The Expanding Footprint of Natural Arsenic Contamination in Asian Groundwaters

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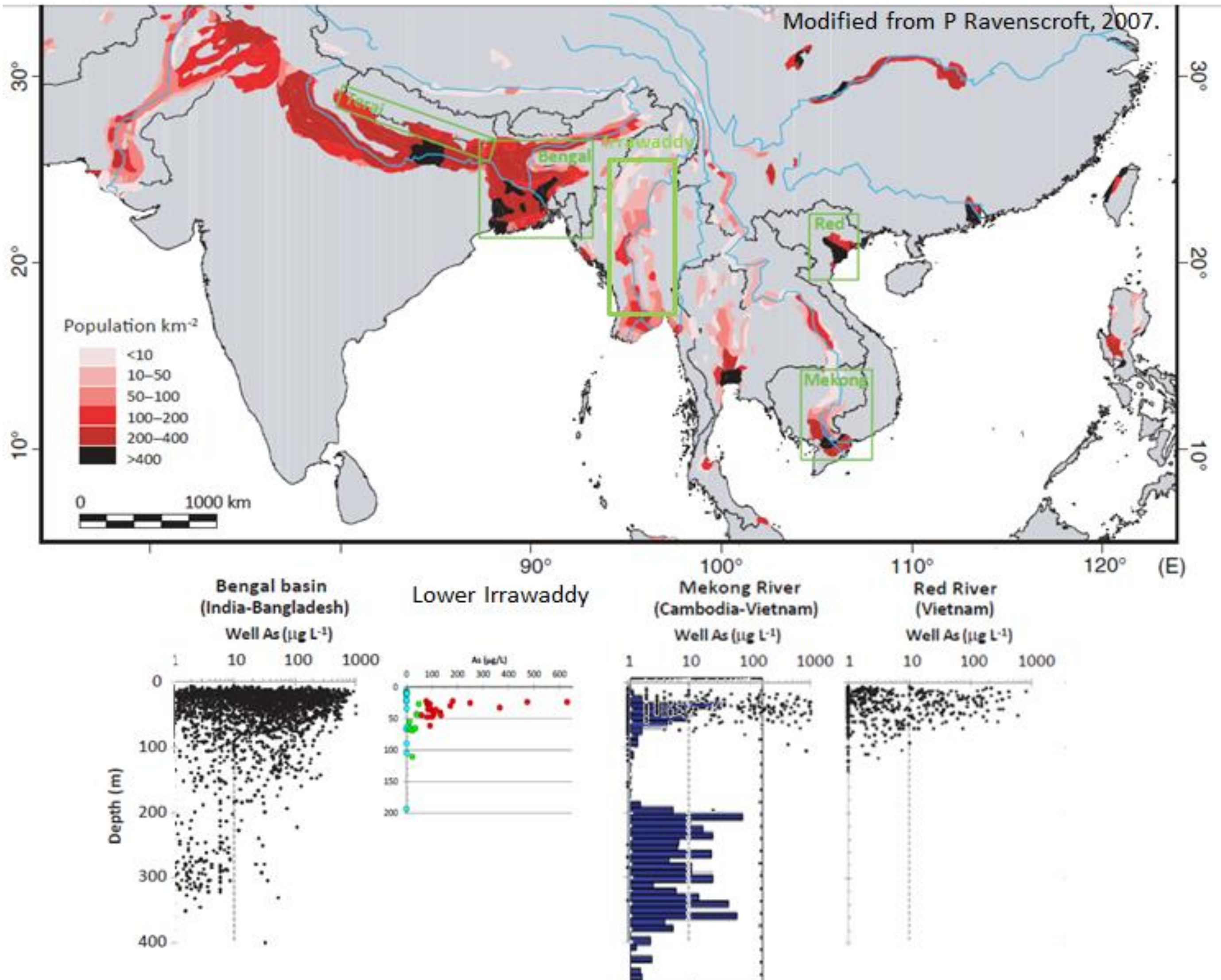
The Global Problem of Arsenic in Water



Erban et al.
PNAS 2013

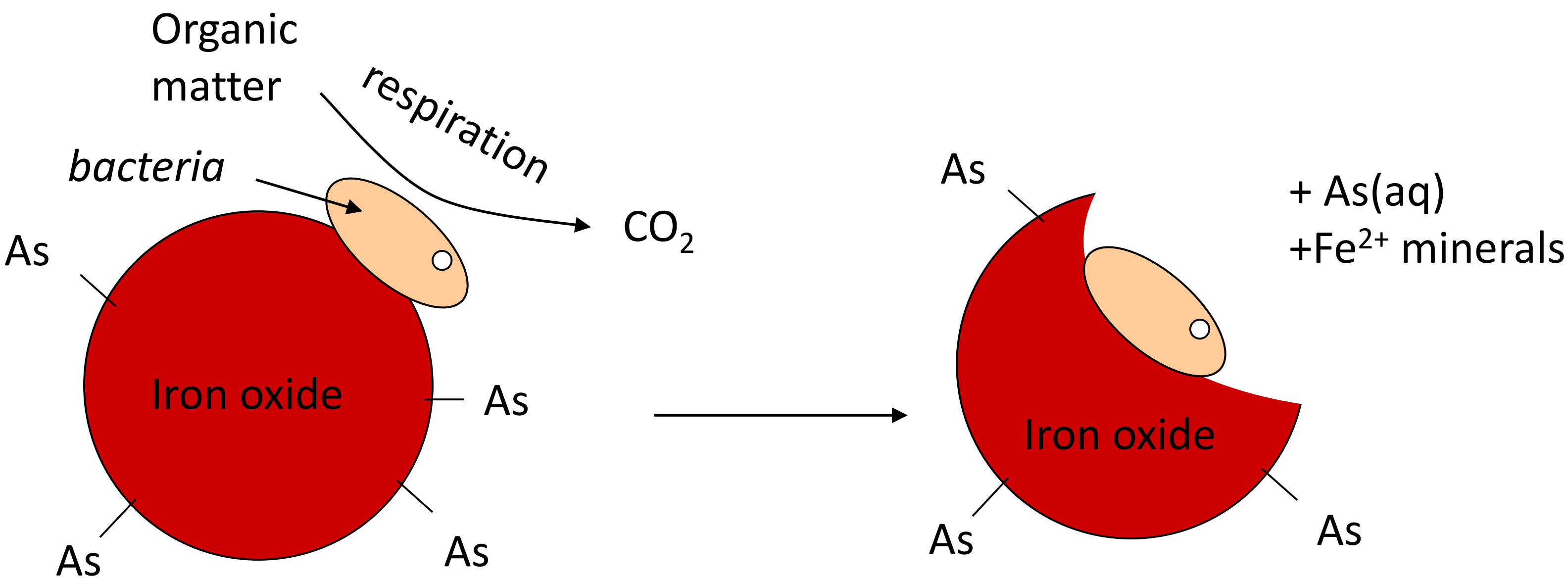
Figure 1a, b, c

Unsustainable Groundwater

Groundwater abstraction in mm/y (Wada et al., GRL, 2010)

- More than 2 billion people globally depend on groundwater for drinking.
- Agriculture uses more water resources than all other uses.
- The large river deltas of the world depend disproportionately on groundwater resources.
- Water quality is the largest single cause of death globally (5% of all DALYs)
- Arsenic in groundwater represents a major health risk globally, even at low conc.
  - Even in the US, arsenic is , after smoking, the most significant cause of cancer and a major contributor to diabetes and heart disease.

What Controls Dissolved Arsenic Concentrations in Wells?



- There is arsenic in most soils and sediments. Usually arsenic stays on the minerals, except when the bacteria "eat" the iron oxides in the soil (also using organic matter).
- Arsenic is normally strongly retained by iron minerals
- Microbes change (metabolize) the minerals in the soil and sediment, thereby releasing arsenic into groundwater.
- Availability of sediment arsenic, reactive mineralogy and sediment age all should impact As levels (must be As for there to be a problem)
- *Adding iron oxide is a common water treatment method to remove arsenic for this reason.*

Groundwater Abstraction and Arsenic

- Arsenic affects millions of people in Bangladesh and elsewhere.
- Well-switching (to low-As groundwater, usually in deeper wells) is the most common means of confronting the problem.
- Large-scale pumping of groundwater resources for drinking water and irrigation has profoundly affected the resource.
- Transport of high arsenic groundwater into low-As aquifers threatens the sustainability of well switching as a solution to the public health problem in Bangladesh.

Motivation

- To assess current and future water quality in the region, we need to know the following:
- *How does water use affect arsenic transport, organic carbon sources, fate and transport?*
  - *Transport: Water flow direction?*
  - *As transport: Where does arsenic come from?*
  - *Organic carbon: where does that carbon come from? Is it reactive?*
  - From where is reactive organic carbon derived?
- How have humans have influenced the answers to these questions?

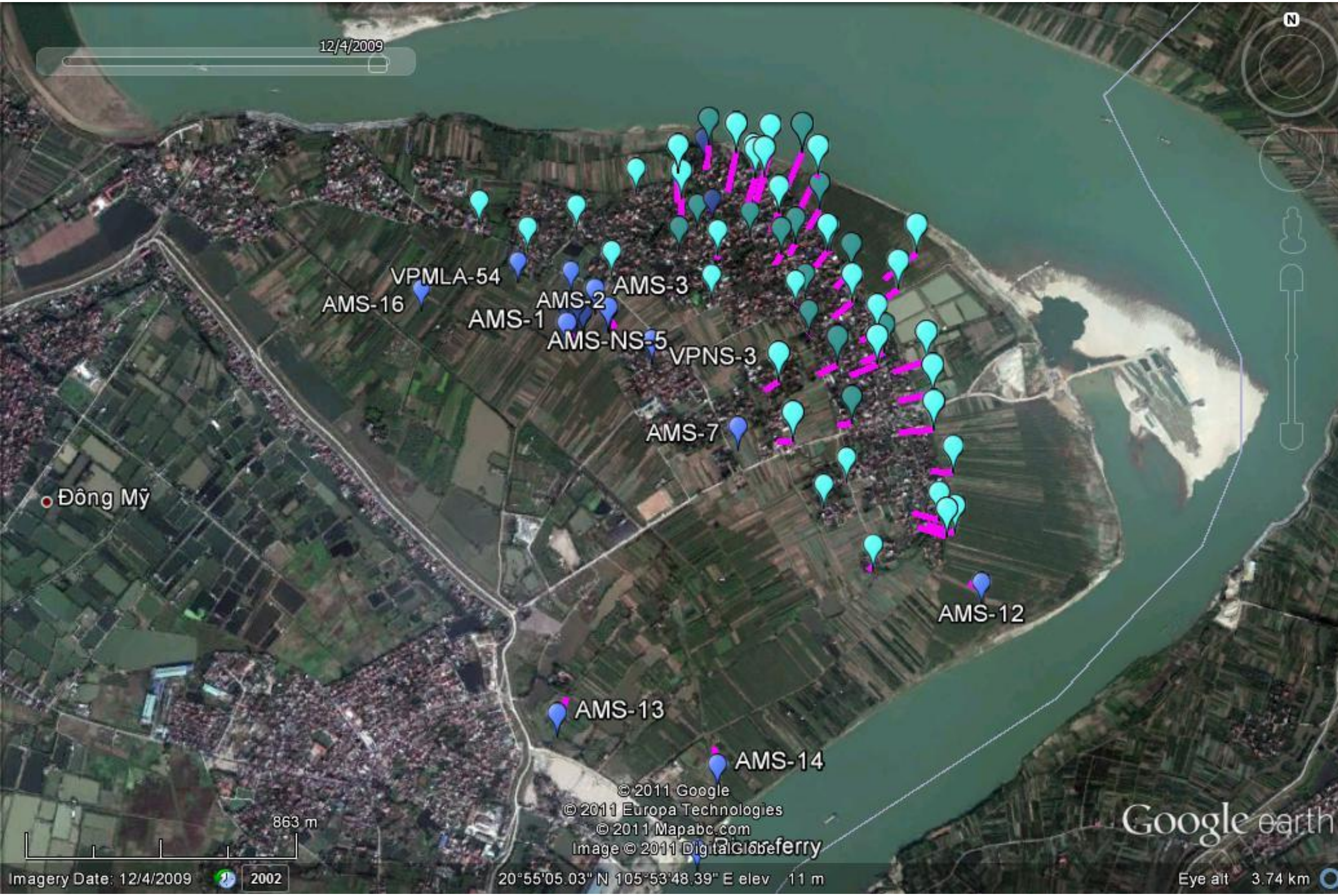

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Image © 2011 DigitalGlobe
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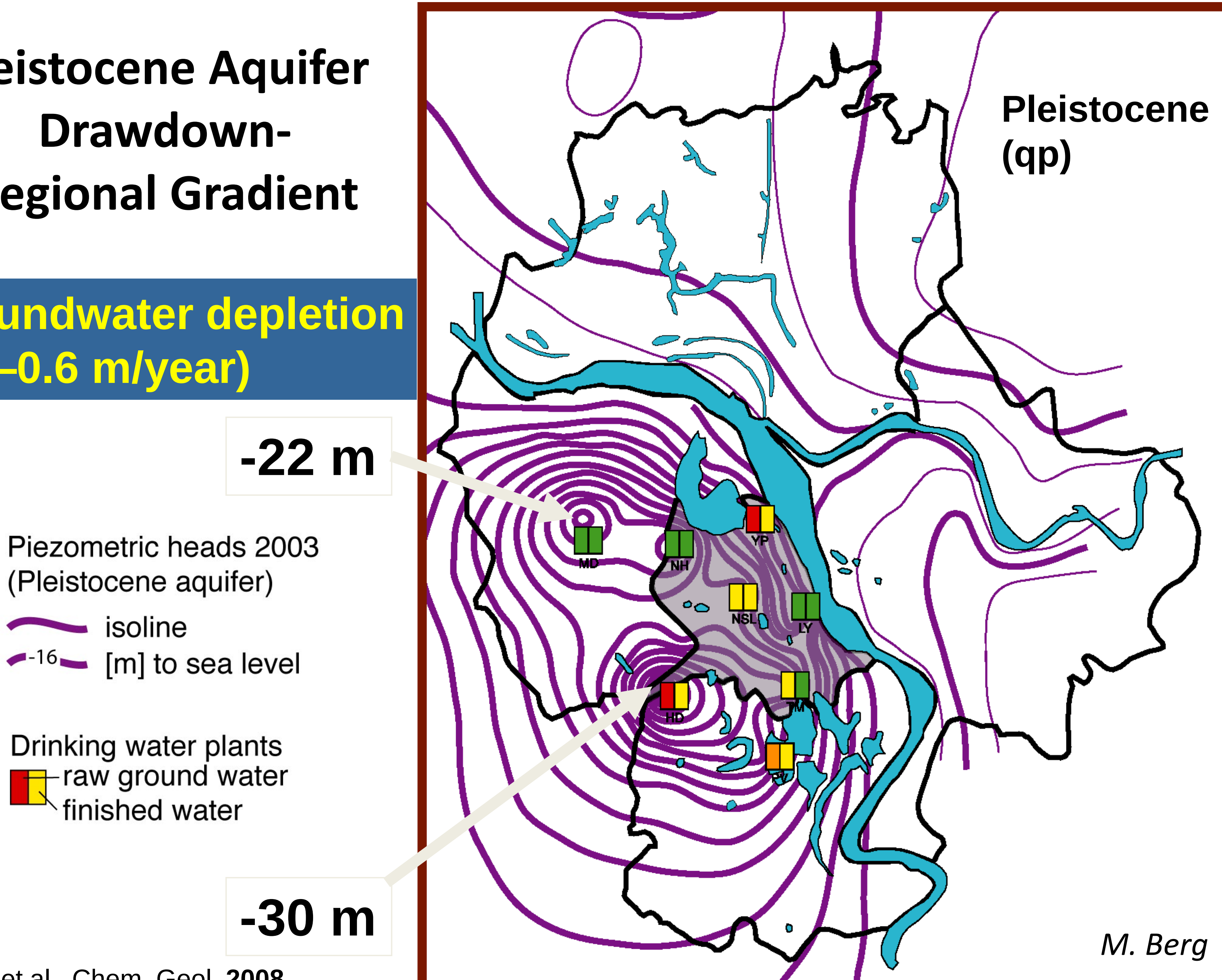
Google earth
Imagery Date: 12/4/2009
2002
20°55'05.03" N 105°53'48.39" E elev 11 m
Eye alt 3.74 km

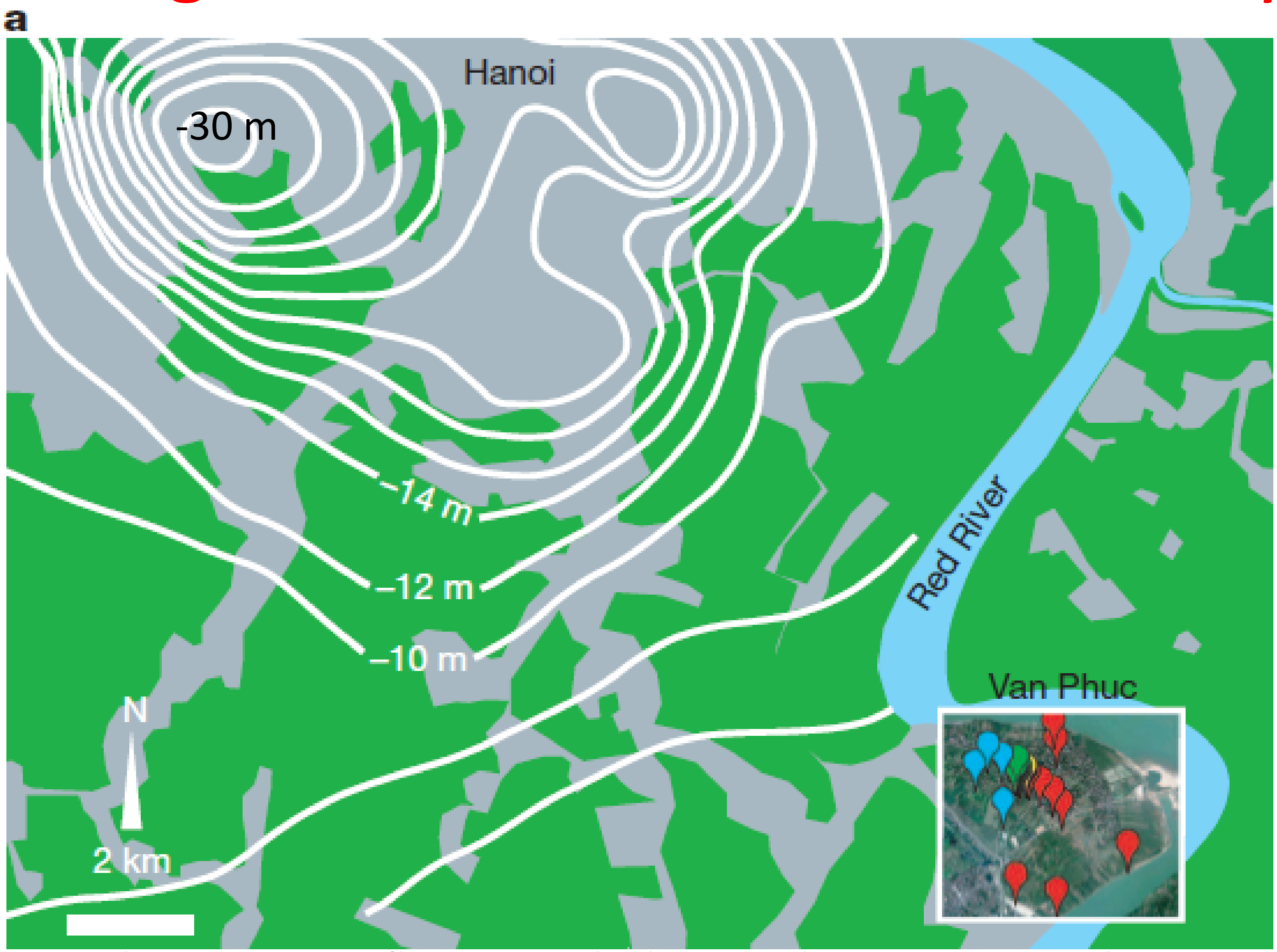
Pleistocene Aquifer Drawdown-Regional Gradient

Groundwater depletion (0.2–0.6 m/year)



Berg et al., Chem. Geol. **2008**

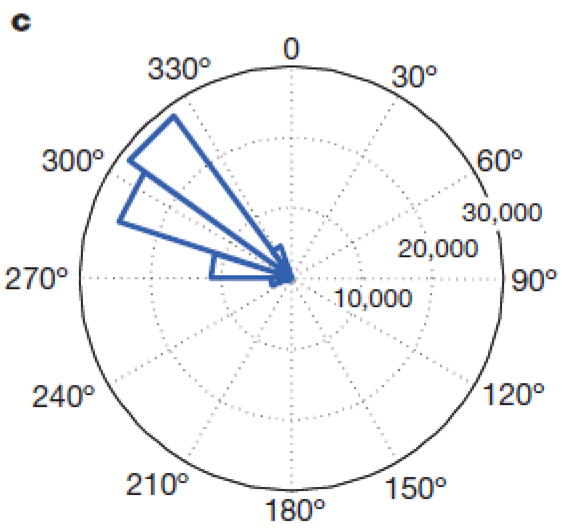
Regional Groundwater Flow Today



- Regional groundwater flow driven by large scale groundwater abstraction in Hanoi

Nature 501, 204–207 (12 September 2013)
http://www.nature.com/nature/journal/v501/n7466/full/nature12444.html

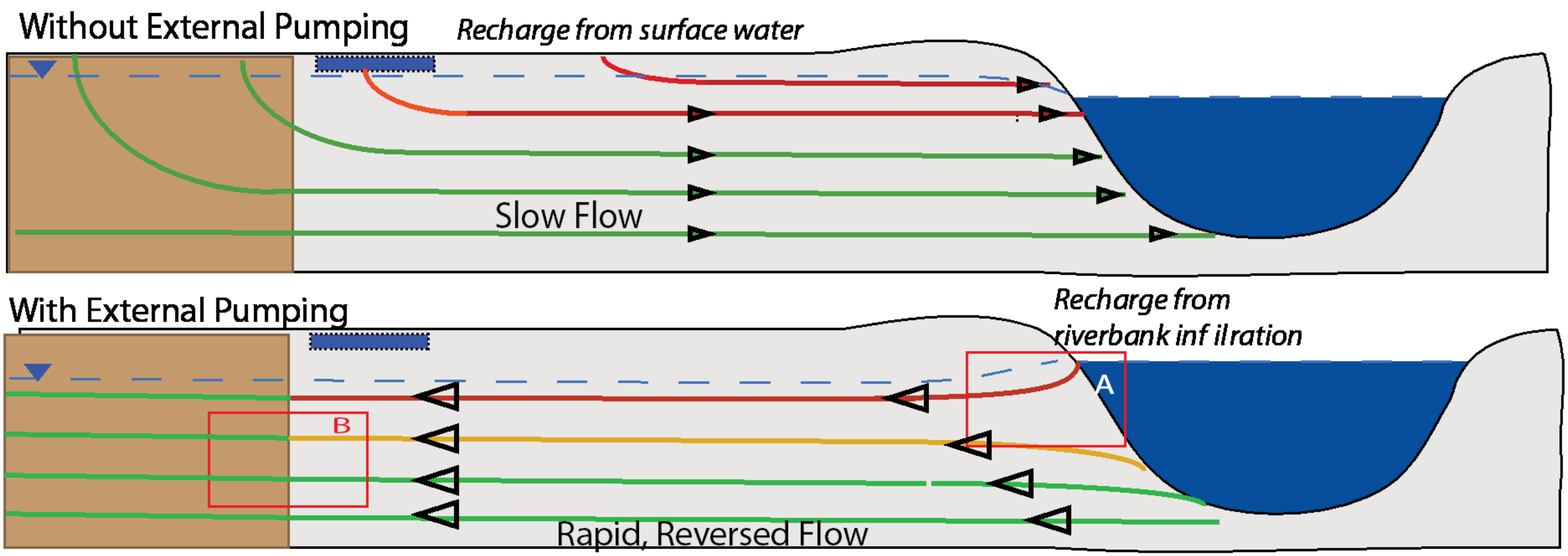
The Van Phuc Site: Transect



Nature 501, 204–207 (12 September 2013)
http://www.nature.com/nature/journal/v501/n7466/full/nature12444.html

- Groundwater Flow to the northwest, transect along flow line and crosses low-to-high As transition zone

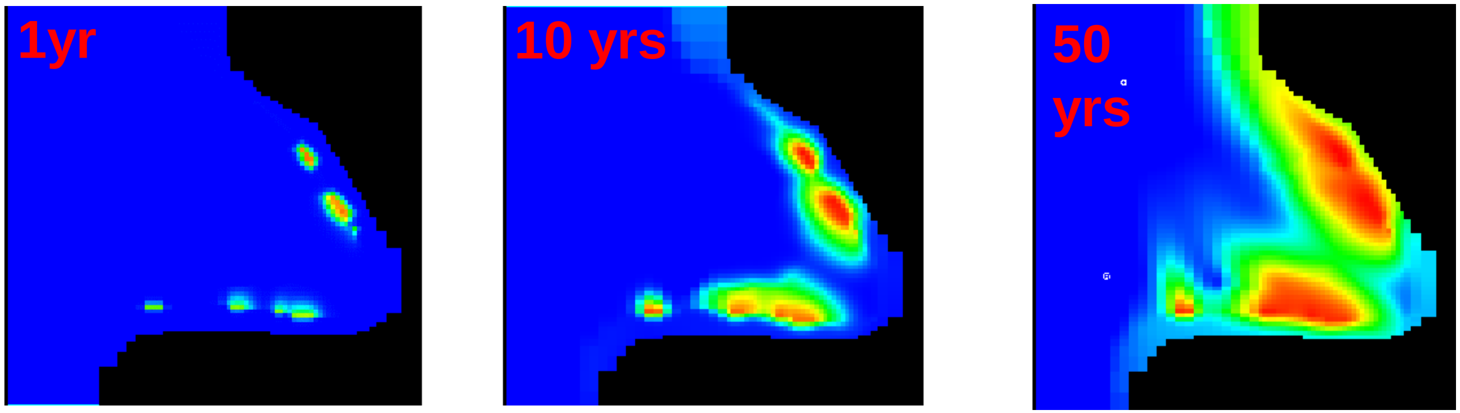
How Pumping Has Affected Flow and Recharge



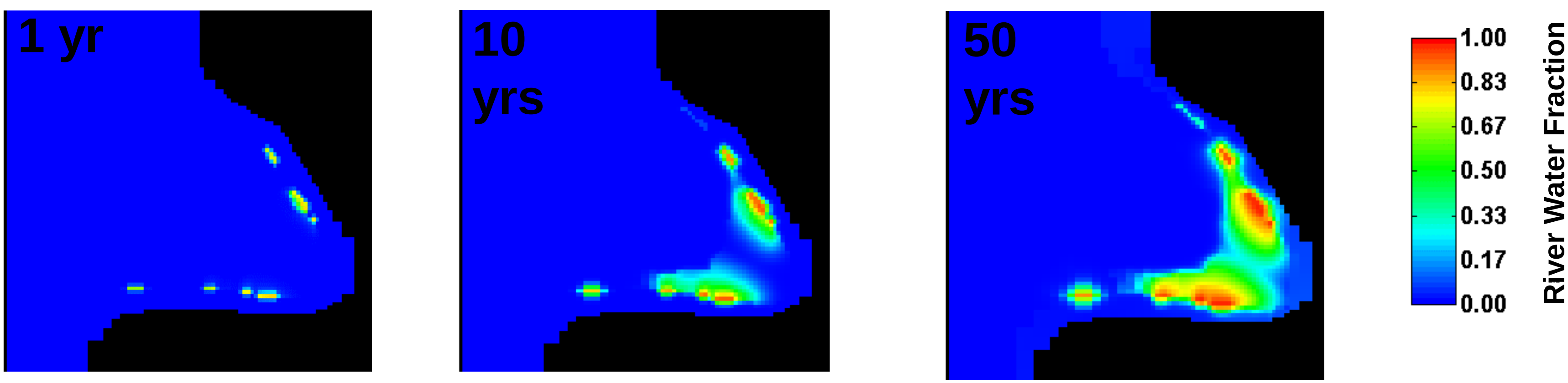
Conceptual model (top) for flow under natural and pumping induced gradients showing both a change in the direction and rate of flow (arrows indicate direction of of flow and are proportional to rates of flow). Boxes A and B represent reaction interfaces influenced by pumping, between surface water and shallow groundwater at points of infiltration (A) and at the boundaries between high- and low-As aquifers (B)

Modeling Groundwater Flow

Hanoi Pumping: Modeled River Water Inflow



Pre Hanoi Pumping: Modeled River Water Inflow

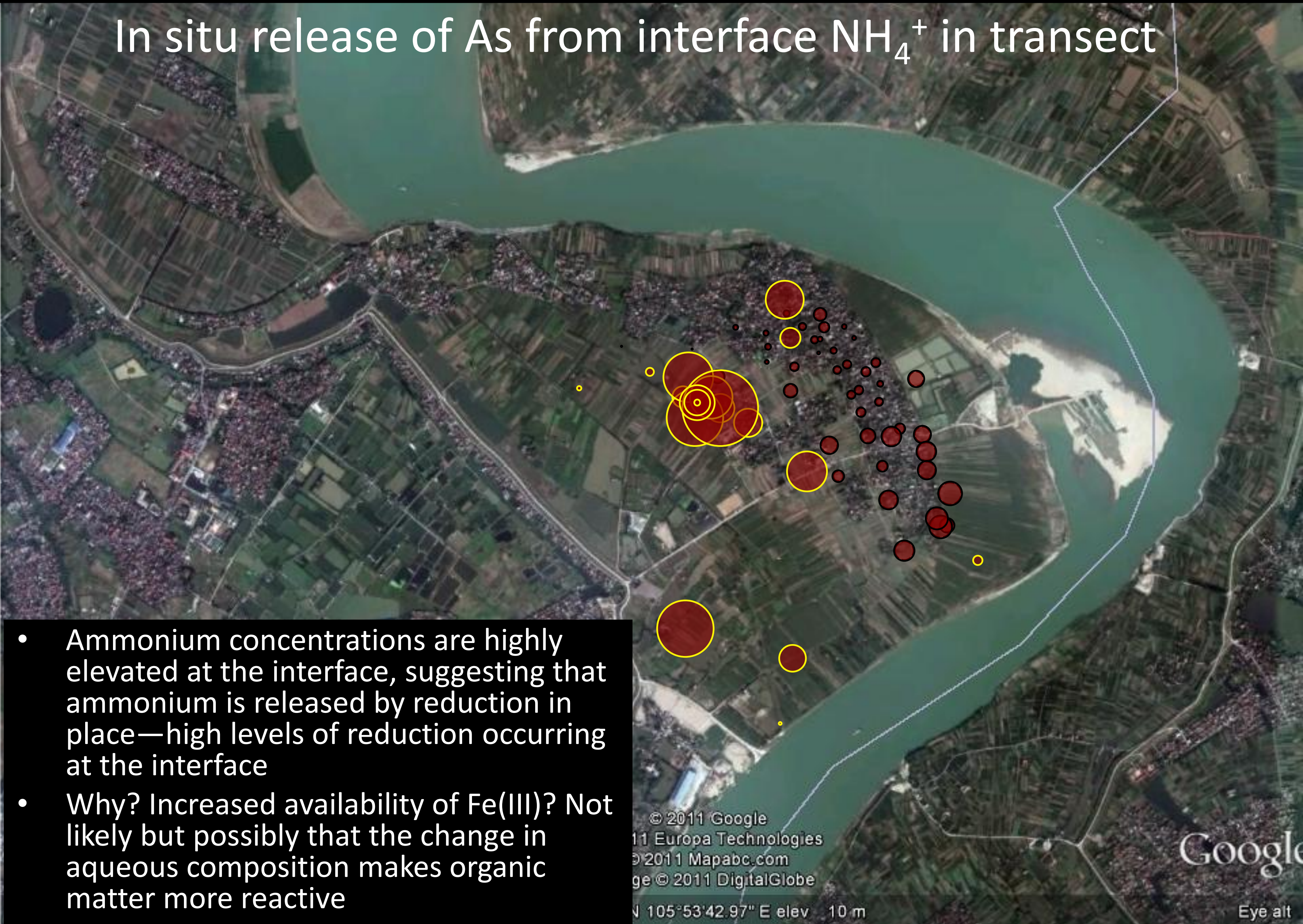


- Steady-state condition prior to groundwater pumping has limited riverbank infiltration relative to the case today (which is accelerating)

Impact of Flow Reversal on Arsenic Advection

- Me on the Red River, Vietnam

In situ release of As from interface NH_4^+ in transect

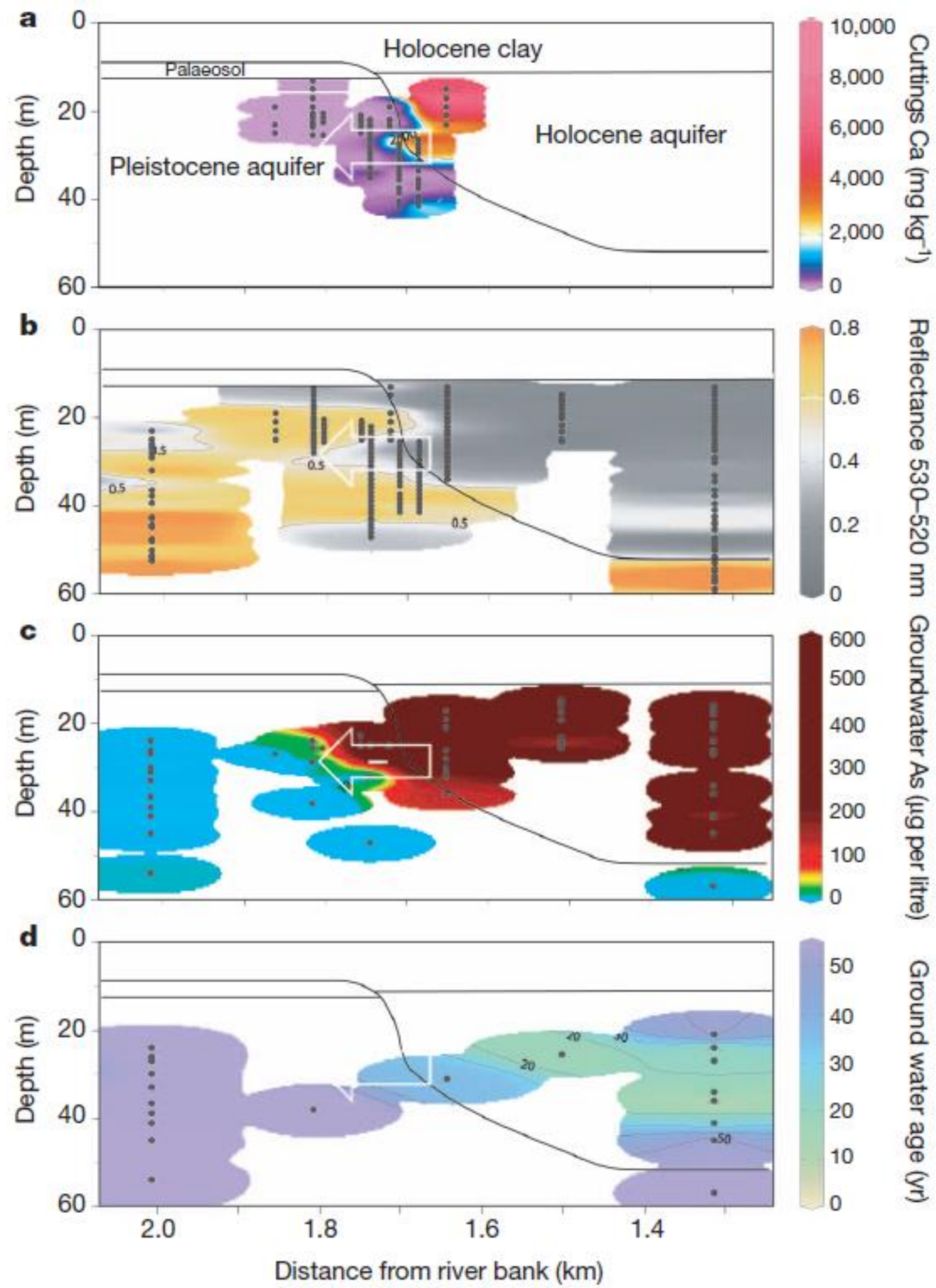


- Ammonium concentrations are highly elevated at the interface, suggesting that ammonium is released by reduction in place—high levels of reduction occurring at the interface
- Why? Increased availability of Fe(III)? Not likely but possibly that the change in aqueous composition makes organic matter more reactive

Transition Zone

- Challenge: We need to know where there is a contrast in sediment age, and to differentiate that from a gradient in water chemistry

- Result: The transition between young and old sediments is sharp at the site, but is also changing rapidly due to induced groundwater flow



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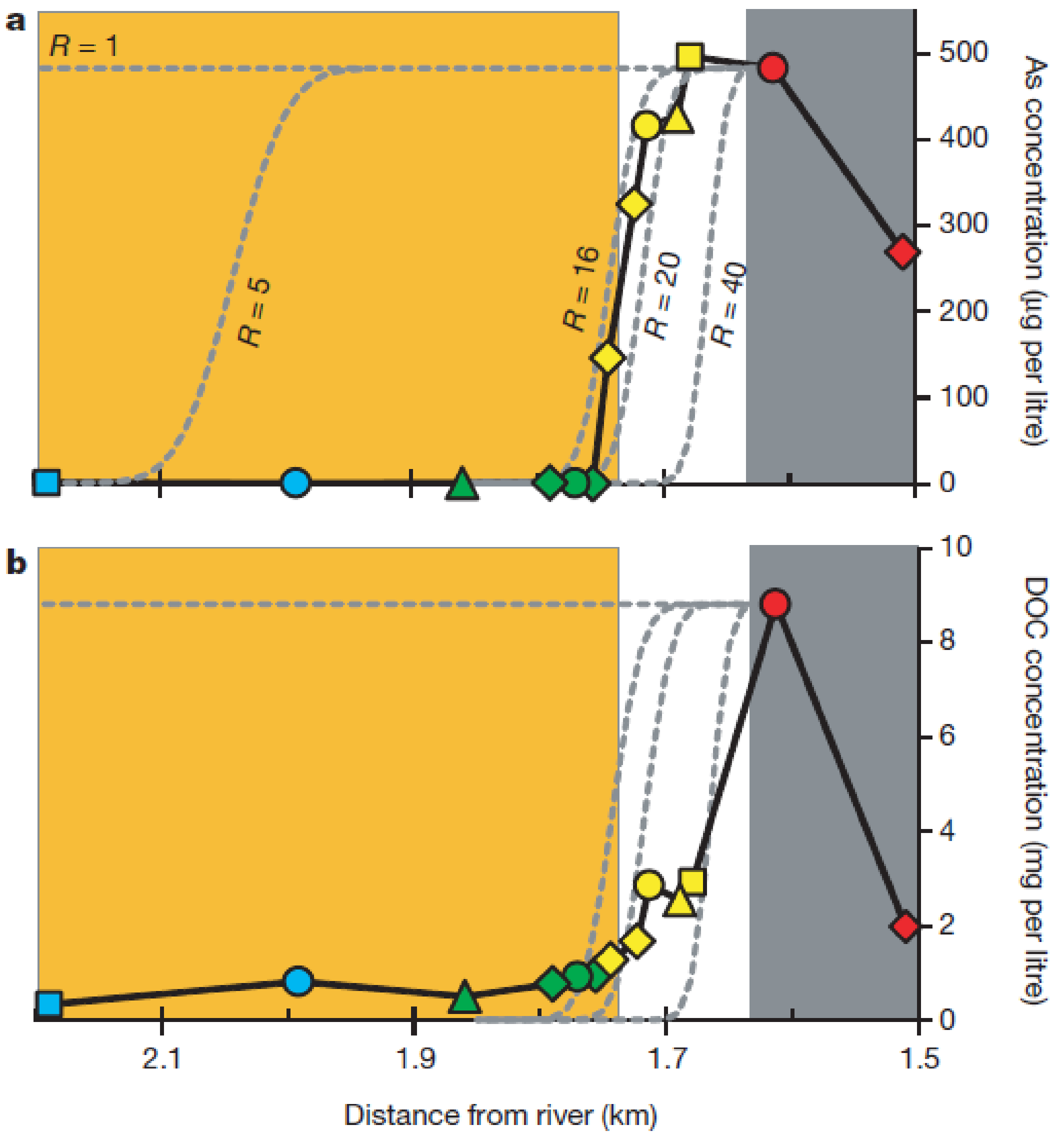
http://www.nature.com/nature/journal/v501/n7466/full/nature12444.html

Result: Advection of DOC and As



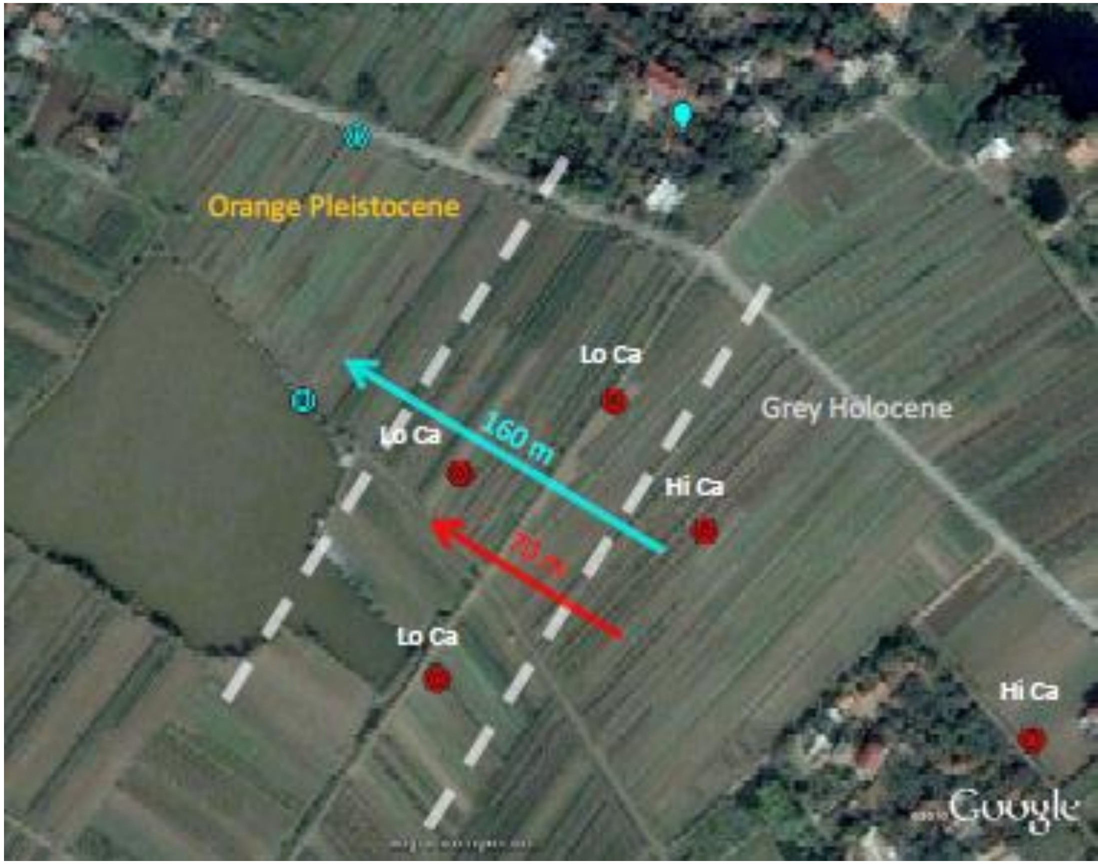
*The Plesitocene-Holocene transition at Van Phuc, Vietnam (**from Van Geen et al., 2013**). Flow right to left.*

TOP: the elevation of dissolved As at the transition zone between gray young gray sediments and older, orange sediments. The dotted lines show the retardation factors determined based on water flow velocities (bracketed by tritium dating) and observed As concentrations. A retardation factor of 17 corresponds with a K_d of 1.7 L/kg .

BOTTOM: The bottom panel shows the production of organic carbon within the Holocene sediments and its efficient removal or retardation down gradient. L/kg in the manuscript, using pretty standard porosity and density parameters.

Constraining Arsenic Transport

- Groundwater arsenic front moved at least 70 m and no more than 160 m in last 30 y, water flow in 30 y is ~1500 m (from T/He dating)
- Retardation factor R_f: 1500 m/(70 to 160 m)
  - **R_f = 9 to 21, or a K_d from 0.9 to 2.2 L/kg**
- Long-term advection at similar speeds would either have stripped all of the As from the system or require R_f > 500-1000.



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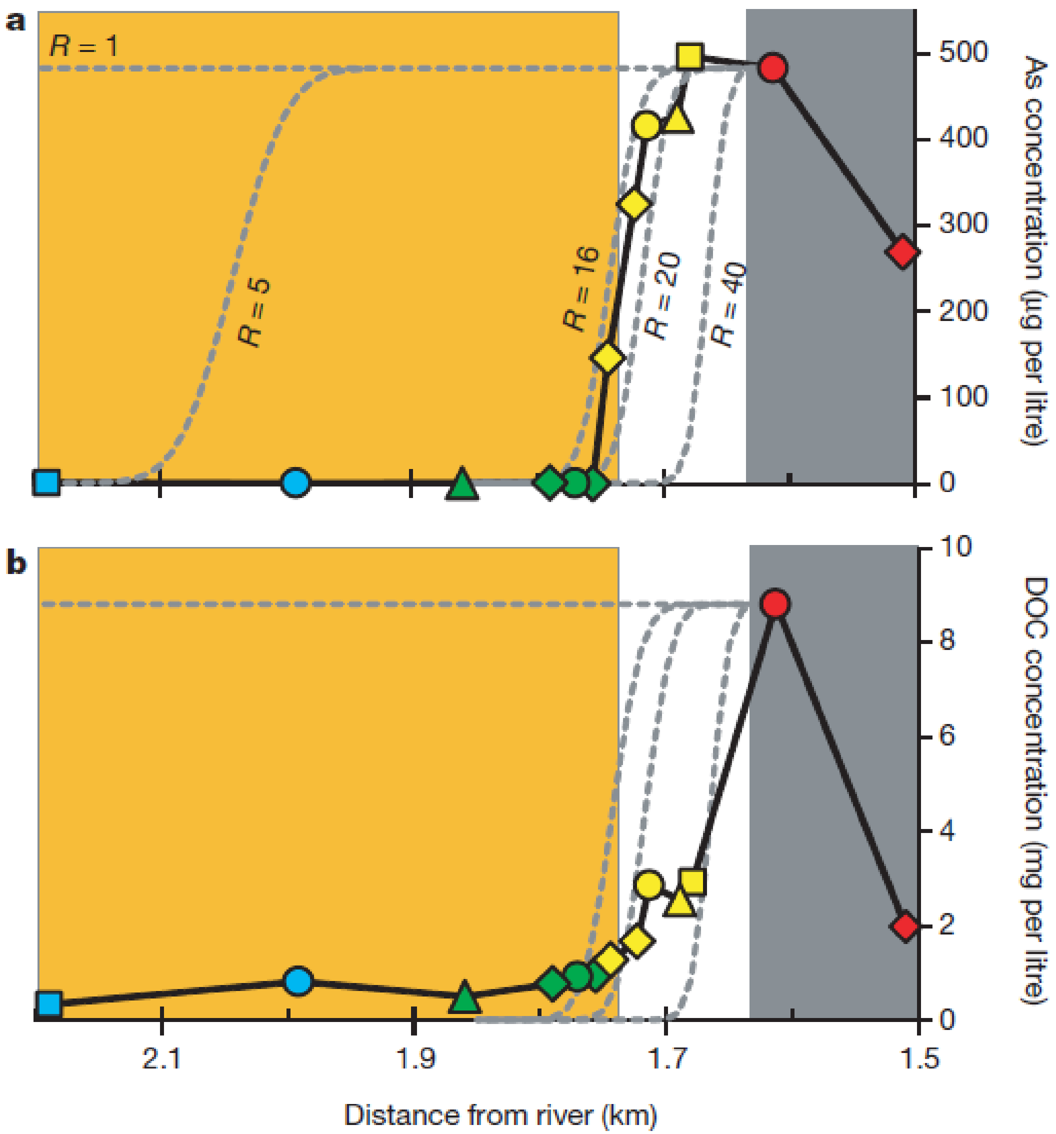

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Alternatives to Arsenic-contaminated Groundwater: A Case for Piped Water in Rural Cambodia

Benjamín C. Bostick[1], Andrew Schantz[2], Ashley Abernathy[2] , Chaing Chanthea[2], Thang Makara[2], Hok Phalla[2] and Bill Daniell[3]

(1) Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, bostick@LDEO.columbia.edu; (2) Resourse Development International, Cambodia; (3) University of Washington School of Public Health

Cambodia

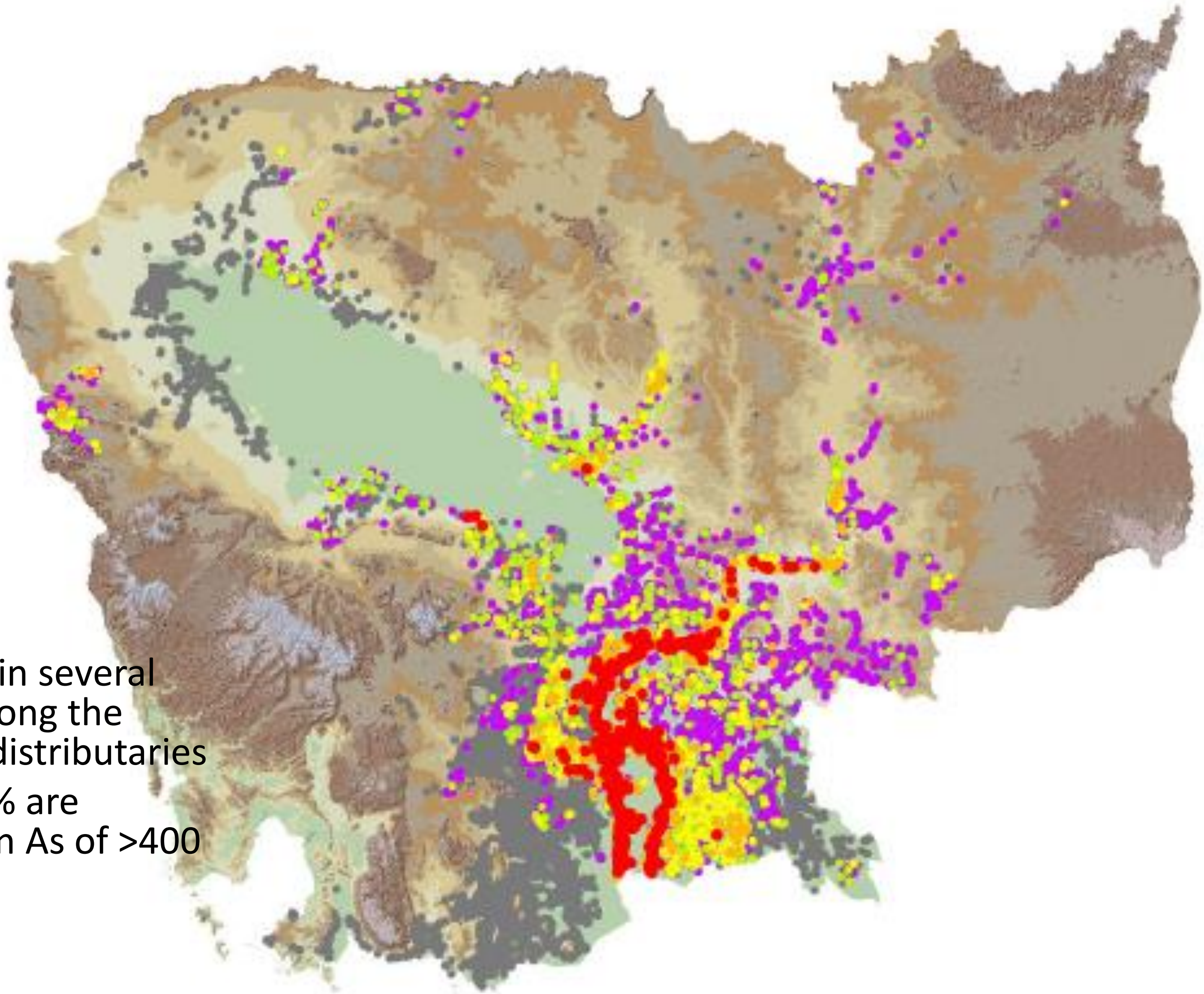
- Population: 15.4 million (2013)
- Rural Population: 12.7 million
- Per capita GDP: $1800 (PPP, 2013), median incomes of $1.70/day
- Growth rate: 1.63% (close to world median)
- Access to sanitation: <~22% (2012) in rural areas
- Numbers of people in high As areas: about 2-3 million

Tube Wells

- Tube wells provide water for numerous people the world over.
- Arsenic in groundwater represents a major health risk globally, even at low concentrations, particularly in groundwater.
  - Water quality is the largest single cause of death globally (5% of all DALYs)
  - Even in the US, arsenic is , after smoking, the most significant cause of cancer and a major contributor to diabetes and heart disease.

Cambodia

Arsenic in Cambodia



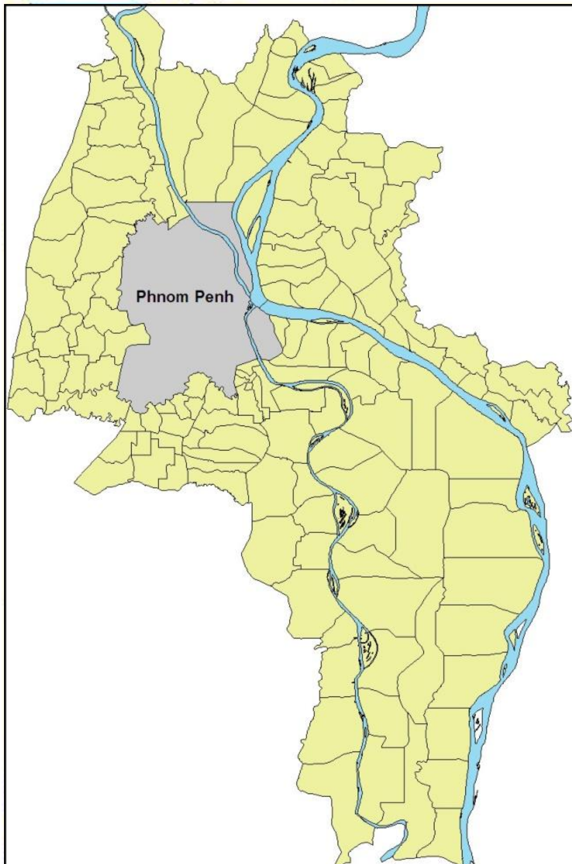
Purple: Non-detect
Green: ≤10μg/L
Yellow: 10-50μg/L
Orange: 50-300 μg/L
Red: >300μg/L

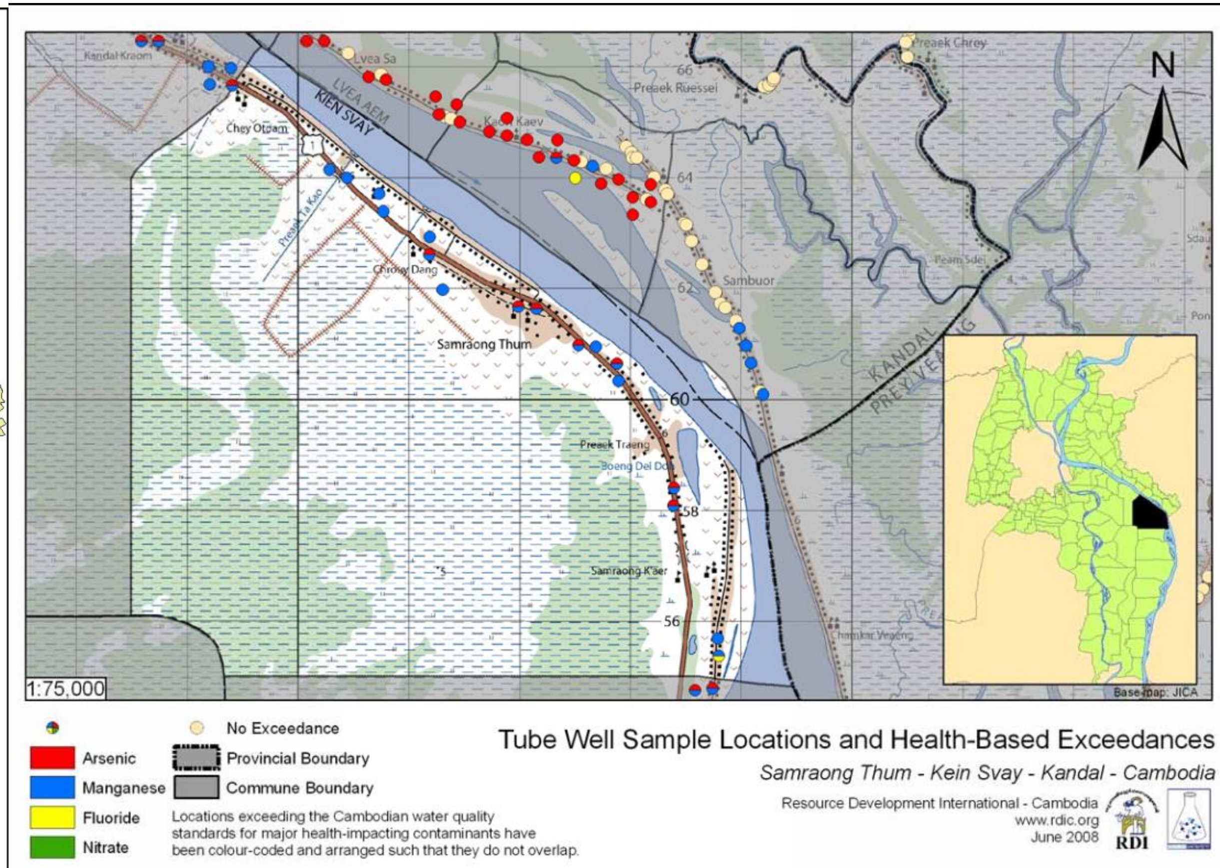
Arsenic is widespread in several provinces, primarily along the Mekong River and its distributaries

Kandal: more than 50% are contaminated, at mean As of >400 ppb

Arsenic in Cambodia: Drinking Water Quality Index Survey

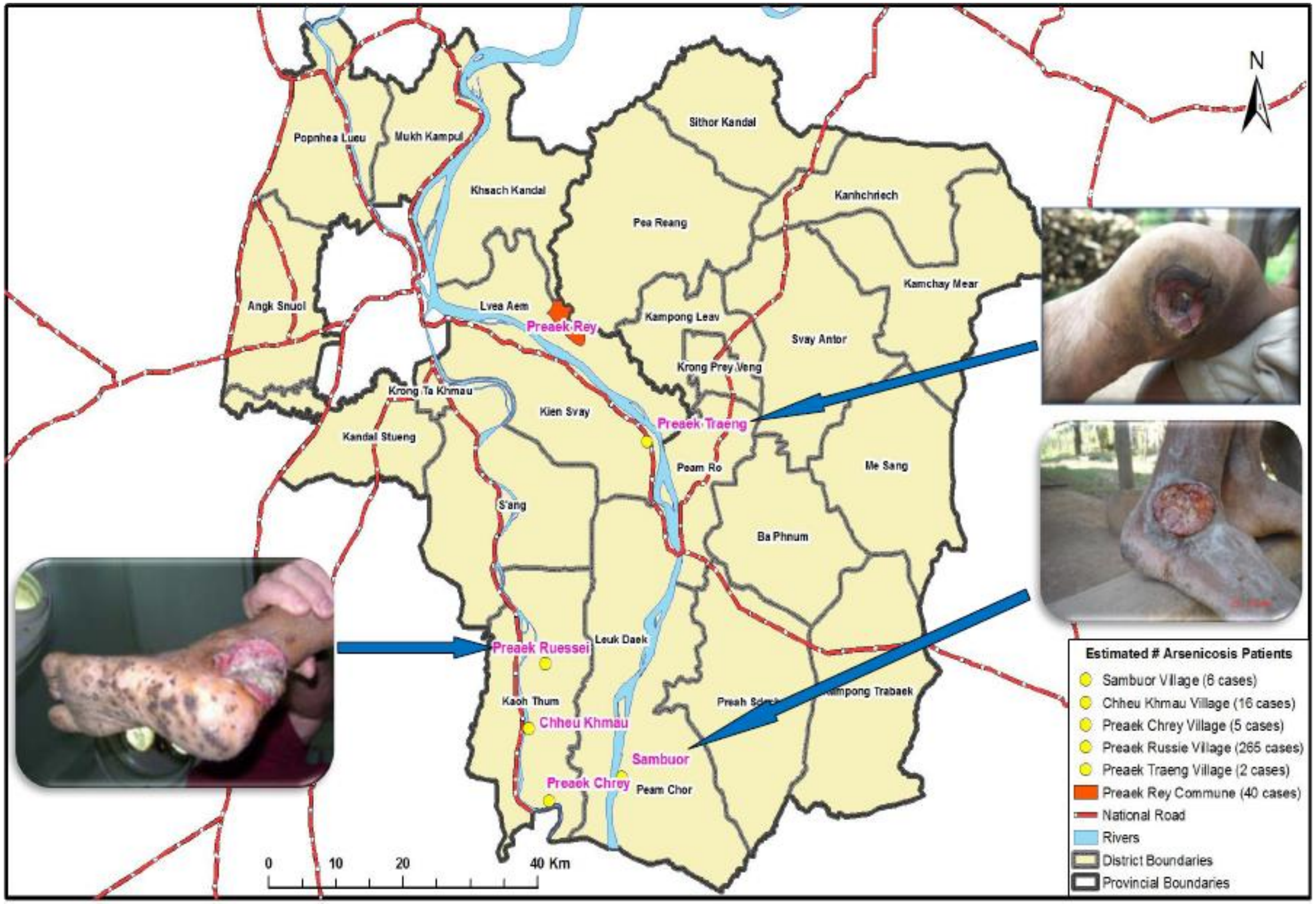
http://www.rdic.org/dwqi-home.php





- DWQI surveyed more than 40,000 wells for a diverse suite of water quality parameters in randomly selected households from each commune (village area, usually <1 km^2).

Arsenic in Cambodia



- Arsenicosis has been documented even in villages where groundwater use has been relatively short-term.

Research Questions

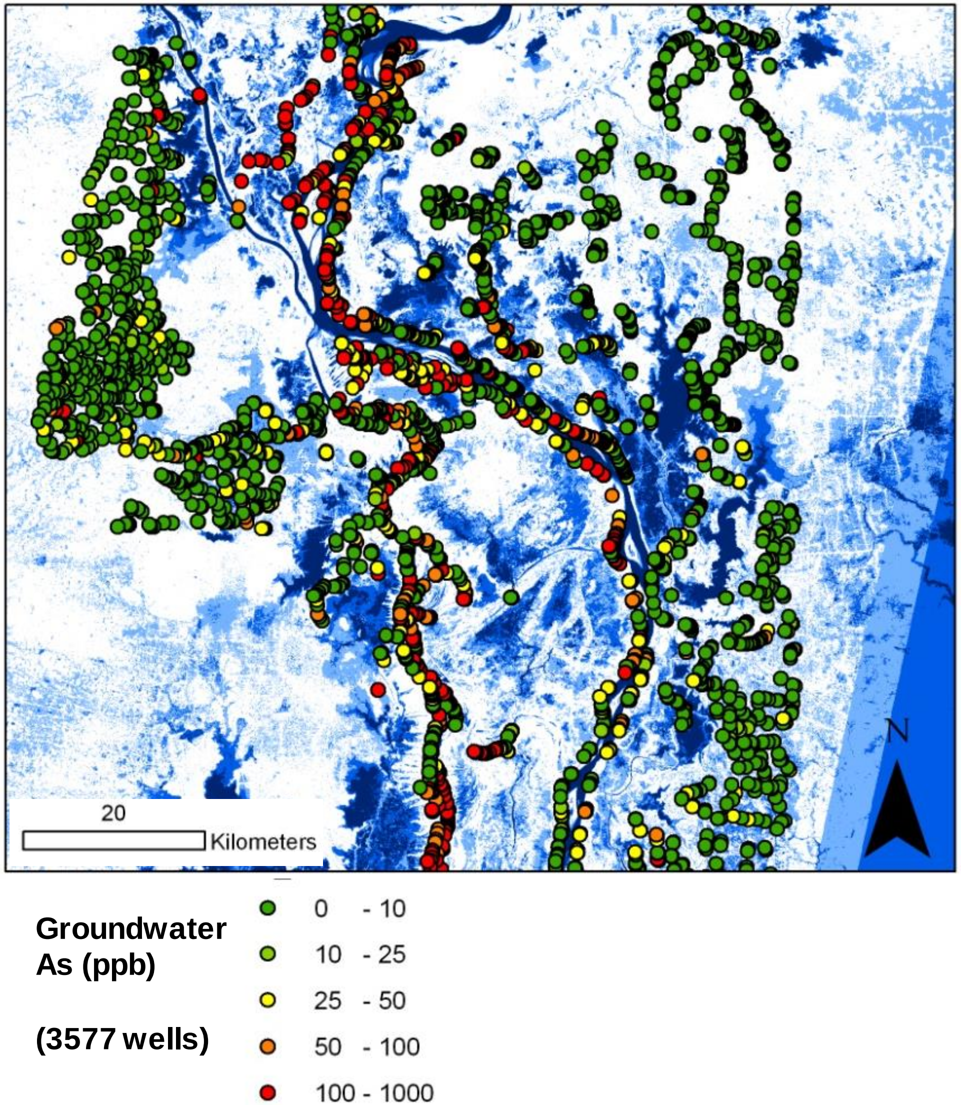
- *How does this groundwater use affect the long-term sustainability of these aquifers?*
- *If groundwater wells are contaminated with arsenic, what should we do (or what should others do)?*

Water Use in Cambodia

- Becoming a common water source.
- Still not used for irrigation (<3% of land is irrigated by anything other than natural flooding
- No urban pumping in most cities.
  - Largest city using groundwater is about 100k people, and uses high As groundwater source.
- Within the As-impacted areas, tube wells are widespread.
- The As concentrations in those tube wells in As-impacted areas are among the highest in the world (mean As = 450 ppb in high As areas of Kandal)

Water Use in Cambodia

Tubewell As Concentrations



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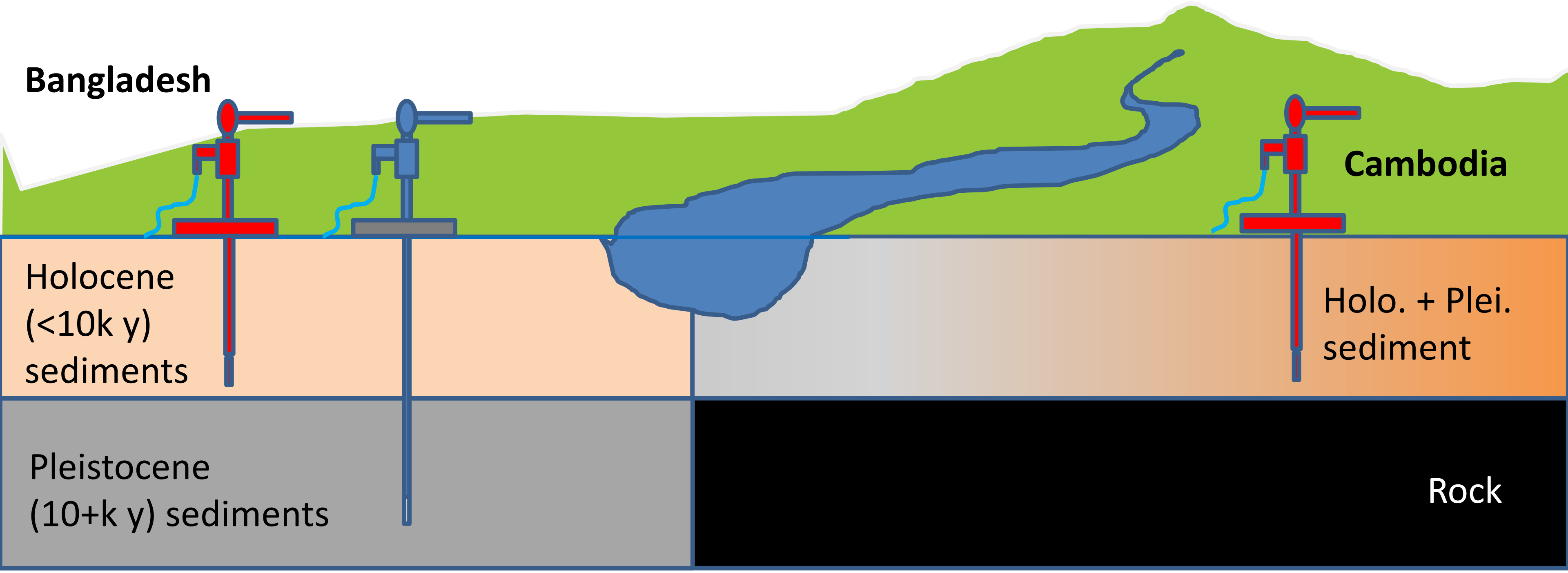
Potential Groundwater Alternatives



- Groundwater resources are limited by differences in the geophysical environment in Cambodia.
- There is little subsidence (sinking) over geologic time in Cambodia. That means that the sediments do not thicken very much, and that there is no accessible “As-safe” deep aquifer as a resource.

What kinds of water sources are used in Rural Cambodia?

Main Source of Drinking Water	1998 Census		2008 Census	
	Number of Households	Percent (%)	Number of Households	Percent (%)
Piped water	27,698	1.5	102,306	4.4
Tube/pipe well	277,657	15.4	681,192	29.5
Protected dug well	-	-	127,927	5.5
Unprotected dug well	810,042	45.1	559,016	24.2
Rain water	-	-	24,292	1.1
Spring, river etc.	561,220	31.2	618,579	26.8
Bought water	73,004	4.1	164,511	7.1
Other	47,884	2.7	33,235	1.4
Total	1,797,505	100	2,311,058	100

Source: National Census

What are the observed water qualities of each of these sources?
What are the differences in real costs of these different water sources?

Evaluating Potential Alternatives

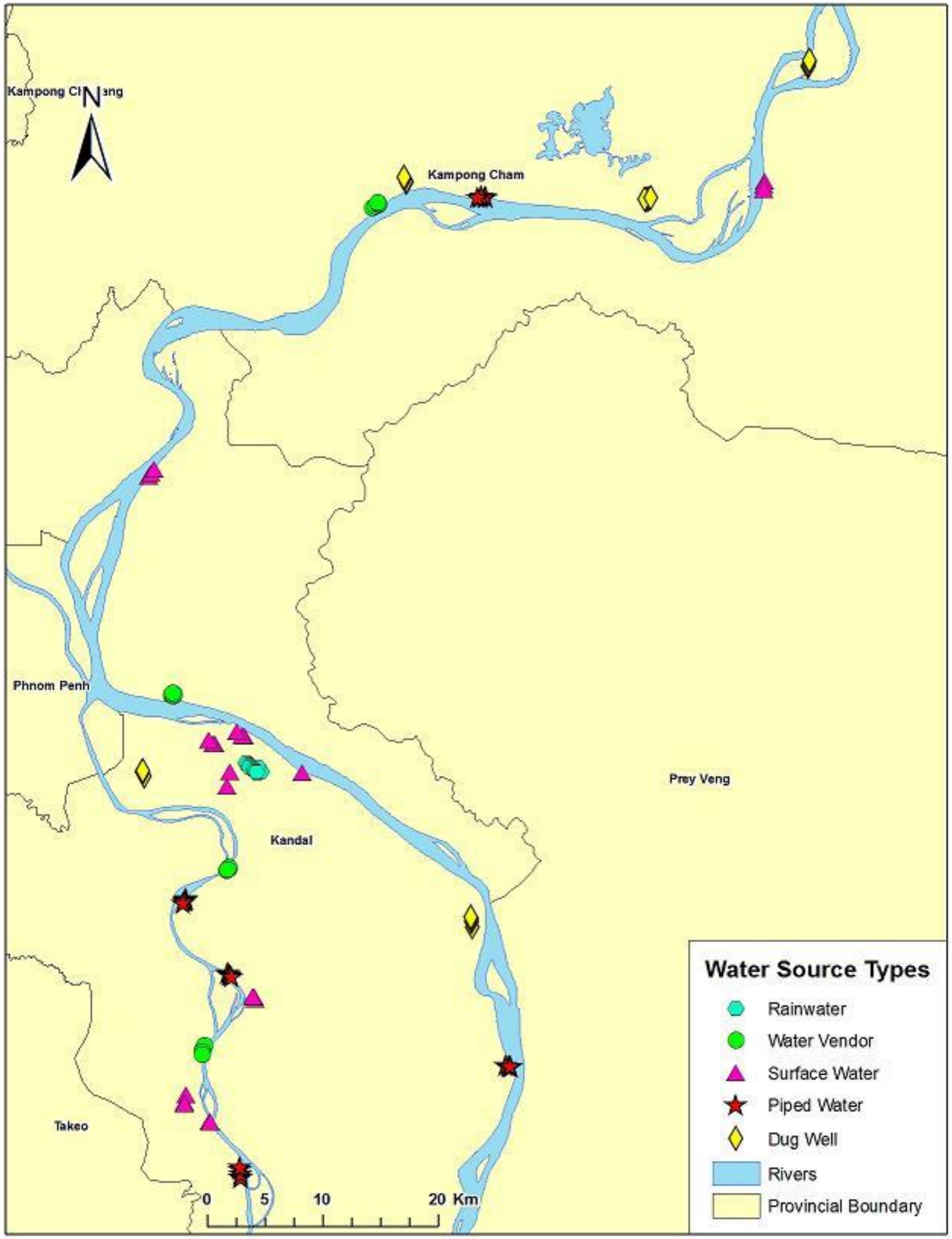
- We have designed a study to compare the water quality and human factors that affect water source selection.
  - Survey: randomized sampling of households within non-random communities (chosen to contain representative water use types)
    - >95% participation (few nonresponses were not refusals, but caused by the lack of a head of household), approximately equally distributed over water source types.
    - More than 400 respondent households.
  - Practitioner survey: Used to determine actual system costs.
  - Water quality measured at the source, during storage, and at the point-of-use (following any secondary treatment).

Water Quality: What is Safe Water?

CRITERIA

- Low As. Ideally WHO Standard of 10 µg/L, or Cambodian standard of 50 µg/L.
- Free of other chemical contaminants like F, Mn, U, Ra, or pesticides. Of these, Mn and F are common in some areas, and others (U, Pb, pesticide) are relatively rare.
- Low levels of biological contamination such as fecal coloform and rotovirus.
- While this set of criteria is straightforward, it is often hard to identify water sources that meet all of these standards as encountered in the environment.

As a result, water treatment is often used to improve water quality prior to use. For example, arsenic and phosphate can be removed by flocculation with iron or aluminum colloids, or water can be boiled or filtered in various ways to remove biological or chemical contaminants.



What is the water quality of existing water sources?

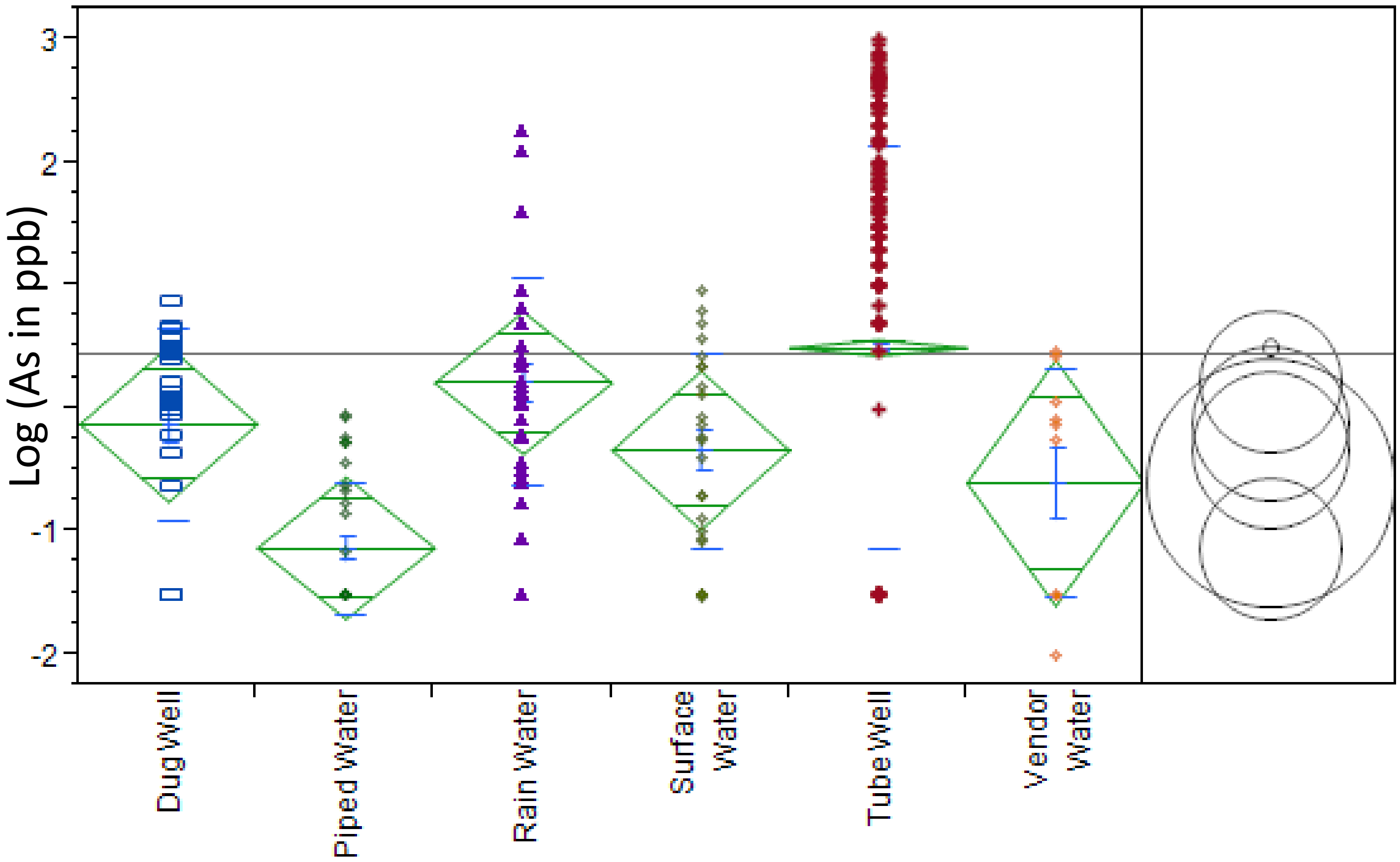
- A number of villages with known dependence on specific water sources (determined by National Census), were chosen to measure water quality parameters.
- ***Water quality was measured from their sources (as stored).***
- These measurements can be compared with a large survey (>40k wells over 5 provinces) in the Drinking Water Quality Index Survey (DWQI).

Point of Sampling

Water Supply Option	Point of Sampling
Piped-water Supply	From pipe (before storage at household)
Water Vendor	From storage jar (during storage at household)
Rainwater Harvesting	From storage jar (during storage at household)
Dug Wells	From dug well (before storage at household)
Tube Wells	From tube well (before storage at household)
Surface Water	From surface water body (before storage at household)

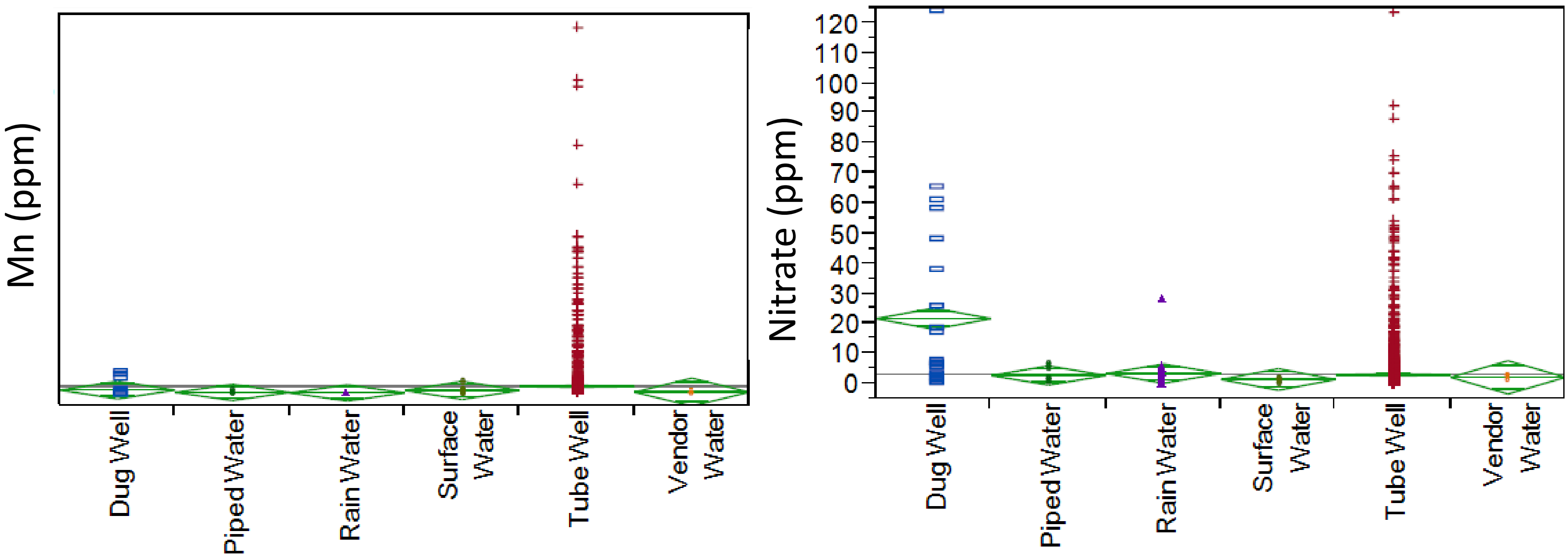
- Affected by Storage. Therefore, we also have measured water following storage, and at the point-of-use (after treatment).

Alternative Water Sources :Water Quality



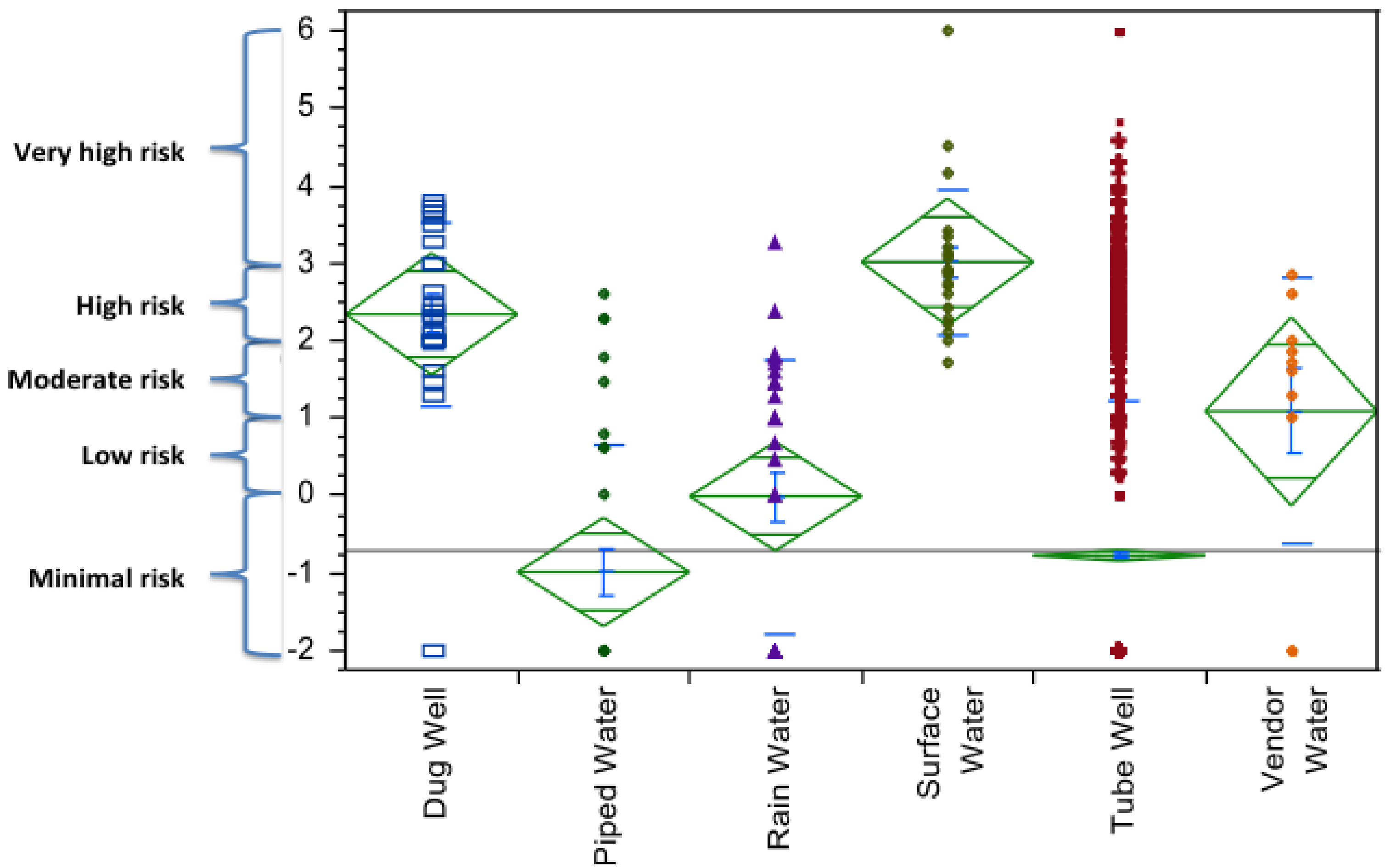
- Most of the alternative sources are low in As.
- Mean As in tubewells was bimodal, low or very high. Rainwater contained more As, either because of contamination from well water, or because of storage.
- Piped water: includes both untreated and treated water systems.

Alternative Water Sources :Water Quality



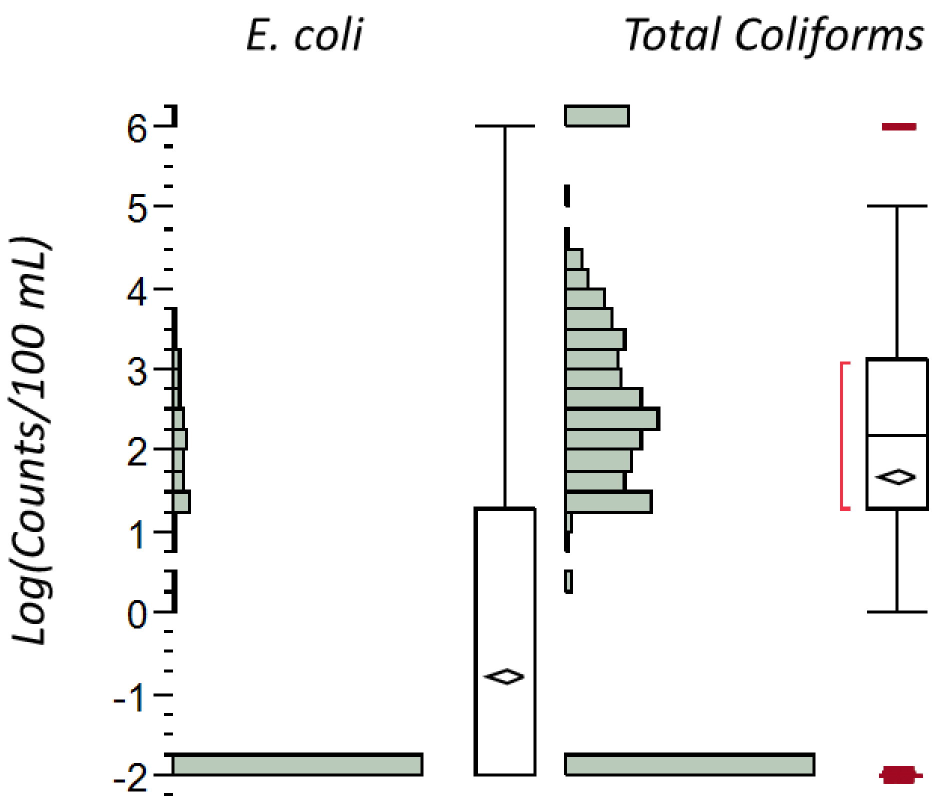
- Most water sources have low levels of other *chemical* contaminants, except occasional contamination in either dug and tube wells
- Mn is dug wells is occasionally measured. In some tube wells it reaches 10 ppm.
- Nitrate levels in dug wells and tube wells is high due to contamination from sewage.
- Most surface waters contain low nitrate, not because they are not affected by sewage, but because the water is exchanged from the water sources that are used.

Water Quality: E coli Risk



- Somewhat unexpectedly, the water quality of biological pathogens was less different than expected between water sources.
- **All water sources have some contamination, even prior to storage.**

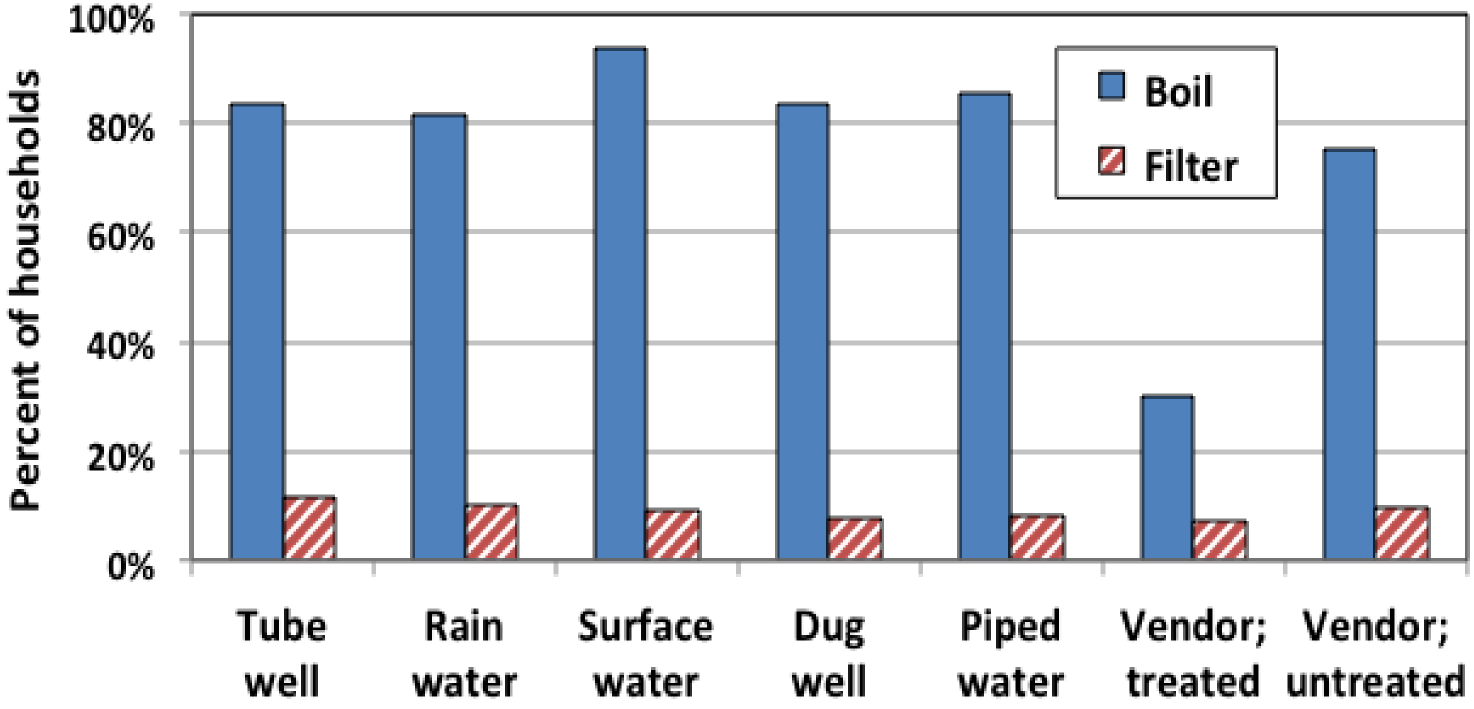
Groundwater Water Quality: Total Coliforms and E coli



Box and whisker plots for concentrations (log-normalized) of E. coli and total coliforms in tubewells. The high incidence of "outliers" at the low concentration portion of the tail represent assumed values from below detection.

- Biological contamination of ground water supplies also appears to be non-trivial.
- More than 25% of deep tube wells appear to have this excessive level of microbial contamination based on total coliform concentrations,
- 25th percentile concentration of E coli is nearly $10^{1.3}$ CFU/100 mL, between 10-100 CFU/100 mL.

The Outcome: Most Alternatives Require Water Treatment Prior to Use

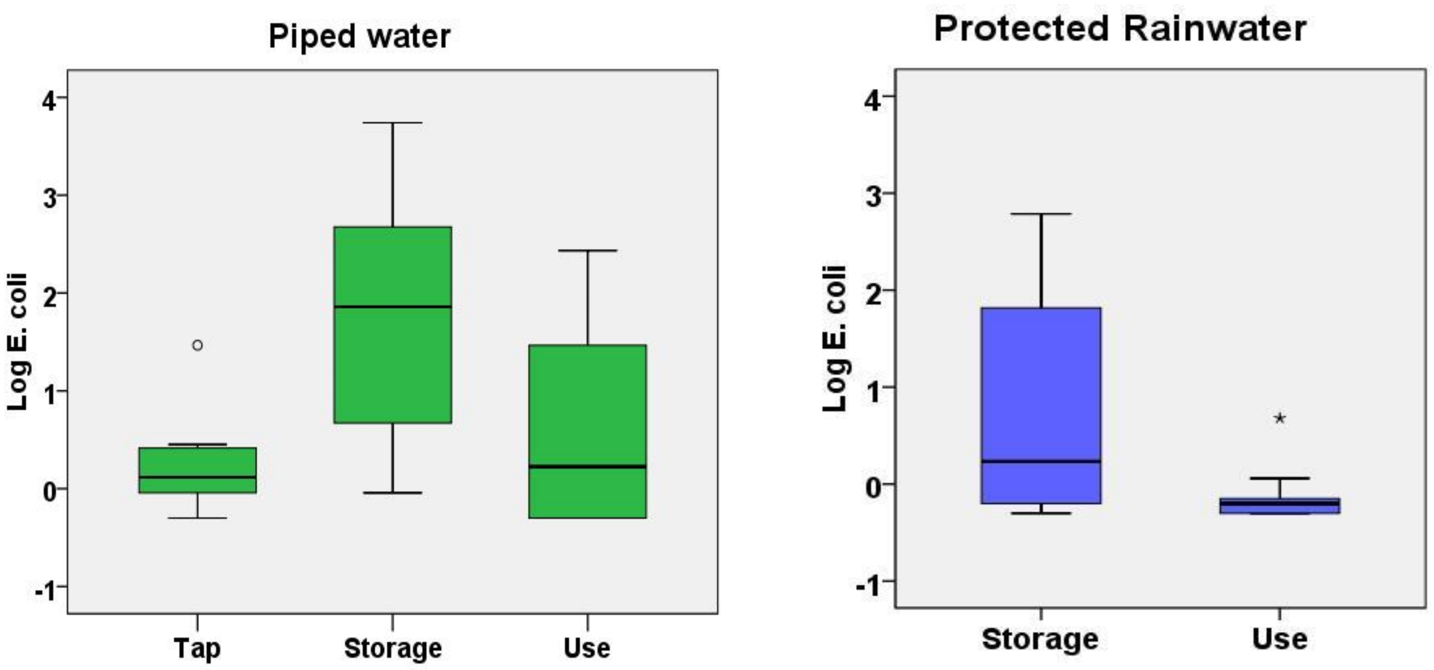


- Most people treat their water (~80%) prior to use.
- 84% boil their water. 8-10% filter their water (sand or ceramic filter most often), almost none use chemical treatment.

Household Water Storage

- Regardless of the source or treatment, water storage is a major mechanism of water contamination or recontamination.
- Unfortunately, water storage is a necessity when households do not have a continuous water supply, or when the water source is not located in or near the household.

Risk: Effect of Storage



- Storage increases risk (even after secondary treatment such as additional boiling or filtration just prior to use)

Results: Water Quality

- Only tubewells have high As (or waters that are contaminated by tubewells).
- Other kinds of groundwater contamination affect more than 50% of low As wells.
- *Result: Most low-As groundwater sources have considerable risks associated with their use.*
- Microbial contamination is measurable even in tubewells.
- *Result: people should and do boil/treat groundwater prior to use.* This is an added cost for their use, and it is not completely effective.
- *Implication: We need to develop a small number of 'safe' groundwater resources, or surface water technologies.*

Alternative Water Supplies: Different Organizations = Different Approaches

Organization	Activities
UNICEF	Dug wells, ceramic water filters, rainwater harvesting
GRET	Piped water supplies, rainwater harvesting
1001 Fontaines	Potable water vendor systems
Rainwater Cambodia	School and household-scale rainwater harvesting
RDI	Dug wells, piped water, school and household-scale rainwater harvesting

Most organizations make their decisions without any facts about which water supplies are superior, or how they work. At very least, many make significant assumptions about which are plausible, or technologically appropriate. That aside, most water sources contain other contaminants, even though they are being recommended and installed as solutions.

We need real data.

Acknowledgements

- Mickey Sampson and RDI
- World Bank WSP
- The people of Cambodia