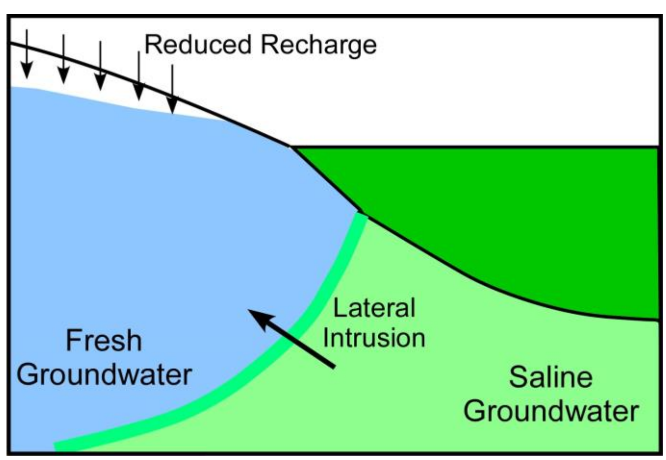
Vulnerability of Groundwater to Salinization & the Case of the Bengal Delta

Holly Michael, Lindsay Byron, Christopher Russoniello, Kaileigh Calhoun, and Mohammad Koneshloo, Mahfuzur Khan
University of Delaware

Lawrence Feinson, Clifford Voss
US Geological Survey

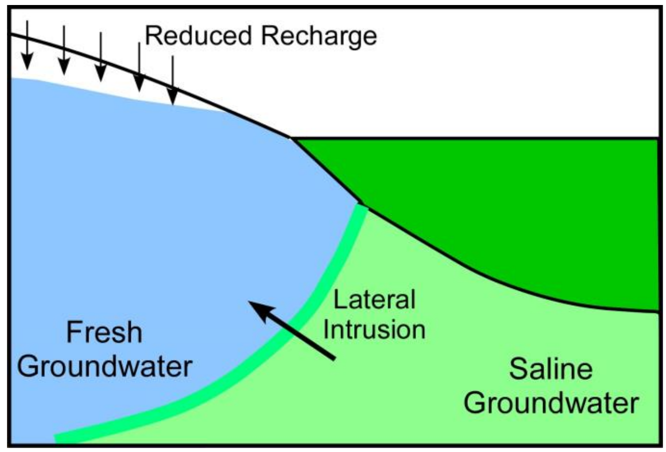
Climate change-induced groundwater salinization:

- Reduced groundwater recharge
- Sea level rise (vertical and lateral intrusion)
- Storm surges – increased frequency and intensity



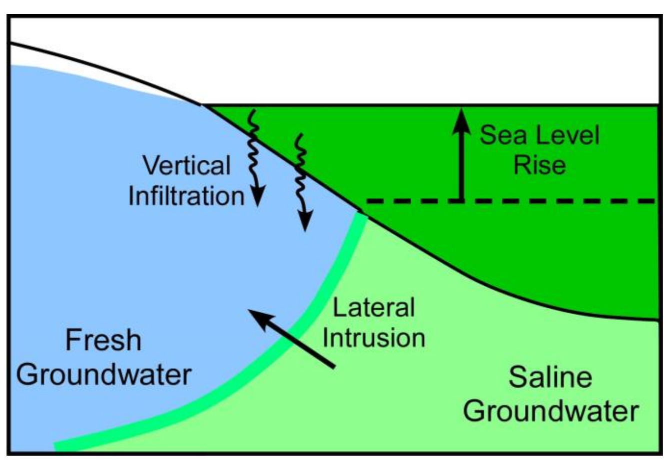
Climate change-induced groundwater salinization:

- Reduced groundwater recharge
- Sea level rise (vertical and lateral intrusion)
- Storm surges – increased frequency and intensity



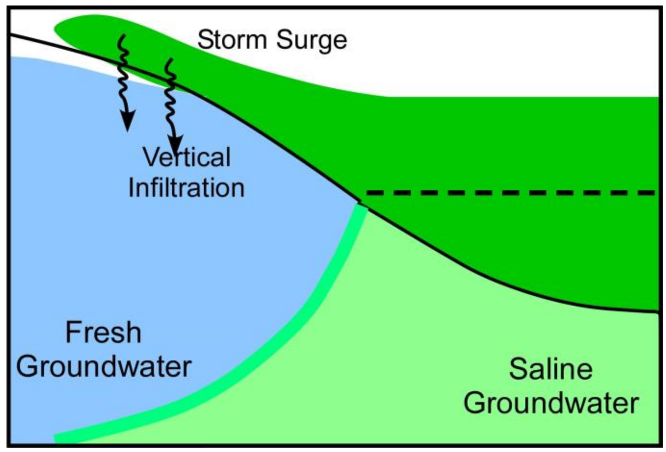
Climate change-induced groundwater salinization:

- Reduced groundwater recharge
- Sea level rise (vertical and lateral intrusion)
- Storm surges – increased frequency and intensity



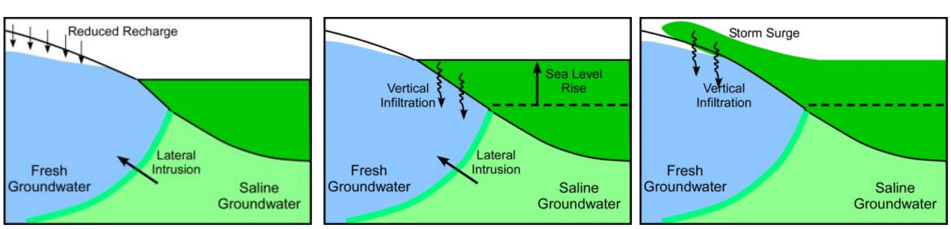
Climate change-induced groundwater salinization:

- Reduced groundwater recharge
- Sea level rise (vertical and lateral intrusion)
- Storm surges – increased frequency and intensity



Vulnerability depends on:

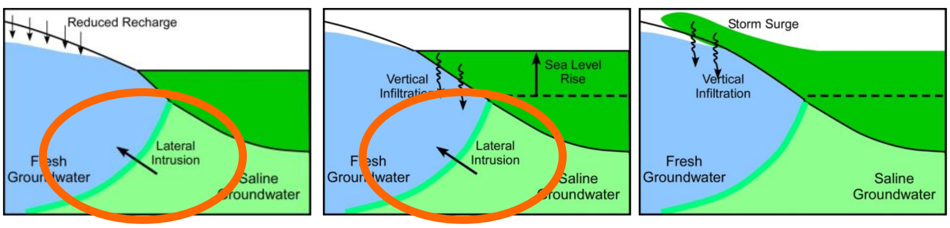
- Hydrology/climate
- Hydrogeologic properties
- System geometry (topographic slope, hydraulic divides)
- Type and scale of potential changes (sea level rise and climate)
- Human impacts (pumping)



Vulnerability depends on:

- Hydrology/climate
- Hydrogeologic properties
- System geometry (topographic slope, hydraulic divides)
- Type and scale of potential changes (sea level rise and climate)
- Human impacts (pumping)

Part 1: Typology for lateral intrusion vulnerability

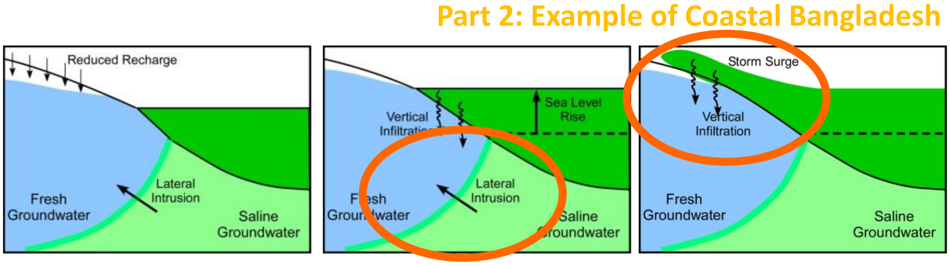


→ Deltas are highly vulnerable to lateral intrusion

Vulnerability depends on:

- Hydrology/climate
- Hydrogeologic properties
- System geometry (topographic slope, hydraulic divides)
- Type and scale of potential changes (sea level rise and climate)
- Human impacts (pumping)

Part 2: Example of Coastal Bangladesh



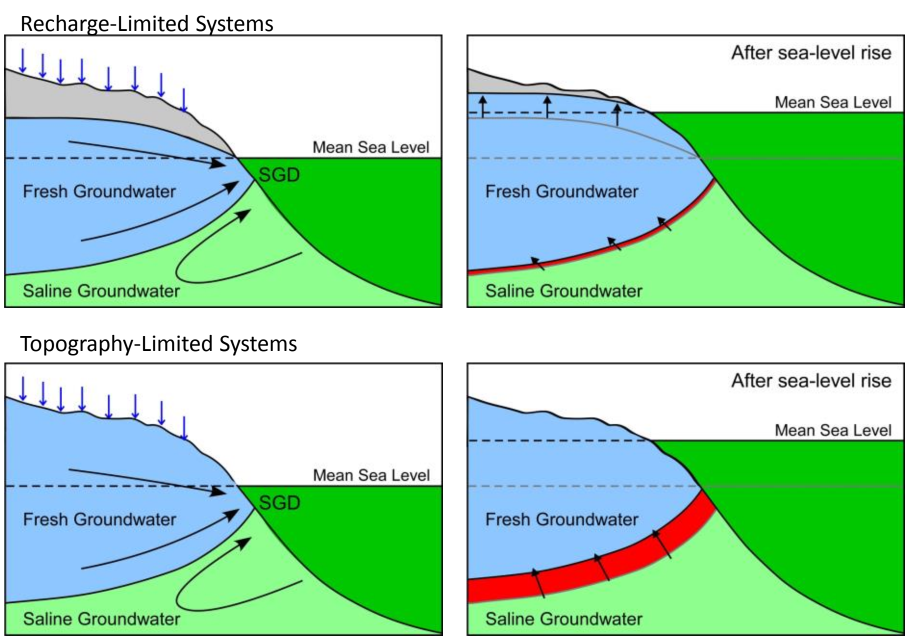
Vulnerability depends on:

- Hydrology/climate
- Hydrogeologic properties
- System geometry (topographic slope, hydraulic divides)
- Type and scale of potential changes (sea level rise and climate)
- Human impacts (pumping)

→How do each of these factors affect vulnerability to different modes of salinization?

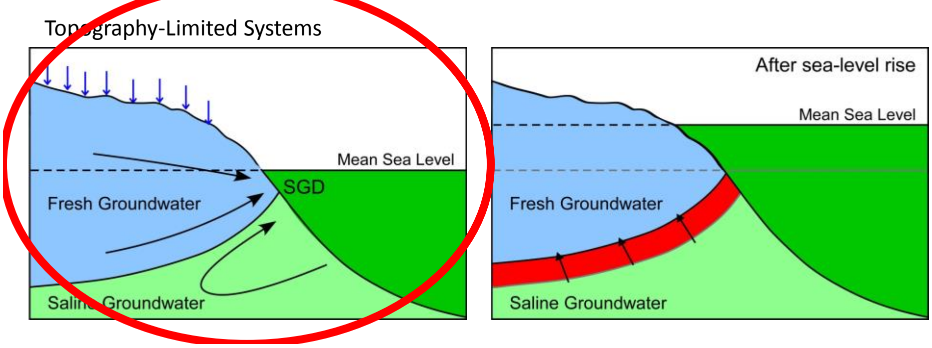
→Can we classify coastal vulnerability using these factors?

A typology for vulnerability to lateral salinization?

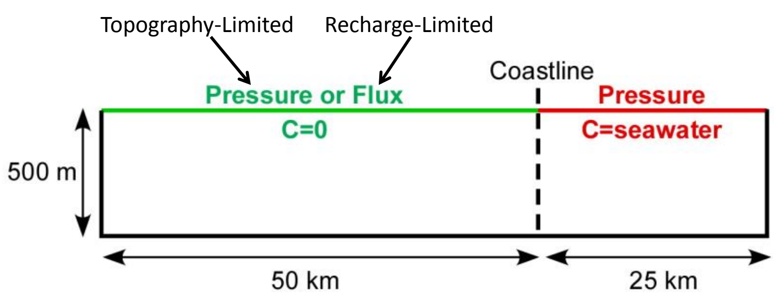


A typology for vulnerability to lateral salinization?

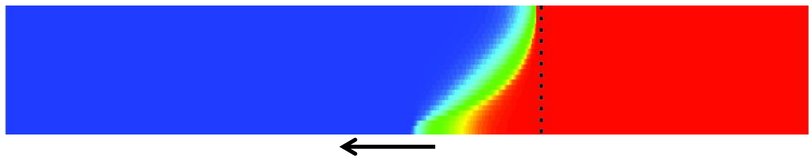
Deltas
- Low topographic gradients
- Often high recharge
- *(Dense populations and groundwater use)*



Typology → Boundary Condition



Typology → Boundary Condition



Numerical simulations of variable-density groundwater flow and transport (SUTRA)

Considered (after 1m SL rise, no transgression):

- Rate of salinization (movement of toe)
- Area salinized after 200 y
- Change in groundwater flow to sea, fresh and saline (Ecosystem, ocean chemistry impacts)

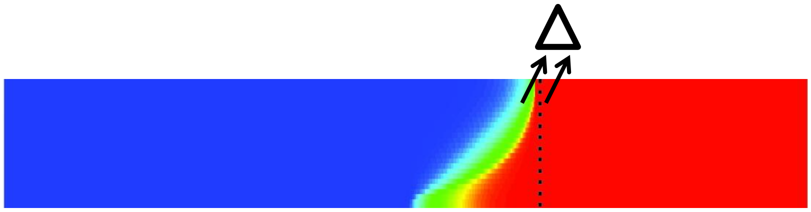
Typology → Boundary Condition

Numerical simulations of variable-density groundwater flow and transport (SUTRA)

Considered (after 1m SL rise, no transgression):

- Rate of salinization (movement of toe)
- Area salinized after 200 y
- Change in groundwater flow to sea, fresh and saline (Ecosystem, ocean chemistry impacts)

Typology → Boundary Condition

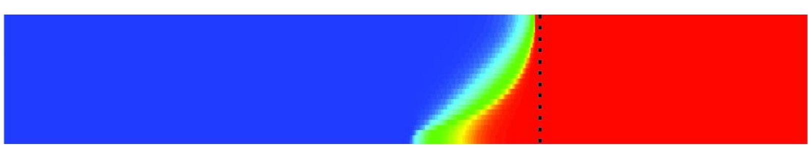


Numerical simulations of variable-density groundwater flow and transport (SUTRA)

Considered (after 1m SL rise, no transgression):

- Rate of salinization (movement of toe)
- Area salinized after 200 y
- Change in groundwater flow to sea, fresh and saline (Ecosystem, ocean chemistry impacts)

Typology → Boundary Condition

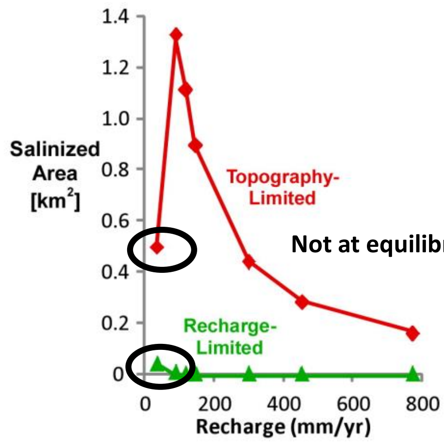


Numerical simulations of variable-density groundwater flow and transport (SUTRA)

Sensitivity to:

- Recharge
- Permeability
- Vertical anisotropy in permeability

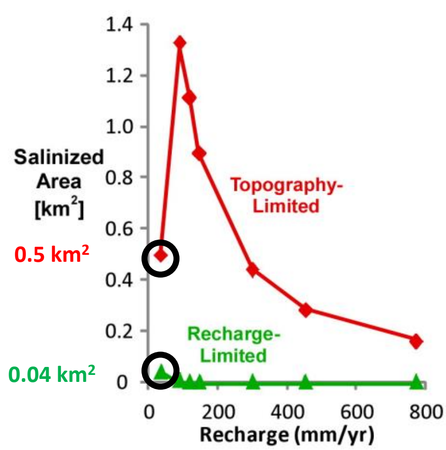
Area Salinized after 200 years
→ Recharge sensitivity



Not at equilibrium

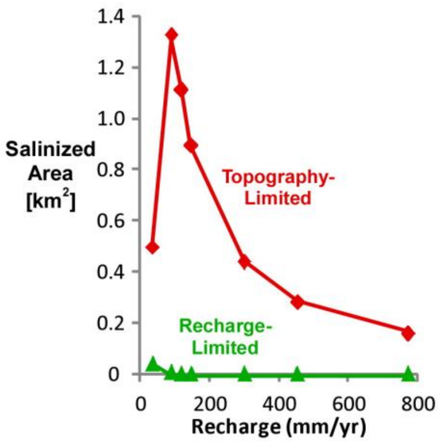
Low Recharge → Salinization

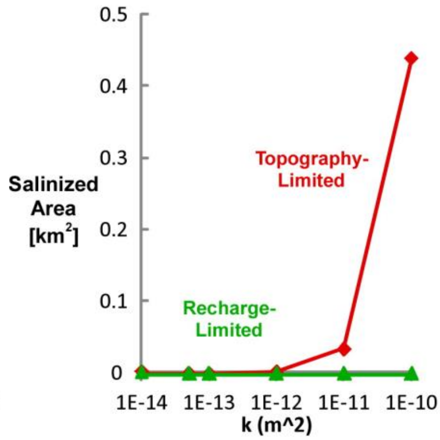
Area Salinized after 200 years
→ Recharge sensitivity



Low Recharge → Salinization

Area Salinized after 200 years
→ Recharge sensitivity
→ Permeability sensitivity



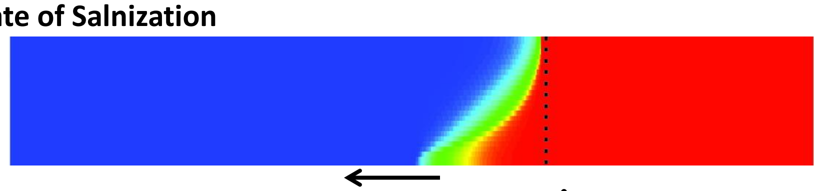


Low Recharge → Salinization **High k → Salinization**

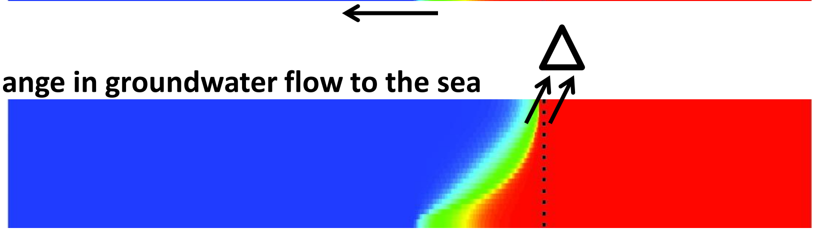
Similarly…

Topography-limited vulnerability >> Recharge-limited for:

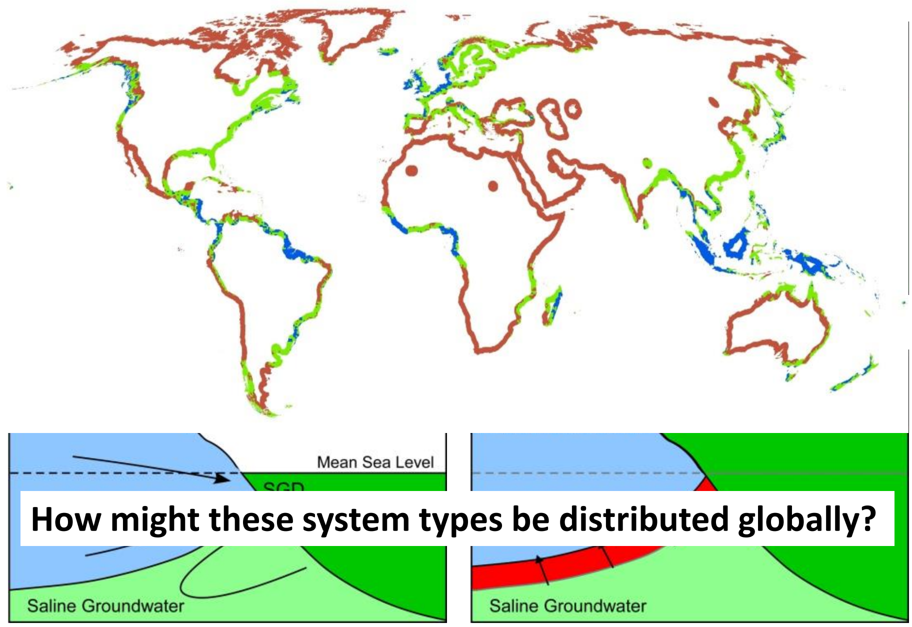
Rate of Salnization



Change in groundwater flow to the sea

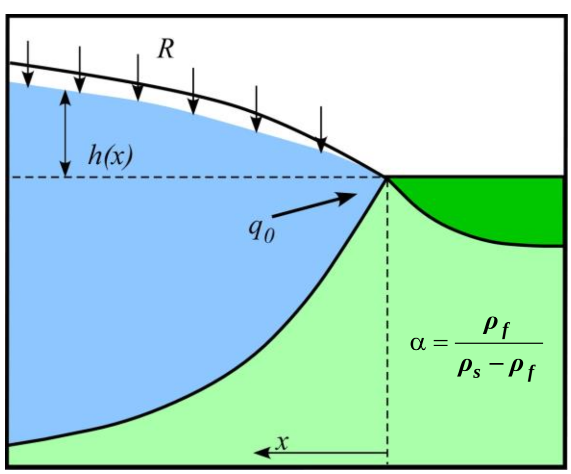


A typology for vulnerability to lateral salinization?



How might these system types be distributed globally?

Compare Head Estimates to Topography…



$$h = \sqrt{\frac{2q_0 x - Rx^2}{K(1+\alpha)}}$$

(Custodio, 1987)

Need:

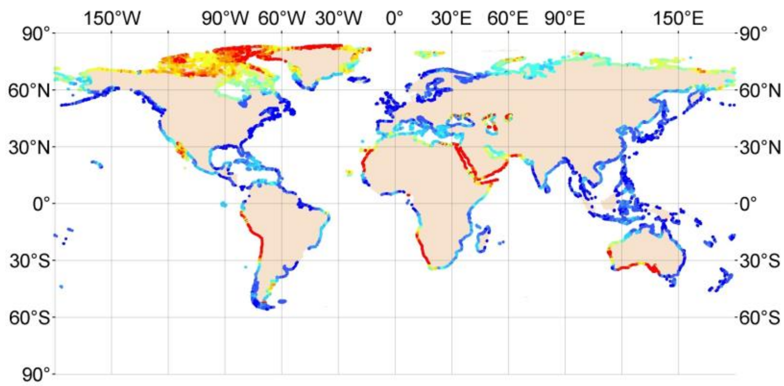
- R
- K
- q_0

IOP Publishing — Environmental Research Letters
Environ. Res. Lett. 4 (2009) 035006 (12pp) — doi:10.1088/1748-9326/4/3/035006

Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment

Petra Döll
Institute of Physical Geography, Goethe University Frankfurt, Frankfurt am Main, Germany

Recharge Rates: Döll, 2009



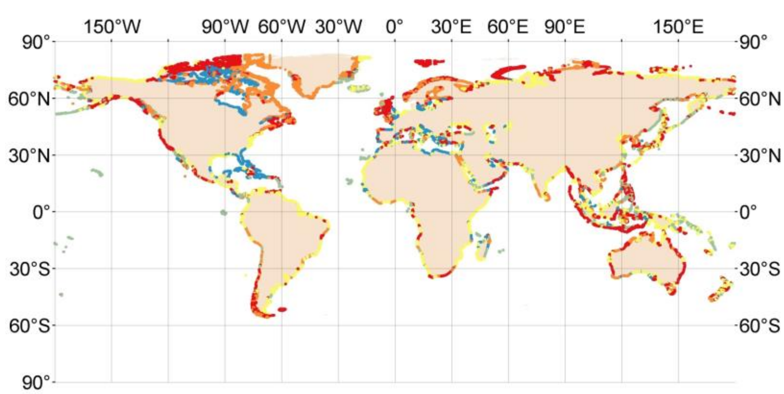
GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L02401, doi:10.1029/2010GL045565, 2011

k: Gleeson et al., 2011

Mapping permeability over the surface of the Earth

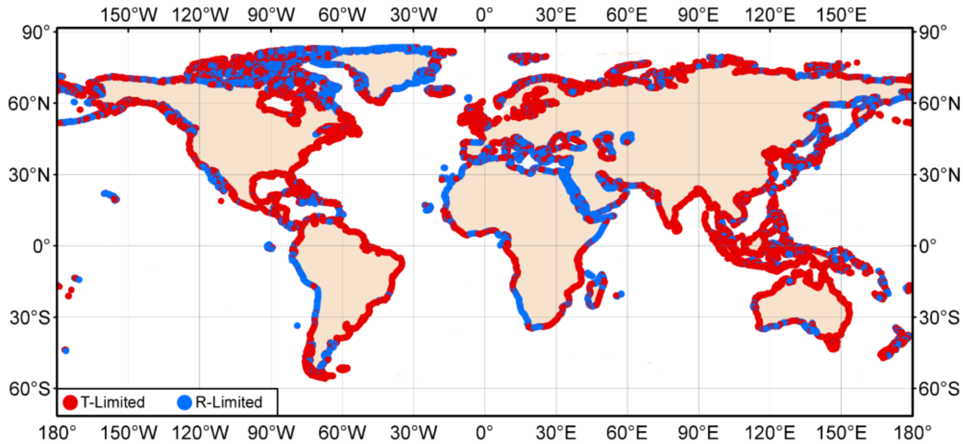
Tom Gleeson,[1] Leslie Smith,[1] Nils Moosdorf,[2] Jens Hartmann,[2] Hans H. Dürr,[3] Andrew H. Manning,[4] Ludovicus P. H. van Beek,[3] and A. M. Jellinek[1]

Received 20 September 2010; revised 10 November 2010; accepted 23 November 2010; published 21 January 2011.



32% Recharge-Limited

68% Topography-Limited



R: Döll, 2009

k: Gleeson et al., 2011

q_0: Defined by 10km hydraulic divide

Michael et al., WRR, 2013

System type depends more on local aquifer conditions than the magnitude of sea-level rise or change in recharge:

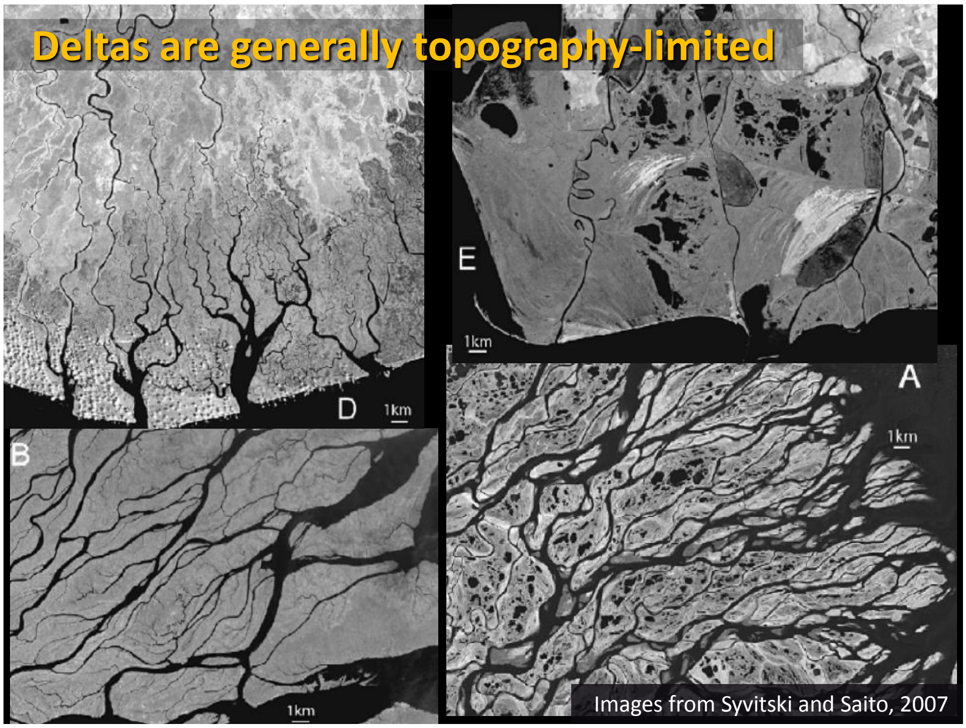
% Topography-Limited

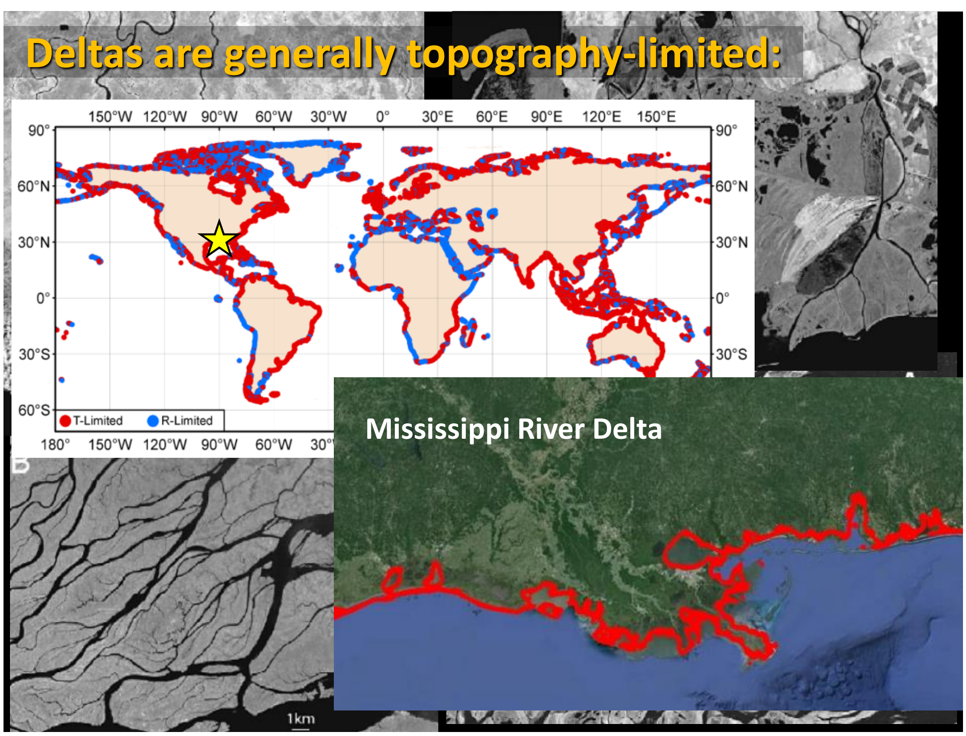
Permeability [m²]	Current Sea Level: Current Recharge	Current Sea Level: Future Recharge	1 m Sea-Level Rise: Current Recharge	1 m Sea-Level Rise: Future Recharge
10^{-10}	16%	16%	24%	24%
10^{-12}	40%	41%	42%	42%
$10^{-13.4}$ (Distributed)	68%	68%	69%	69%
10^{-14}	75%	76%	76%	76%

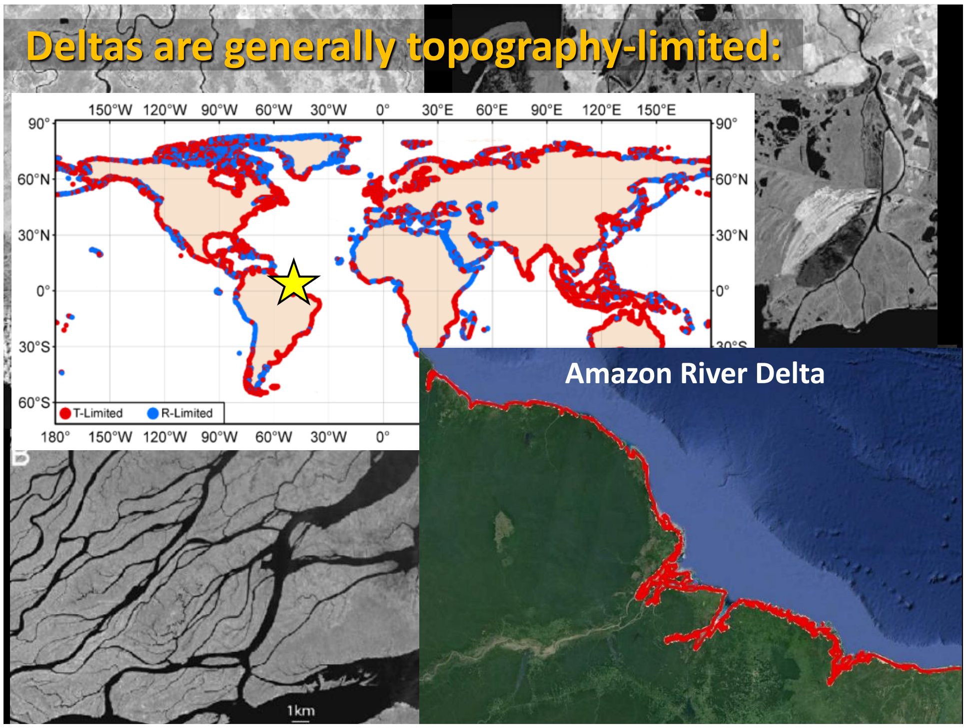
k is important

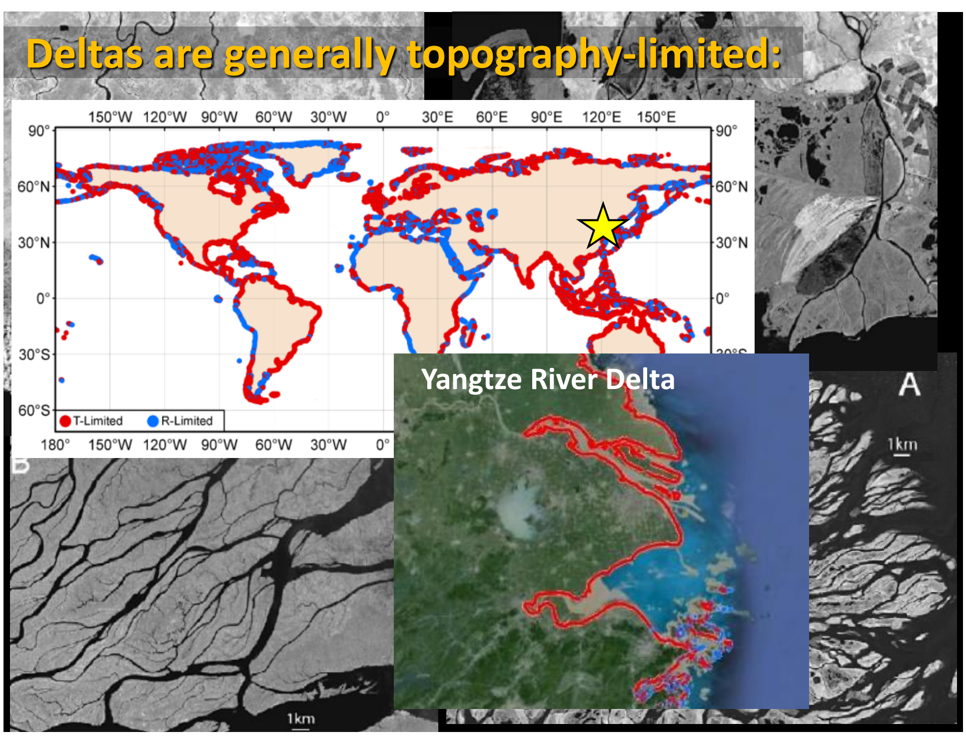
Sea-Level Rise uncertainty less important

Michael et al., WRR, 2013

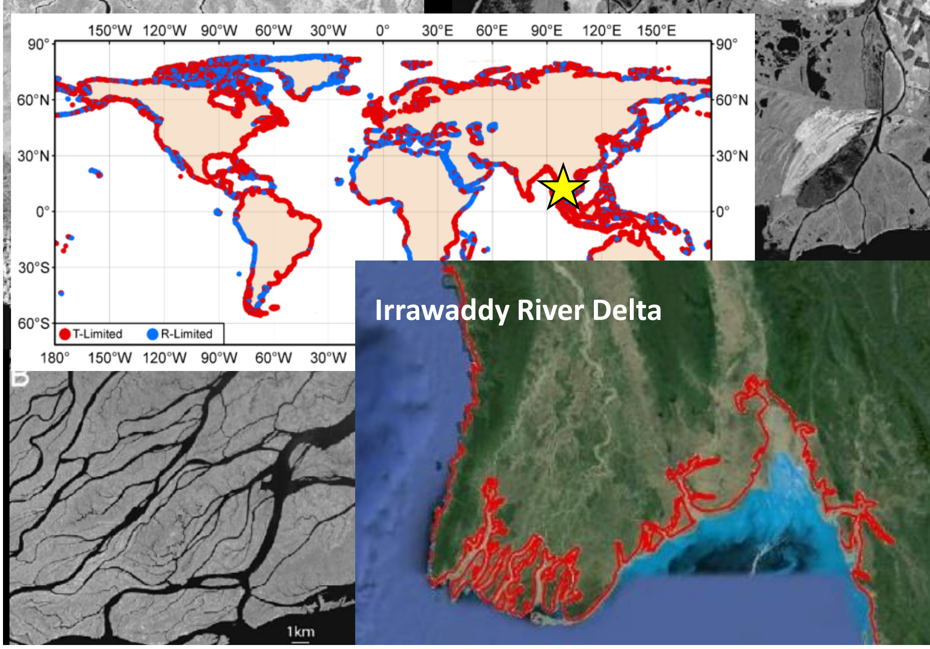

Deltas are generally topography-limited
E
1km
A
1km
D
1km
B
1km
Images from Syvitski and Saito, 2007


Deltas are generally topography-limited:
T-Limited
R-Limited
Mississippi River Delta


Deltas are generally topography-limited:
150°W 120°W 90°W 60°W 30°W 0° 30°E 60°E 90°E 120°E 150°E
90° 60°N 30°N 0° 30°S 60°S
T-Limited
R-Limited
180° 150°W 120°W 90°W 60°W 30°W 0°
Amazon River Delta
1km


Deltas are generally topography-limited:
150°W 120°W 90°W 60°W 30°W 0° 30°E 60°E 90°E 120°E 150°E
90° 60°N 30°N 0° 30°S 60°S
T-Limited
R-Limited
180° 150°W 120°W 90°W 60°W 30°W 0°
Yangtze River Delta
A
1km
1km

Deltas are generally topography-limited:



Deltas are generally topography-limited:

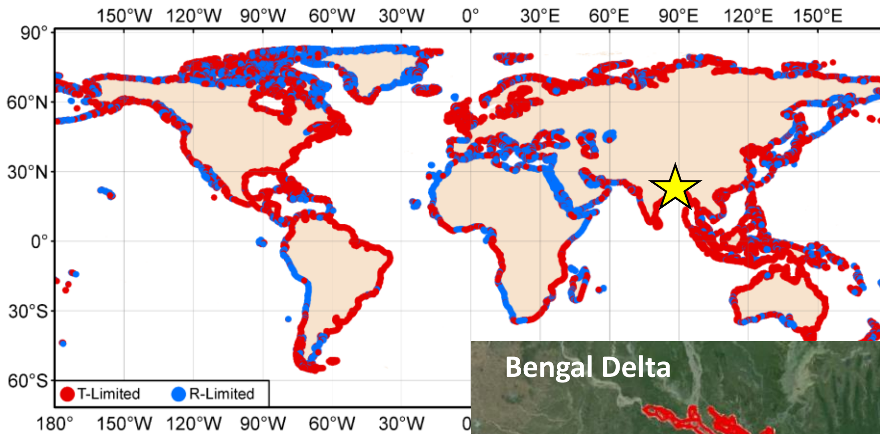
- ***Low-lying:*** >10% of deltaic areas are <2m above mean sea level
- ***Flat:*** The average gradient is 0.3 m/km
- ***Wet:*** Mean deltaic rainfall is **1200mm/year** (22 deltas), global mean is **960 mm/year**

(*Sources*: Syvitski, 2009; Syvitski and Saito, 2007; Coleman and Huh, NASA)

Deltas are also highly populated → water stress:

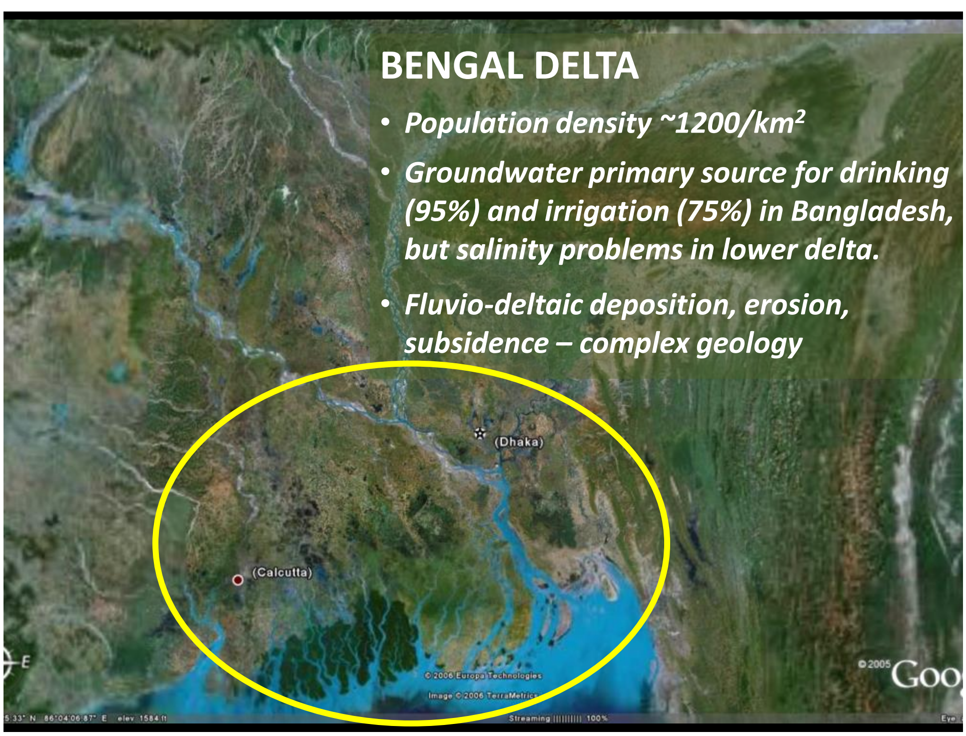
- ***Delta average:*** 340/km² (51 deltas; 600/km² excl Amazon)
  World average: 55/km²
- ***Mega-cities:*** Many of the largest are in deltas: Shanghai (Yangtze), Bangkok (Chao Phraya), Yangon (Irrawaddy), Calcutta and Dhaka (Ganges–Brahmaputra), Karachi–Hyderabad (Indus), Vancouver (Fraser), Ho Chi Minh City (Mekong), Alexandria and Cairo (Nile)

(*Sources*: Syvitski et al., 2007; World Bank)



Coastal Bangladesh:

Example of a Topography-Limited System



Coastal Bangladesh:

Example of a Topography-Limited System

- Role of Heterogeneity in salinization processes
- Effects of storm surges…how important?
- Effects of pumping…how important?

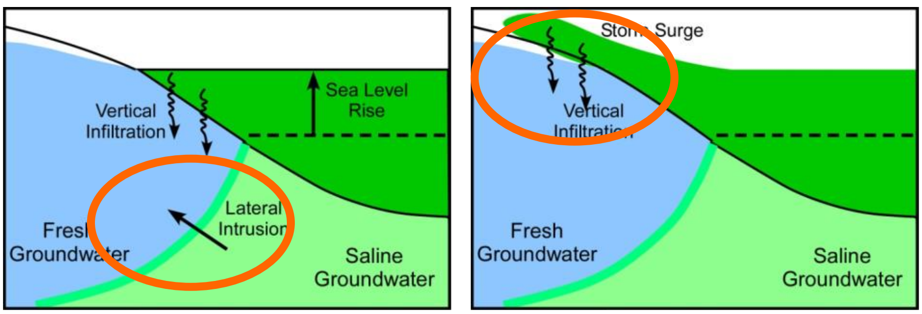
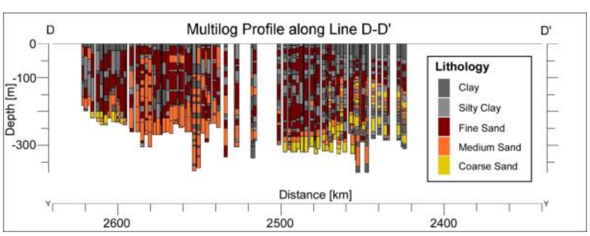
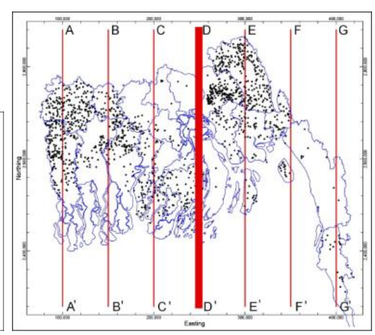
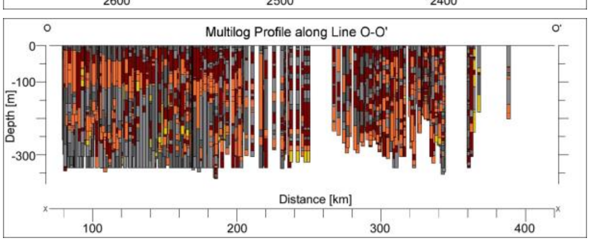
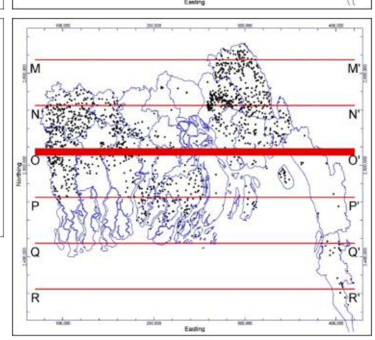


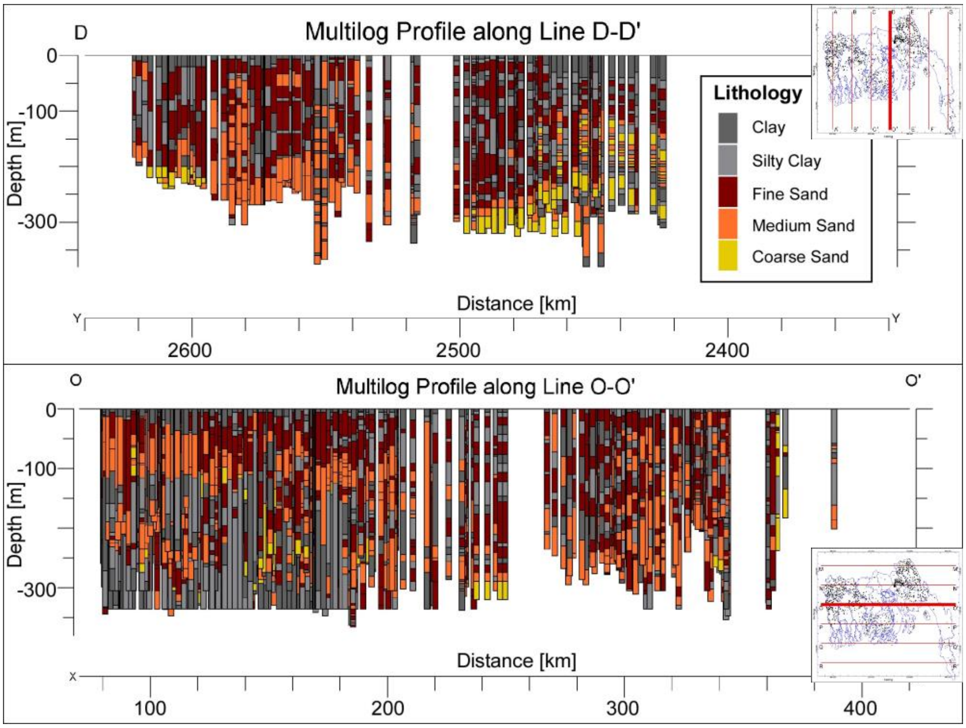

Image © 2008 TerraMetrics
Image © 2008 DigitalGlobe
4.08 km
©2008 Google


D
Multilog Profile along Line D-D'
D'
Depth [m]
0
-100
-300
Lithology
Clay
Silty Clay
Fine Sand
Medium Sand
Coarse Sand
Distance [km]
2600
2500
2400

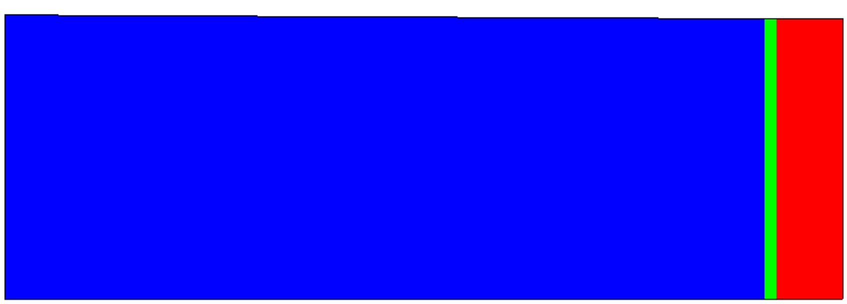

A
B
C
D
E
F
G
A'
B'
C'
D'
E'
F'
G'
Northing
Easting


O
Multilog Profile along Line O-O'
O'
Depth [m]
0
-100
-300
Distance [km]
100
200
300
400


M
M'
N
N'
O
O'
P
P'
Q
Q'
R
R'
Northing
Easting

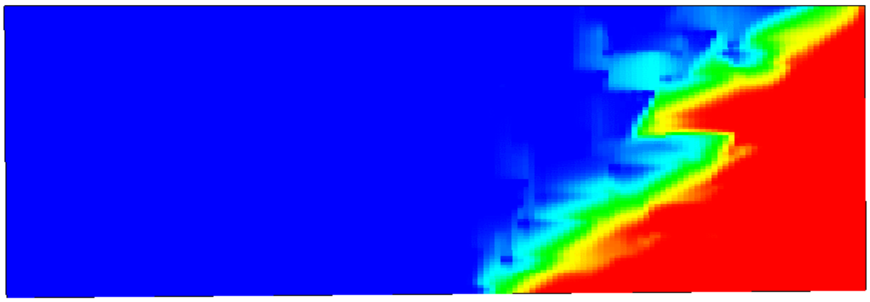


Lateral Seawater Intrusion



Final Time = 50,000 years

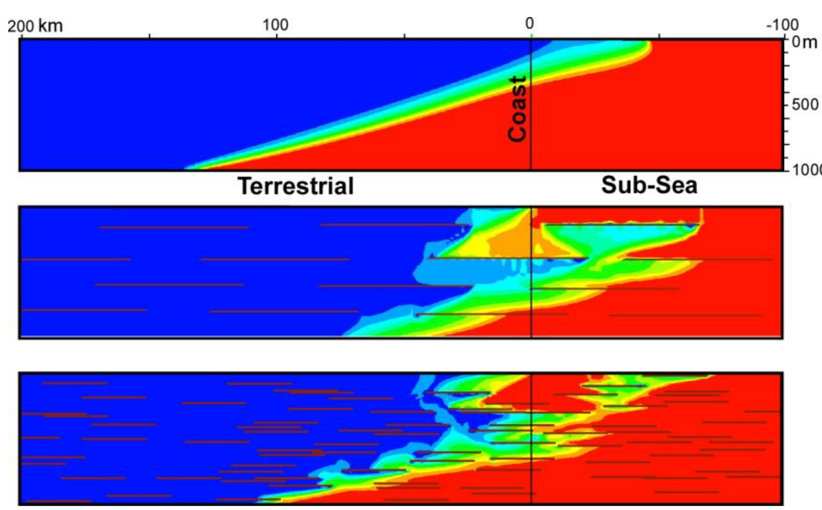
Vertical Seawater Intrusion



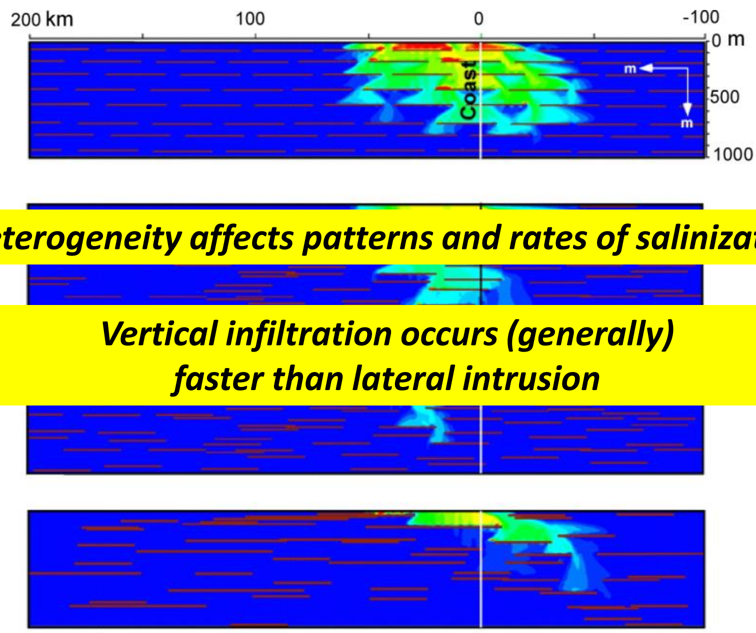
Final Time = 241 years

Rate of vertical infiltration >> lateral intrusion

Lateral Salinization



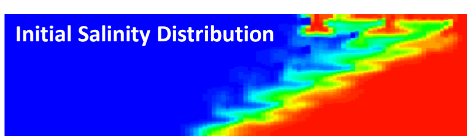
Vertical Salinization



Heterogeneity affects patterns and rates of salinization

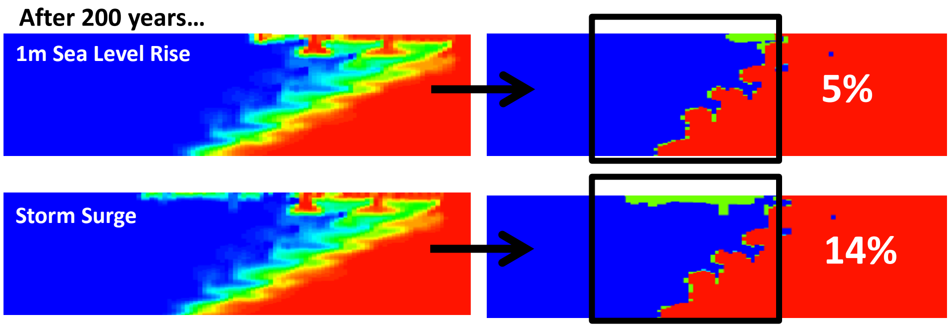
Vertical infiltration occurs (generally) faster than lateral intrusion

Lateral & Vertical Salinization - Heterogeneous



Red: Always saline (>2% seawater)
Blue: Always fresh (<2% seawater)
Green: Salinized

After 200 years…

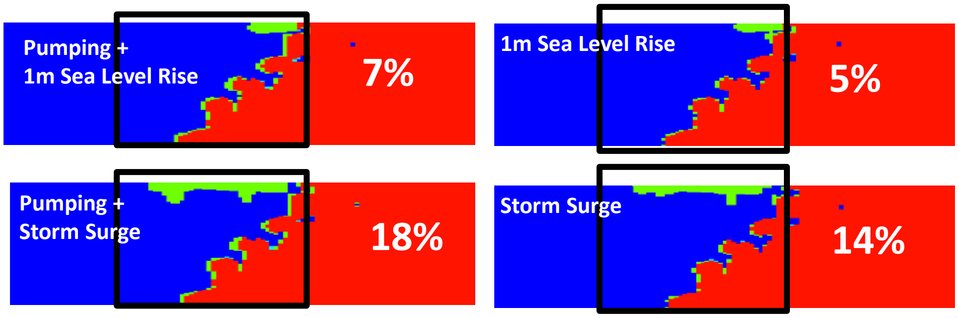


(2m every 10 years…a lot)

Lateral & Vertical Salinization - Heterogeneous

Red: Always saline (>2% seawater)
Blue: Always fresh (<2% seawater)
Green: Salinized

With Pumping…



Pumping accelerates, does not dominate

→ Storm surges in recharge-limited systems?

Summary:

Modeling Shows…

- T-Limited systems more vulnerable to lateral salinization than R-Limited systems :
  - Salinization magnitude
  - Salinization rate
  - Changes in groundwater flow to the sea

Global Analysis Shows…

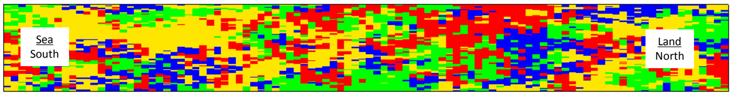
- Many world coastlines (>50%?, including many deltas) could be T-limited
- Hydrogeologic parameters primary indicators of categorization – not magnitude of SL rise or change in recharge…local characterization

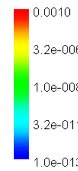
In Coastal Bangladesh…

- Heterogeneity important for salinity evolution
- Vertical infiltration faster than lateral (but depends on frequency, intensity, properties)
- Pumping accelerates both, but not dominant

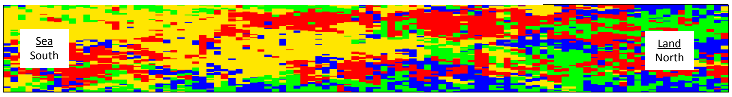

Thank You!
Collaborators:
Kazi Matin Ahmed and Md. Mahfuzur Rahman Khan, Dhaka University
Albert Tuinhof, Acacia Water
Winston Yu, World Bank Team Leader
Thanks to:
Petra Döll, R dataset
Tom Gleeson, k dataset
Funded by:
University of Delaware Research Foundation
The World Bank
US National Science Foundation
USGS

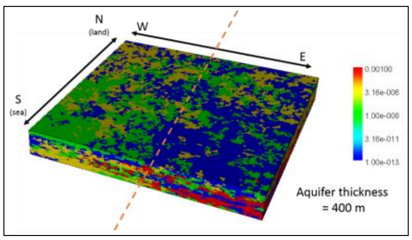
"Original" hydraulic conductivity field: Ky=5.1e-6 m/s, Kz=1.8e-8 m/s

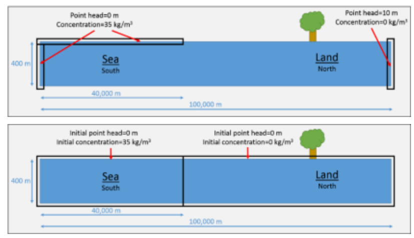


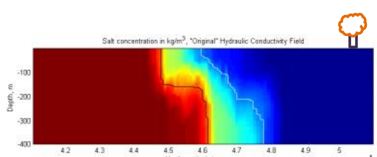


"Connected" hydraulic conductivity field: Ky=7.2e-6 m/s, Kz=1.5e-8 m/s

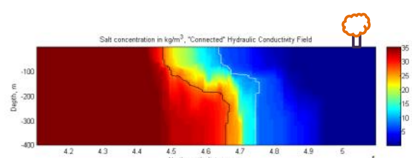




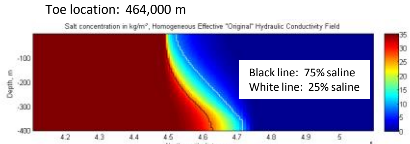




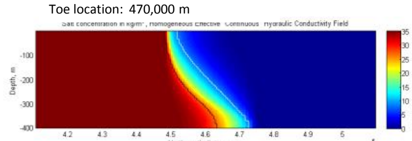
Saltwater circulation: 3.2e-4 m^3/s
Total SGD: 5.2e-4 m^3/s
Toe location: 464,000 m



Saltwater circulation: 1.2e-3 m^3/s
Total SGD: 1.4e-3 m^3/s
Toe location: 470,000 m



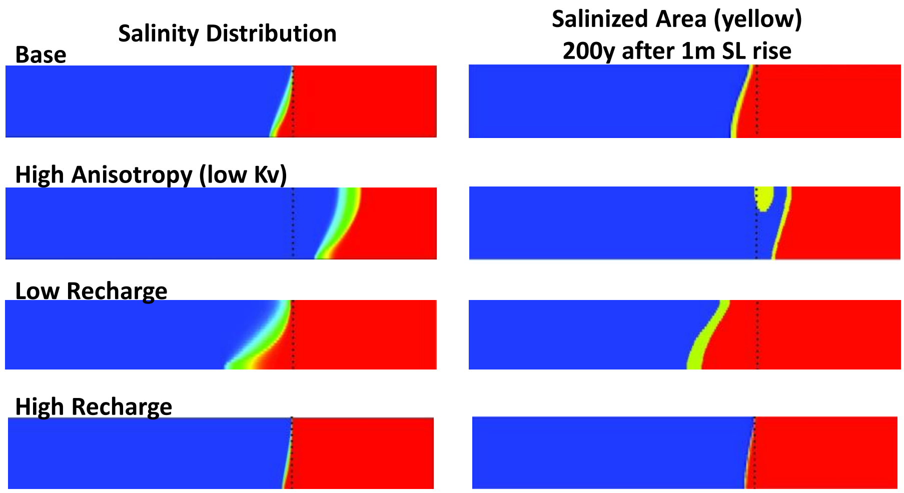
Saltwater circulation: 1.5e-4 m^3/s
Total SGD: 5.2e-4 m^3/s
Toe location:468,500 m



Saltwater circulation: 1.8e-4 m^3/s
Total SGD: 4.4e-4 m^3/s
Toe location: 468,000

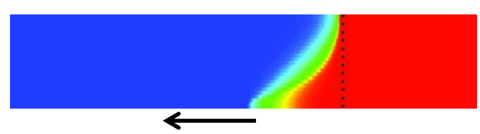
- Heterogeneous fields created wider saltwater-freshwater interfaces, more saltwater circulation, and more SGD than homogeneous fields
- The "continuous" field (normalized by the homogeneous equivalent) produced 3x more saltwater circulation and 2x more SGD than the "original field" (normalized by the homogeneous equivalent)
- The position of the toe of slope after upscaling may be impacted by geologic connectivity (more simulations are needed)

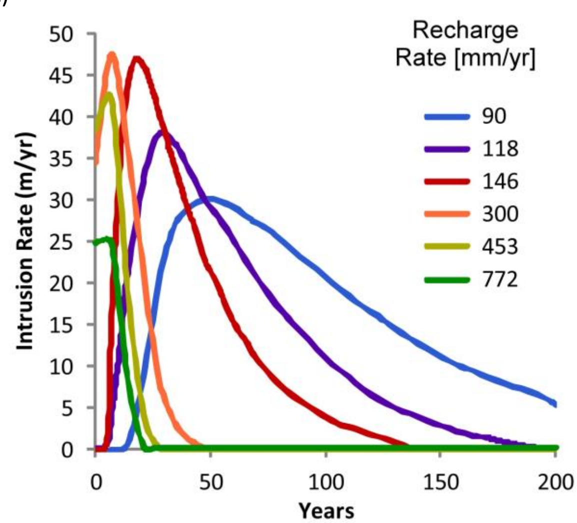
Simulation Results



Rate of Seawater Intrusion: Topography-Limited Systems

(Landward toe movement)





k=10^{-10} m^2

Rate of Seawater Intrusion: Topography-Limited Systems

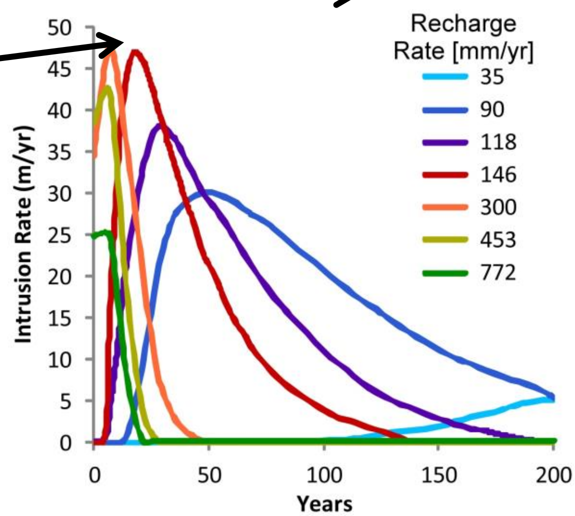
(Landward toe movement)

Decreasing Recharge →

Increasing Lag →

Increasing Equilibration Time →

Peak Intrusion at Intermediate Recharge



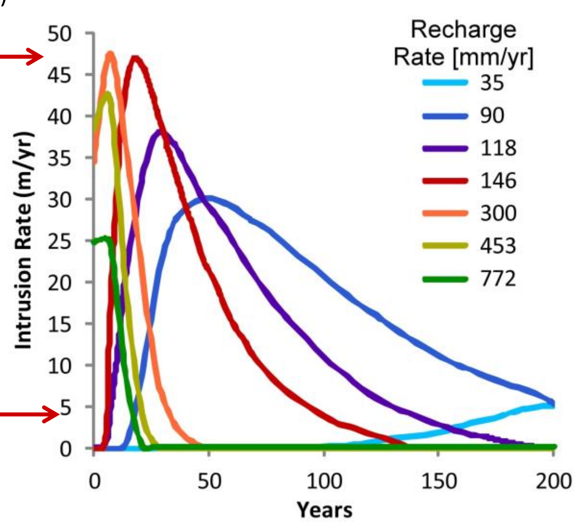
k=10^{-10} m^2

Rate of Seawater Intrusion: Topography-Limited Systems

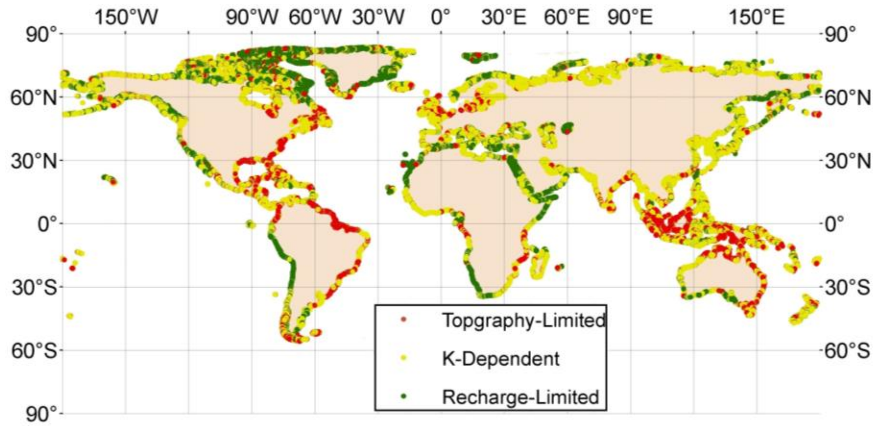
(Landward toe movement)

Rate = **46** m/y at R=146 mm/yr (Topography-limited)

Rate = **4** m/y at R=146 mm/yr (Recharge-limited)



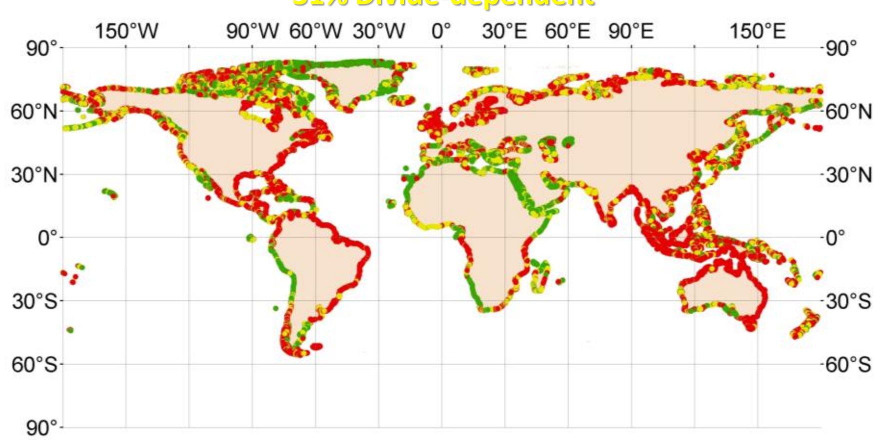
24% Always Recharge-Limited
16% Always Topography-Limited
60% K-dependent



R: Döll, 2009
k: $10^{-14} – 10^{-10}$ m^2
q_0: Defined by 10km hydraulic divide

Michael et al., WRR, 2013

22% Always Recharge-Limited
47% Always Topography-Limited
31% Divide-dependent



R: Döll
k: Gleeson et al., 2011
q_0: Defined by 1km-50km hydraulic divide

Michael et al., WRR, 2013