last minute by a rule-ridden editor or insisted upon even before the paper has been written by a deadline-bedeviled program chairman. However, in terms of market reached, the abstract is *the most important part of the paper*. For every individual who reads or listens to your entire paper, from ten to five hundred will read the abstract. It is much better to please than to antagonize this great audience. Papers written for oral presentation should be prepared with the deadline the abstract date instead of the delivery date. Later discoveries can be incorporated within the paper—and they would miss the program abstract anyway.

My dictionary describes an abstract as "a summary of a statement, document, speech, etc." and "that which *concentrates in itself the essential qualities of anything more extensive* or more general, or of several things; essence." The definition I like best has been set in italics. May all writers learn the art (it is not easy) of preparing an abstract containing the *essential qualities* of their compositions! With this goal in mind I append an abstract that I believe to be an improvement over the one appearing at the beginning of this discussion.

ABSTRACT

The abstract is of utmost importance, for it is read by 10 to 500 times more people than hear or read the entire article. It should not be a mere recital of the subjects covered, replete with such expressions as "is discussed" and "is described." It should be a condensation and concentration of the *essential qualities* of the paper.

[1] Manuscript received, May 5, 1951.

[2] Editor of the *Bulletin*.

1580

Writing an abstract for research you have conducted

- There is a temptation to hint in the abstract about the results you hope to get in two months time.
- DO NOT BE TEMPTED
  - you can put new results into the poster, even if they are not in your abstract
  - Retractions are less easy!
- Check the word limit and formatting conform to conference requirements.

The submitted abstract

- The title is important
  - In theory the title of submitted abstract and poster should match
  - BUT… your abstract title needs to be detailed enough that people know what you have done

Now, it's your turn.

- Take a look at the Molz et al., 2006 paper about the MADE site.

  Write a 100-word abstract.

How to make a poster

What is a poster session?

- Most scientific meetings have more presenters than time for talks
- Posters provide the means to present additional short communications
- There's plenty in it for you!
  - The poster communication often provides the means to get to the conference
  - Posters provide a launch point for networking
  - Some poster submitters may be given talks
  - Many meetings run poster competitions - some have worthwhile prizes, all winners have a boost to their resumes

The Goal

- Goal is to give the audience the most information plus a notable message in the most efficient and straightforward manner
  - The poster should be for the most part self-explanatory
  - Minimize words...strike a balance between words and pictures
  - Should be simple, well organized, and reader friendly

Problems of the Poster Session

- Posters are presented in large groups
- The environment is usually crowded
- The time allotted to poster sessions is limited
  - Most people are in a hurry
  - You have about 3 seconds to persuade the average passer-by to read your poster.

Audience

- The audience is knowledgeable in general science only
  - It is never a mistake to introduce your material assuming no background knowledge
- Avoid too much technical detail, everyone should be able to understand your poster
- People are usually just walking by posters, you have to draw them in and make them interested in your poster

Titles

BAD!!

Sub retinal administration of AAV-PDE6B in the rcd-1 Beagle X Irish setter cross: photopic responses

Better

Gene transfer restores cone function in an animal model of retinitis pigmentosa

Consider the Audience

- Sometimes you will be trying to appeal to a wider group
- Some members of any audience may be colorblind*, have reduced vision or suffer dyslexia
  - Fonts and figures (*see *http://www.bio.cam.ac.uk/gradschool/current/courses/comms-links.html)*

The poster - planning the text

- You have 3 seconds to capture the audience
  - Title!
- You have about 30 seconds to persuade them to stay
  - The poster abstract (and/or "main points")
- In poster competitions, judges are asked to review posters at an average of 1-2 minutes per poster
  - faster at larger meetings.
- No-one will stay to read for more than five minutes
  - So make sure they can read all of it in that time!

The poster - planning the text

- Don't forget to include all authors and contact addresses (including email) under the title.
- You need to introduce the topic, describe any unusual methods, describe your results and set them in context
  - Methods should be brief
  - Results and their discussion should be close to the relevant figures

Overall Scientific Message

- Abstract
  - There is debate about whether or not it is proper to include/omit an abstract
    - If include, keep it short and sweet, ideally one or two bullets for each section of your poster
    - If omit, your entire poster should cover the contents of an abstract
- Intro/Background (why was the project undertaken?)
  - Start with a statement of significance
    - This may determine whether the audience will appreciate the rest of the poster…find real world references and comparisons that the non-scientific reader can relate to
  - Make sure to include the purpose of your experiment
    - The purpose should be easy to locate at the beginning of the poster…I.e. don't hide it in the middle of a long paragraph
  - Include relevant equations and figures

Overall Scientific Message

- Conclusion (What does it all mean? What is the take home message?)
  - This, along with the purpose, is the most important section
  - Try to sum it up in about two sentences or bullets
  - Should directly answer your purpose statement
  - Should follow directly from your results
  - Should not be a simple summary…should be used to put results in a big picture perspective, as well as outline the specific implications of your findings

A take home message as a set of bulleted points is very helpful

- **use a box to make it more visible**

Textual style

- Use short sentences (average 8-10 words)
- Do not use jargon or unexplained abbreviations
  - Some of your audience will not be specialists in your area
- Keep references to a minimum
- Avoid excessive detail
  - Edit ruthlessly: ask yourself - is this absolutely necessary? If not, omit it.

Powerpoint tips for posters

- Create text by cutting and pasting or typing directly into PowerPoint - Do not use "insert".
- Graphics should be "Inserted" as a picture. Do NOT import graphics by cutting and pasting.
- Leave a one-inch margin all the way around the outside edge of the poster to avoid having your content "cut off."
- Ideally graphics and photos should be scanned at the size you want to use them on your poster (not necessarily actual size). Scanning resolution should be 150 dpi.
  - If you are enlarging a file for the poster, import at up to 300dpi maximum.

Layout

- **Keep fonts simple**
  - **This is Times New Roman, a serif font: these are easy to read quickly and are compact, but can look fussy. Good for main text but less good for headings.**
  - **This is Ariel, a sans-serif font with a very clean look, but harder to read in big blocks. (Look also at Helvetica and Verdana).**
  - **And this is Comic Sans MS, with a less formal feel.**
- *Do not be tempted to use anything more elaborate*
  - complex fonts are hard to read

Layout

- Do not use more than two fonts across the whole poster.
- Text should be readable from at least 1.5 meters without strain.
  - For Times New Roman this means at least 24 point; most other fonts are larger, but don't use less than 20 point.
- Titles should be at least twice as big.
  - Author names, addresses etc. intermediate.
- Choose background and text colors to maximize reading ease.

Layout

In a light room, and in the absence of projection, dark text on a light background is easier to read than light text on a dark background.

(The converse is often true in a dark room with projected images, or when viewing the phosphorescent image on your computer screen.)

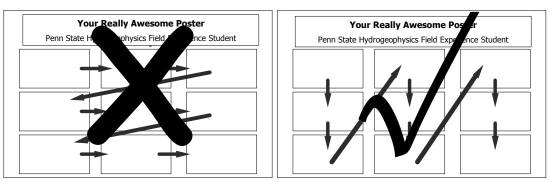
- Graded and patterned backgrounds look pleasant
- But avoid strongly graded backgrounds
- There is no font colour that will let you read the whole poster!
- Avoid strongly patterned backgrounds for the same reason

Arrangement and Design

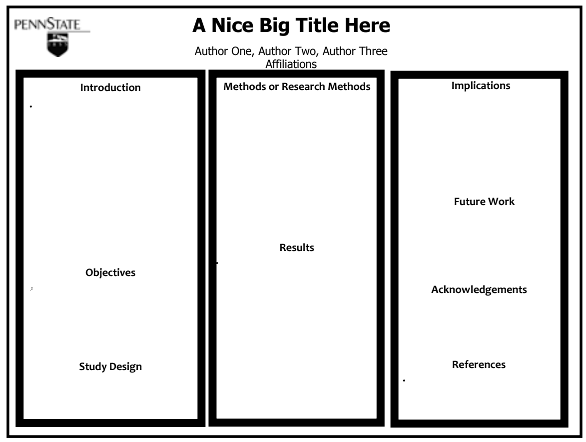
- Arrangement
  - Use standard lab report order for each of your sections reading top to bottom, left to right
    - Abstract/Intro, Methods, Results/Discussion, Conclusion, Future Work
  - Consider the overall arrangement of the sections within your poster…each section should transition smoothly to the next
  - The entire poster should be readable from 3-4 feet

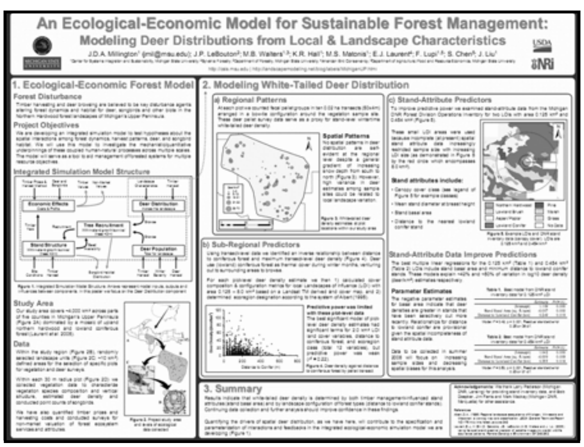
Layout

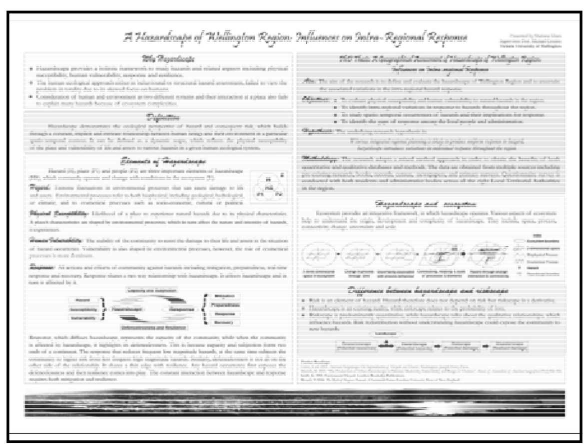
- Plan your poster in vertical columns, not horizontal rows

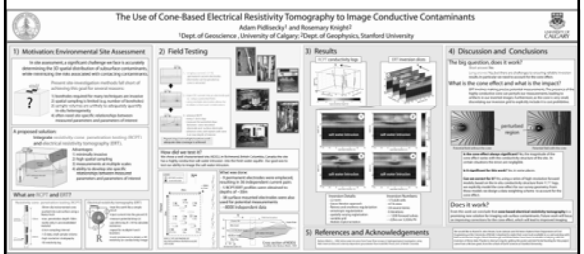


This prevents gridlock among those trying to read your poster



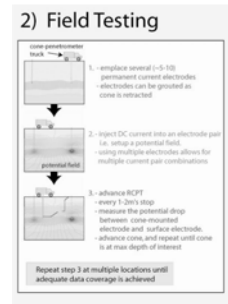






Layout

- Show, don't tell!
  - Very good for methods
  - <u>But</u> don't let the audience miss important results
- Use a simple visual grammar that reflects the importance of the elements: Large titles, Medium text, Small legends
- Large figures are easier to read
- Where text linked to a figure has to be in a different section or column, you can use an arrow
- Try to leave some blank spaces
  - They rest the reader's eye



Layout

- The main results should be summarised
- State conclusions from these results separately.
  - These sections should be easy to find

BOX!

- Don't forget acknowledgements

Your poster session

- You can leave a notepad and/or a small poster copies attached to the poster board when you are not there
- Collect email addresses of anyone interested

Your poster session

- Wear your conference badge.
  - People will know who you are
- The best way (the only good way) to get across the message of your poster is to talk people through it.
  - It ensures that your work is understood
  - It makes more impression
  - It gets you known

Your poster session

- Engage people who glance over the poster
  - Offer an explanation
  - DON'T WAIT TO BE ASKED
- Think about a short way to take people through the poster
  - Use the figures
  - Keep to the main points
- Try to make a note of any good suggestions

Presentation of the Poster

- Be ready with a short oral summary of your experiment outlining the contents of your poster
- Again clarity and conciseness are key

Four Topics for Posters

1. Determining lithologic boundaries
2. Properties controlling flow
3. Heterogeneity controls on transport
4. Quantifying non-ideal behavior
5. …others of your own making!

Thoughts on using power point.

Thoughts on using power point.

Thoughts on using power point.

Thoughts on using power point.

Thoughts on using power point.

Thoughts on using power point.

Thoughts on using power point.

Thoughts on using power point.

Thoughts on using power point.
Thoughts on using power point.
Thoughts on using power point.
Thoughts on using power point.
Thoughts on using power point.
20pt → Thoughts on using power point.
Thoughts on using power point.
Thoughts on using power point.

Thoughts on using power point.
Thoughts on using power point.
Thoughts on using power point.
Thoughts on using power point.
Thoughts on using power point.
Thoughts on using power point.
Thoughts on using power point.
Thoughts on using power point.

My storey

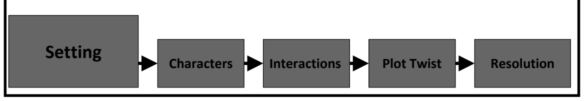
- Outline
- Setting
- Characters
- Interactions
- Major Plot Twist
- Resolution

My story

- Outline
- Setting
- Characters
- Interactions
- Major Plot Twist
- Resolution

Unless you have an hour, DO NOT USE THIS IT IS A WASTE OF A SLIDE

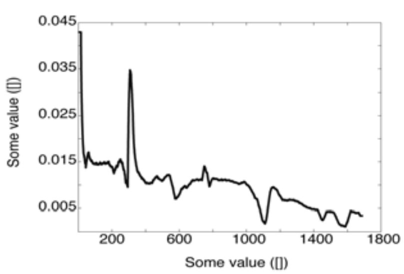
My story



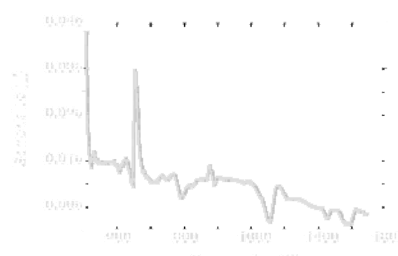
Figures

- Make axes readable!
- Transparency can be very nice, and easy on the eyes.
- Try and make the y-axis horizontal!

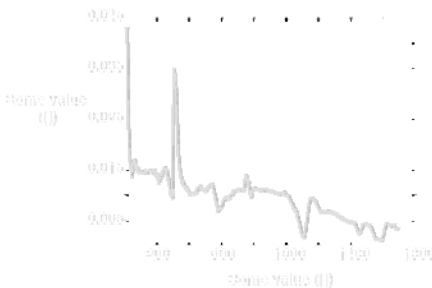
Figures



Figures

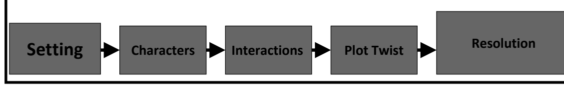


Figures



Conclusion

- Bring up each part of the story line.
- Remind us why we care.
- Thumb nails of figures can be good.
- Lists are also useful (numbered or not)



Thinking About Grad School

- Outline: Useful things I've learned, stuff I wish someone told me before I applied to grad school

Thinking about grad school?

- Things to think about:
  - Opportunities at the universities you're considering
    - Multiple advisors you could work with?
    - Possibility to do interdisciplinary science?
    - Will you be funded in full?
    - What opportunities will you have with other students wrt outside research, networking?
  - Opportunities to enjoy your hobbies
    - If you love going to museums, could you do that? If you love the outdoors, is there green space?
  - Why you are going to grad school

Who needs to go to graduate school?

Perhaps you do …

… if you aspire to be an educator/researcher, especially in higher education

…if you are in one of the sciences and want to work as a 'professional' in that field or you are an engineer who wishes to take a leadership role.

Today, the level of technology has advanced to a level that does not necessarily permit full preparation at the BSc-level

Who can forego graduate school?

Perhaps you …

…if you want to be 'working' engineer, or are considering being an oil-field geologist (at least, a doctorate is not needed).

Time is money!

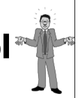
Top Reasons NOT to Go To Grad School

- Tough job market
- Trying to please / annoy parents
- Are actually a ski bum
- Always wanted to see what 22nd grade looked like

Top Reasons to Go

- Want to do research
- Want to write a thesis / dissertation
- Realize that having a higher degree opens doors
- Want to solve a specific problem

Applying to Graduate School



The Changing Educational Climate . . .

- 2002 UCLA Survey of over 282,000 freshmen at 450 colleges and universities: . . . over 75% of freshmen expect to earn a degree *beyond* the bachelor's degree
- The Master's degree is becoming the "expected" degree for most professions (just as the bachelor's degree did after WWII).
- In many professions, the Master's degree is already identified as the *entry-level degree* in those professions (e.g., public administration, business, civil engineering, social work, psychology, human resources, education, etc).

When should I start planning for graduate school?

Now!

It is all about 'relationships'

At this point, I don't know if I will go to graduate school or not.

There are some things you can do now that will improve your chances when and if you decide to go to graduate school.

All of these things will improve the quality of your undergraduate education and your employability – even if you never go to graduate school.

What sorts of things will help?

Become a member of your *departmental community*.

- Join the geology club/honorary society
- Visit your professors and learn about their research interests
- Join a research group
- Work on a research project or help a graduate student – even if it is as a volunteer

How does the application process work?

Online vs. paper apps

- Letters of recommendation – Want them to speak positively of your research experience and potential
- Transcripts of all college work - What you took and how well you did
- Statement of interest/Study Plan - tailored to department where you are applying
- GRE and other test scores

What will improve my chances of being accepted to my dream graduate program?

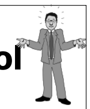
- Have established relationships as an undergraduate
- Tap into those relationships for your letters of recommendation
- Research involvement as undergraduate
- Contact prospective mentors before applying
- GPA – as high as you can get it, $\geq$ 3.0 is key
- GRE test scores – as high as you can get them, within reason

What if my GPA isn't that good?

There may be hope.

- Is it a case of poor grades as an underclassman, but good grades as a junior and senior?
- Are your grades good in your major, but not good in general degree courses?

Applying to Graduate School



What are **they** looking for?

Good Letters of Recommendation

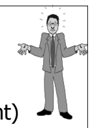
Primarily from *faculty* who know you and can add to what your transcript says

- your commitment to the field
- your potential for success in grad school & beyond
- your interpersonal "style" (e.g., leadership, maturity)
- other "stuff" that gives a clearer picture of you (e.g., internship experience, research experience, Geology Club, etc.)

Advice for Requesting Letters

- Give your writers 3-4 weeks before application deadline
- Give your writers important information about you:
  - Resume
  - List of courses taken with grades received
  - GRE Scores
  - Other relevant information (career plans, internship experience, research experience, employment history)
- Give your writers stamped, addressed envelopes for mailing letters to the intended programs

What else?



Good Personal Statement (Letter of Intent)

- What are your interests in geology and how did you come to those interests?
  - - Why are you seeking a career in that field?
- What are your ultimate career plans?
- How will their graduate program assist with your plans?
  - - Have you done your homework about their program (e.g., type of program, orientation of program, faculty strengths, application requirements, etc) ?

How do I go about selecting a graduate program?

- Assess your ultimate career goals
  - Career in private sector
  - Academia
- Who to ask? (advisor, graduate students, professionals)
- Online (GradSchools.com/Petersons, etc.)

Should I skip the M.S. and go straight to the Ph.D.?

- Some schools (Harvard, Columbia, …) only admit doctoral students
- Some schools admit only to the masters-level

In general, you should exercise caution before electing to go straight for the doctorate.

How many programs should I apply to?

As many as seem reasonable. Application fees are typically $50+

Keep an "ace in the hole" – apply to a school where you are reasonably sure you will be admitted with support.

When should I apply?

The earlier, the better. Typical calendar for Fall admission:

- October 1st (latest) – take GRE examinations and arrange for letters of recommendation
- December 1st (latest) – send off applications
- December 1st thru January 30th – Application materials (GRE scores, letters of recommendation) arrive at graduate schools
- February 1st – Departments begin review of applications
- March 15th – Offers of admission
- April 15th – The deadline for telling schools whether you accept or not

Is the application enough?

Not unless you rely entirely on luck. Before you apply:

- Study each department carefully to determine if it meets your needs.
- Identify faculty with whom you might like to work.
- Call faculty and determine if their interests and yours coincide.
- If you are left with the impression that a person is a jerk – they probably are.
- When you have settled on a potential advisor – talk to one or more of their graduate students.

Who makes the admissions decision?

Undergraduate Admission:

- The admissions decision was almost certainly made by the admissions office based on your grades, class standing, etc.
- Your major department never saw your application.

Graduate Admission:

- Admission decision made by major department.
- Assistantship awards made by major department.

My friend and I applied for the same graduate program.

I have a better academic record than my friend who applied, but he was admitted with support and I wasn't even admitted. What's with that?

You're gonna pay me to go to graduate school?

- Teaching assistantships
- Research assistantships
- Fellowships

Ways to Do Research

- Solve a problem
- Answer a question
- Make it possible to do something new
- Make it easier / cheaper / faster to do something old

- What makes a research-grade problem?
  - Advances the state of the art
  - Chance of failure
  - More than implementation

How to Fail in Grad School

- Focus only on course work
  - It worked as an undergrad, right?
- Totally blow off course work
- Use your brilliance as a crutch
  - The smarter you are, the later you learn how to work hard
  - Nobody gets out of grad school without working hard
- Avoid reading papers
  - It must be a new idea if you thought of it
  - Invent your own terminology
- Don't ask for help; assume people know what you're doing
- Don't listen when people give you advice
- Do all your work from home

Succeeding in Grad School

- Balanced time management
  - Research, classes, TAing, etc…
- Be visible
  - And audible – talk to people and ask questions at colloquia
- Be proactive and persistent
  - 1% inspiration, 99% perspiration
- Read a lot (but not too much)
- Write a lot
  - Impossible to write too much
  - Write earlier rather than later
    - Writing kills bad ideas
    - Writing helps good ideas develop

Finding an Advisor

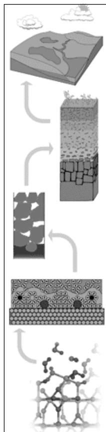
- One of the most important decisions you'll make
- Questions
  - Are you interested in the research?
  - Are your styles compatible?
  - Do you want a new professor or an established one?
  - Do you want a big research group or a small one?

Finding An Advisor

- How to answer the questions?
  - Surf the web, read papers
  - Talk to people
  - Interview at schools you are interested in
  - Start building relationships with faculty that can help you, and write you letters, now

What Penn State Can Offer You

- A large, collegial department
- MS—35 students
  - Recruited by petroleum industry, environmental companies or go on to Ph.D
- PhD—60 students
  - Academia, petroleum industry
- Dual Degree Programs: Astrobiology, Biogeochemistry (water science next!)
- A top ten program (Geology #3, Geochemistry #2, Earth Science #7 in U.S. News 2006)



Research Programs

- Astrobiology
- Earth surface processes/tectonics
- Earth system history/Paleobiology
- Geochemistry and Biogeochemistry
- Geophysics
- Geodynamics
- Hydrogeology/Hydrogeophysics
- Paleobiology
- Petrology
- Volcanology