Coastal Aquifer chemical mixing: Salt-water/freshwater stability issues and possible mechanisms for post-tsunami aquifer mixing

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Talk Outline

- Introduction to density driven mixing
- How does it apply to a tsunami inundated landscape
- Definition of the Rayleigh number and its importance
- Examples of unstable behavior
- Important limitations (heterogeneity)
- Possible observations of density driven flows in tsunami landscape and value of analysis and implications for aquifer cleanup.
- Nevada student programs in water technology transfer
- Questions

INTRODUCTION

- Fluid density variations in aquifers is common and results from many natural (such as geothermal sources) and anthropogenic (disposal of brines) mechanisms.
- The classic example of seawater intrusion represents a “stable” density configuration, with higher density seawater “sliding” underneath fresh water.
- However, even in “density stable” aquifers, convection or motion driven by fluid density gradients can occur.

What about the "Density Unstable" Case

- An unstable density situation can arise when a more dense fluid lies above (or to the side) of a less dense fluid.
- An example would be the infiltration of seawater (density ~1030 kg/m^3) on top of fresh ground water (density ~1000 kg/m^3) from the tsunami flood wave.
- However, just because the overlying fluid is more dense, this does not automatically imply that convection (or overturning) will occur.

Rayleigh or Bénard Convection

- In the early 1900, Benard observed hexagonal convection patterns in a fluid heated from below.
- This is the classic "tea kettle" example. Convection (free convection) occurs when the fluid cannot <u>conduct</u> sufficient heat to keep the density contrast between the top of the pan and the bottom "small".

Rayleigh Number

- Rayleigh in 1916 quantified the critical factors required for a fluid to begin to convect (with or without a porous medium in the way!)

$$Ra = \frac{U_c H}{D_0} = \frac{Buoyancy}{Dispersion}$$

- Where U_c is a fluid velocity, H is a characteristic length associated with the gradient in fluid density and D_0 represents diffusion and dispersion of the solute (or heat)

What about Aquifers

- For porous media, the velocity of the fluid is controlled by the permeability of the sediments, *k*, and the fluid properties (viscosity and the density contrast), and the resisting "force" is either the solute diffusion coefficient within the porous media or mechanical dispersion.

$$Ra = \frac{U_c H}{D_0} = \frac{gk\Delta\rho H}{n\rho\nu_0 D_0}$$

An Analogy

- Consider a "package" of seawater (dense) surrounded by fresh water in an aquifer.
- It would like to sink downward due to its density, but if it only sinks slowly, perhaps due to the low permeability of the sediments, then diffusion will wipe out the density contrast before it can sink far. It then becomes stable.

$$Ra = \frac{U_c H}{D_0} = \frac{gk\Delta\rho H}{n\rho\nu_0 D_0}$$

- In this case the Rayleigh number would be small (the denominator is much bigger than the numerator)

Critical Stability

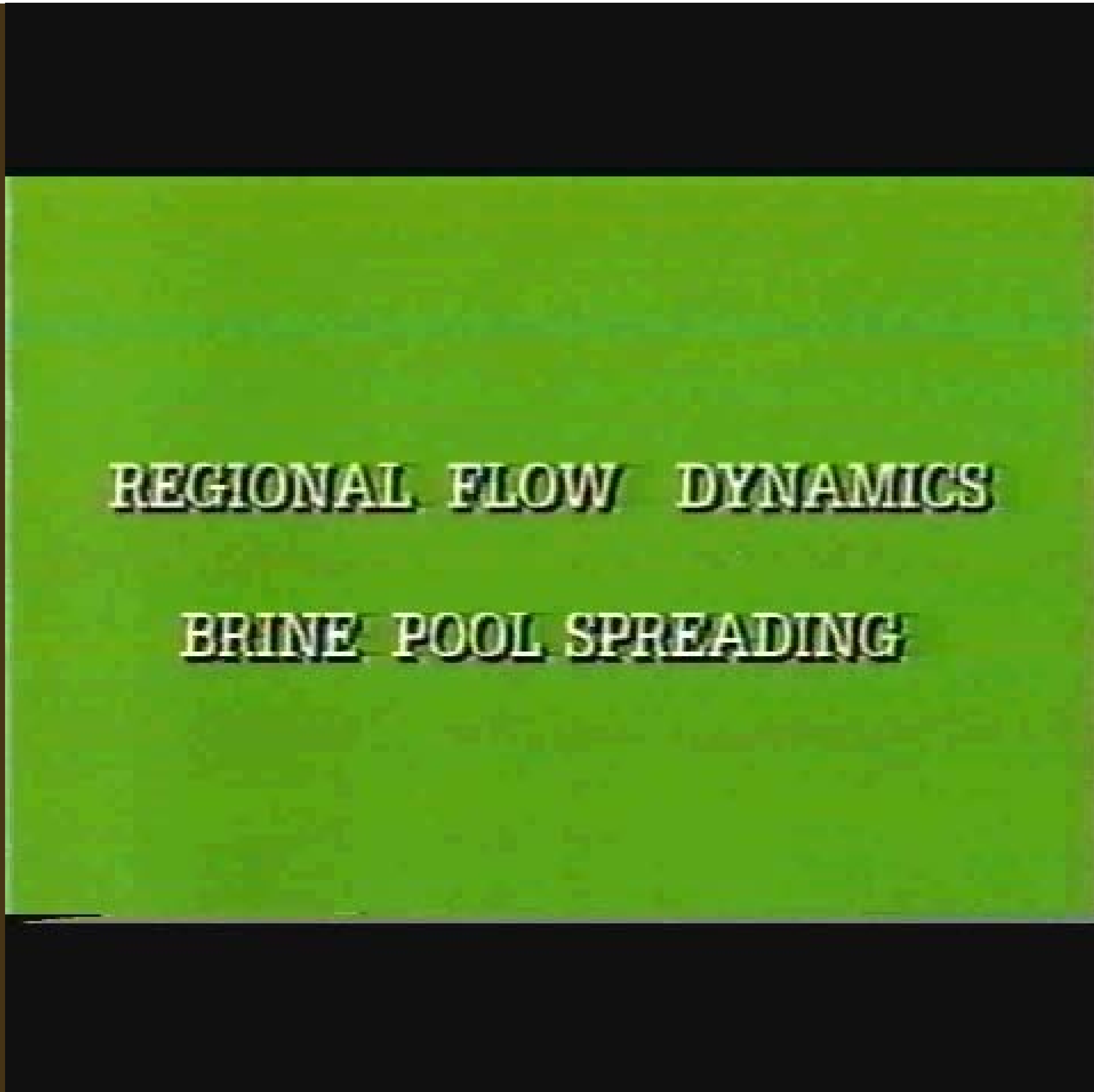
- The boundary between a stable fluid column and a convecting one has been defined, through linear stability analysis of the governing flow equations, for various geometries and boundary conditions.
- For a linear distribution of salinity, the “critical” Rayleigh number, Ra_c , is $4\pi^2$ or ~40. If Ra_c is greater than 40, the fluids will overturn.
- At Ra_c only certain wavelengths of instability can propagate downward.

“Back of the Envelope” Application to the Tsunami Wave infiltrating the Coastal Sand Aquifers

- We can assume a density contrast of 0.03 (seawater to fresh water), a solute diffusion coefficient of 10^{-9} m^2/sec and a viscosity of 10^{-6} m^2/sec.
- Assuming the Coastal Sand Aquifers to have a permeability of 10^{-12} m and the length scale over which the salinity contrast occurs to be 1 m, the Rayleigh number would be ~ 1-10, i.e. marginal stability, but as we will see later, very likely to produce convection and mixing in a natural system.

Physical Modeling of Convection in Aquifers

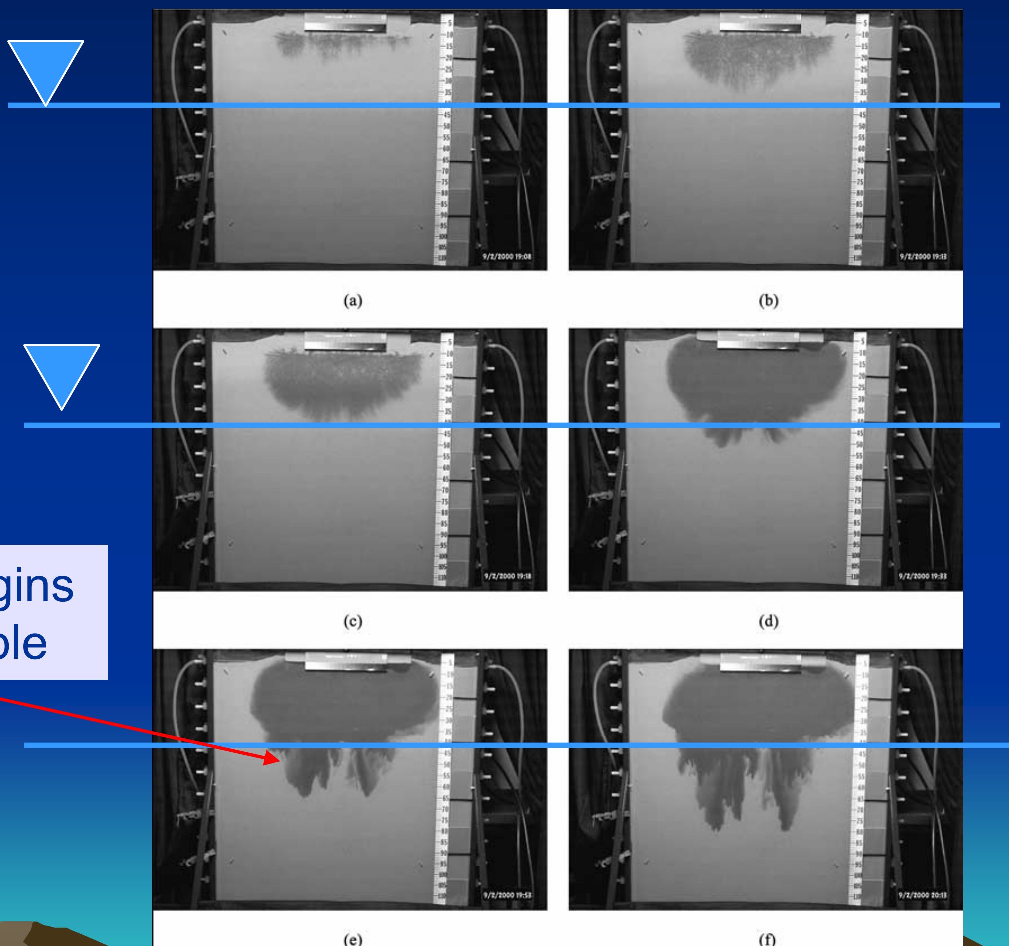
- Wooding et al (1997a,b) conducted stability experiments (both Hele-Shaw and numerical) to investigate the stability of disposing of dense brines at the land surface in Australia and the potential for ground water pollution.
- Unlike the Coastal Sand Aquifers, an upward ground water flow due to evaporation also helps stabilize the dense brines at the surface.
- The video begins with an addition of a blue dyed dense fluid on the left portion of the aquifer.


REGIONAL FLOW DYNAMICS
BRINE POOL SPREADING

Limitations of Rayleigh Stability

- Stability analysis assumes the aquifer properties to be homogeneous and uniform, unlike “real” aquifers.
- Recent work (Simmons, Schincariol, Menand and others) have shown that aquifer heterogeneity a) significantly reduces the critical Rayleigh number and b) reduces the efficacy of dense fingers moving downward (via mechanical dispersion).
- Heterogeneity will dampen instability growth, but at the same time, serve as the triggers for finger development!
- Role of unsaturated zone generally reduces fingering, and instabilities start at the capillary fringe (Simmons et al., 2002)

Infiltration of saline water into sands with a shallow water table

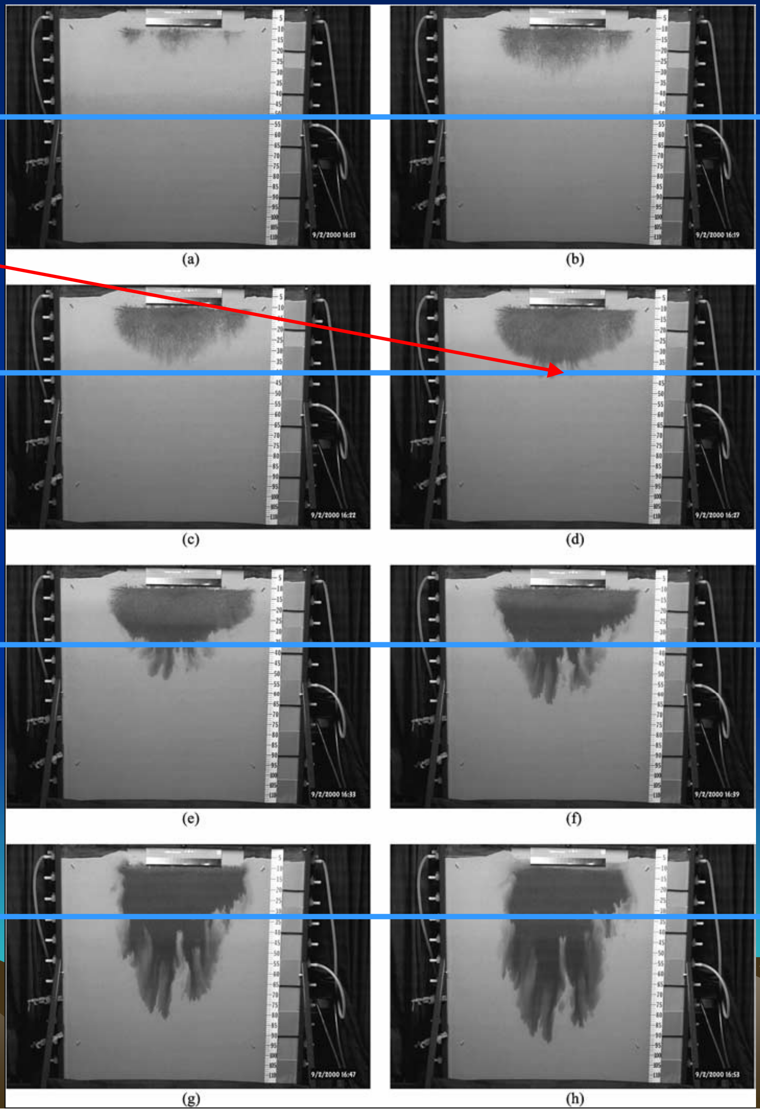


Density contrast ~ 0.04

Fingering begins at Water Table

(From Simmons et al, 2002)

Infiltration of saline water into sands with a shallow water table



Fingering begins at Water Table

Density contrast ~ 0.30

(From Simmons et al, 2002)

Modeling Unstable Phenomenon

- Simmons et al. (2000), using the data from the video shown, was able to reproduce behavior, however required very dense discretization and short time steps. He also observed that numerical instabilities produced “fingers” just as easily as nature!
- Wood et al (2004) and Menand (2005) have recently shown some success in defining “effective” dispersion coefficients for plume migration and convective mixing, but only for very mild instabilities.

Preliminary Thoughts on the Role of Density Driven Convection for Sri Lankan Coastal Sands

- High permeability of aquifers is very conducive to density driven mixing.
- Preliminary Rayleigh calculations show convection very likely.
- Convection likely to produce a rather uniform mixture of brackish water in the upper parts of the aquifer, with a seawater pool at or near the bottom of the aquifer (or salt water wedge)
- Given the low density contrast, using “effective” dispersion parameters may make numerical model very appropriate!

Preliminary Thoughts (cont.)

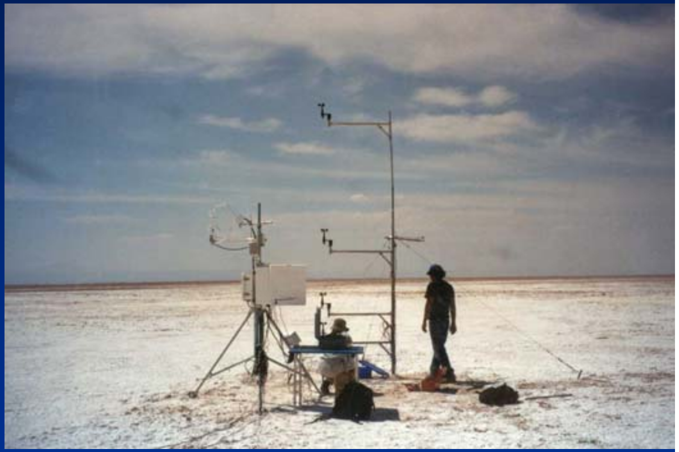
- Temperature may also be a very appropriate tracer of infiltration and mixing, if coastal ocean temperatures were significantly different from monsoon air temperatures
- Contamination, if density driven mixing has occurred, will unfortunately be widespread and require complete flushing of the aquifers.

UNR Student Association for International Water Issues

- **SAIWI formed by Univ. of Nevada students in 2001 to develop exchange/aid projects between UNR and developing countries.**
- **Provide technical assistance in developing countries for safe drinking water.**
- **Provide exposure and training to American students in international affairs and world politics.**
- **All volunteer effort, open to all UNR students; project funds primarily from donations.**

UNR's Hydrology Graduate Program

- Over 70 MS and Ph.D. Students Enrolled
- Ranked as one of the top programs in the US. Trained over 400 Water Professionals since 1967.



Areas of Expertise

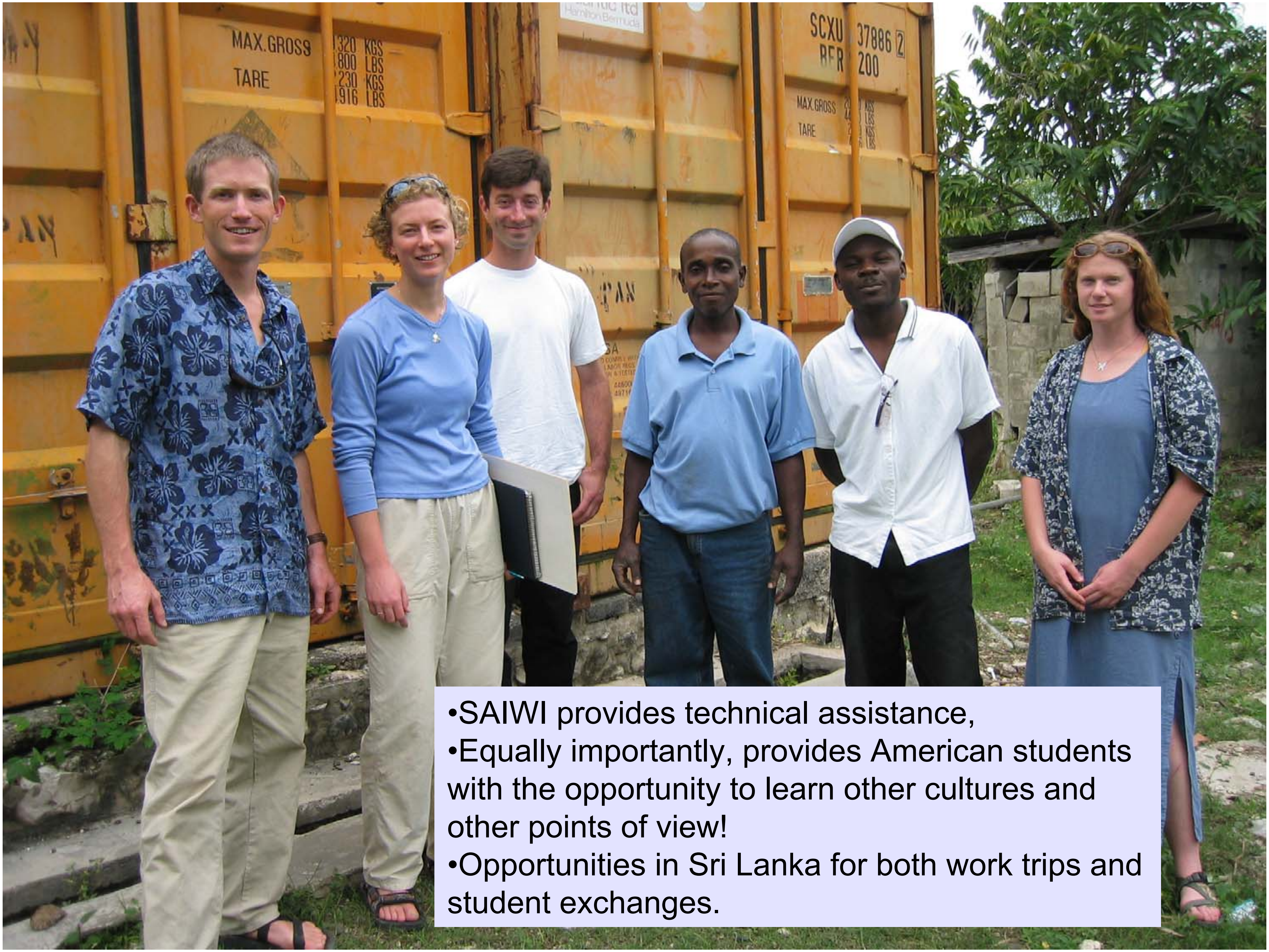
- We teach a hands-on water well drilling course each semester using mud rotary technology.
- Students are well-trained for water quality testing and well siting using appropriate geophysical techniques.
- GIS and GPS trained.
- Able to teach at local levels on hygiene and water quality.
- Willing to work and learn!

Typical Project

- We first network with government, established NGO’s and university faculty in host country to a) Define work needs and b) develop work plan that most effectively uses our expertise.
- 3-4 week duration, with 4-7 students (graduates and undergraduates) and one faculty advisor.
- Project(s) are well-defined, with goals achievable during our work trip.
- All funding is derived from donations and fund raising efforts locally.

Projects to Date

- Water well hand pump repair in Haiti (2001 and 2003)
- Drilling of water wells in Rabondo, Kenya (2004 and 2005)
- Arsenic and fluoride sampling in Ghana, Africa (2002)
- Rainwater harvesting design and fund-raising in Ghana (2004)
- Water related ecotourism development and assessment in Chile (2001, 2002 and 2003)



- SAIWI provides technical assistance,
- Equally importantly, provides American students with the opportunity to learn other cultures and other points of view!
- Opportunities in Sri Lanka for both work trips and student exchanges.