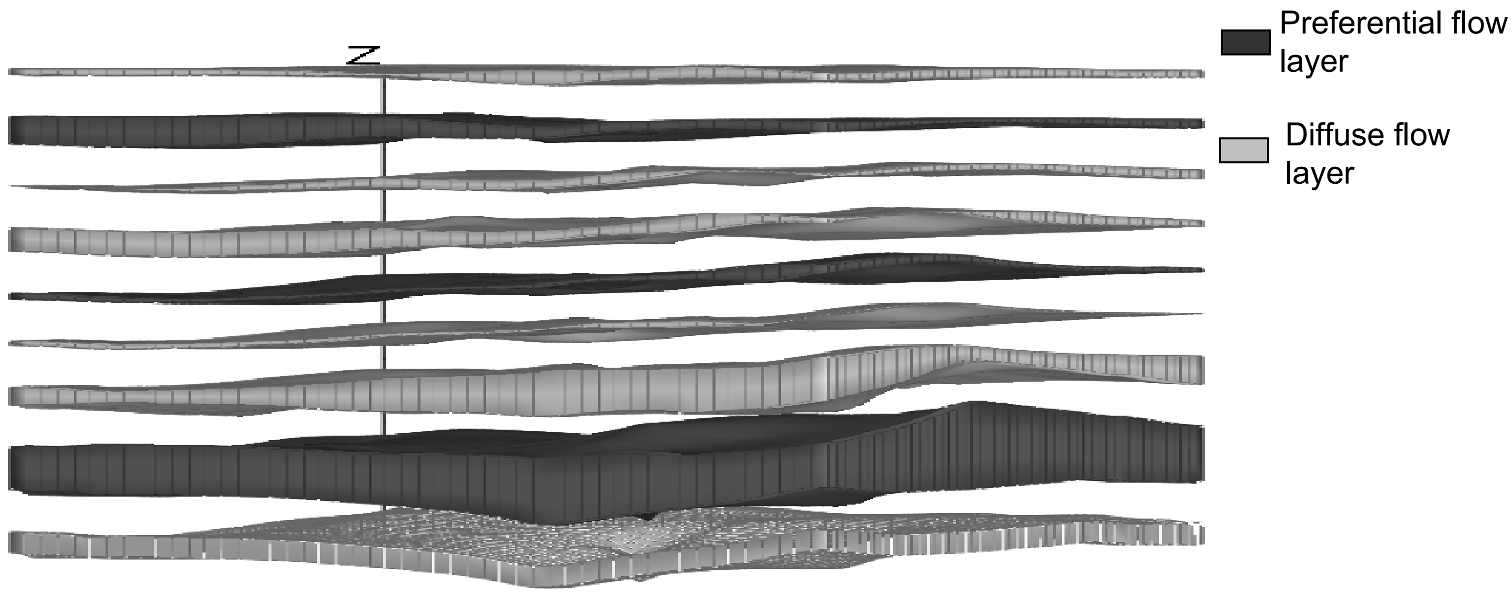
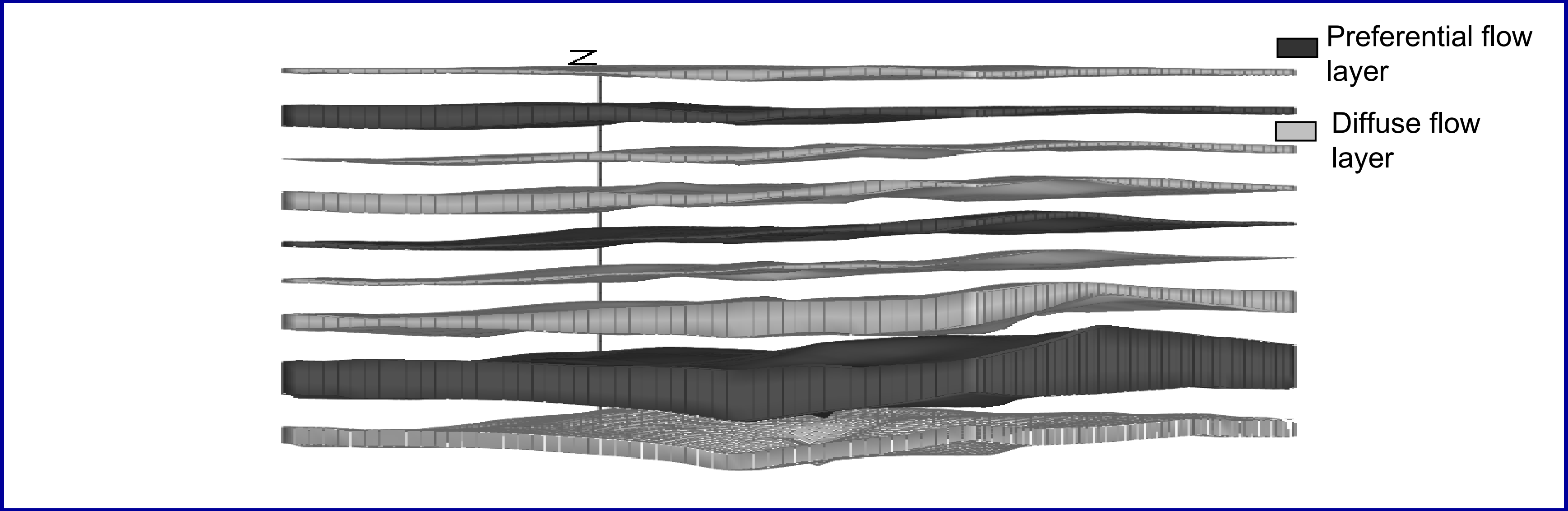
Effects of Turbulence on Hydraulic Heads and Parameter Sensitivities in Preferential Ground-Water Flow Layers



Barclay Shoemaker and Eve Kuniansky
U.S. Geological Survey

Project Funded by USGS Ground-Water Resources Program
Kevin Dennehy, Program Manager



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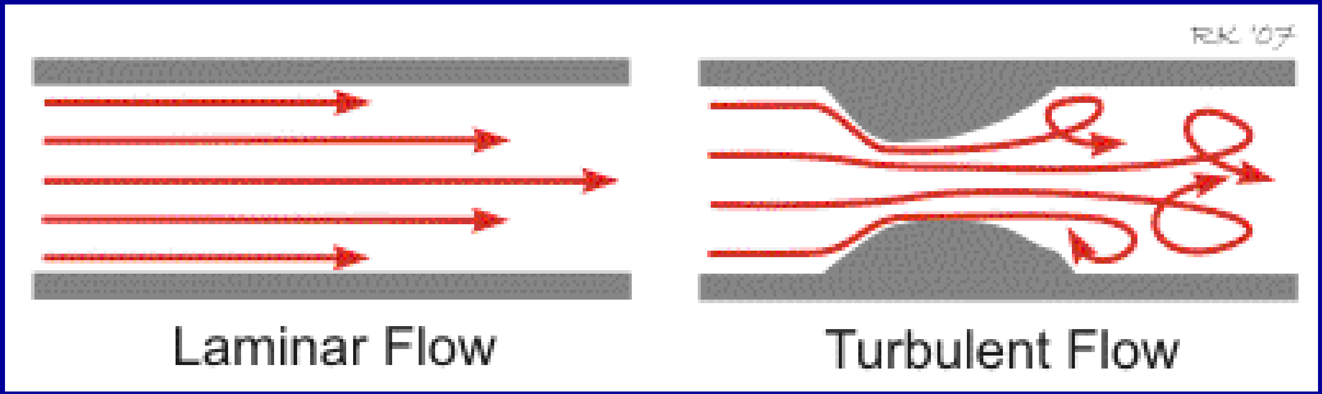
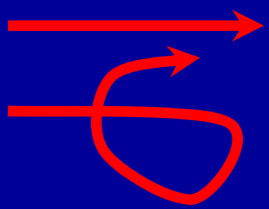
Keith J. Halford (USGS)

WHAT IS TURBULENT GROUND-WATER FLOW ?



Fluid Inertial Forces > Viscous Forces



Streamlines trace out the path of a ‘mass-less’ particle moving within the ground-water flow system.

WHAT IS TURBULENT GROUND-WATER FLOW ?

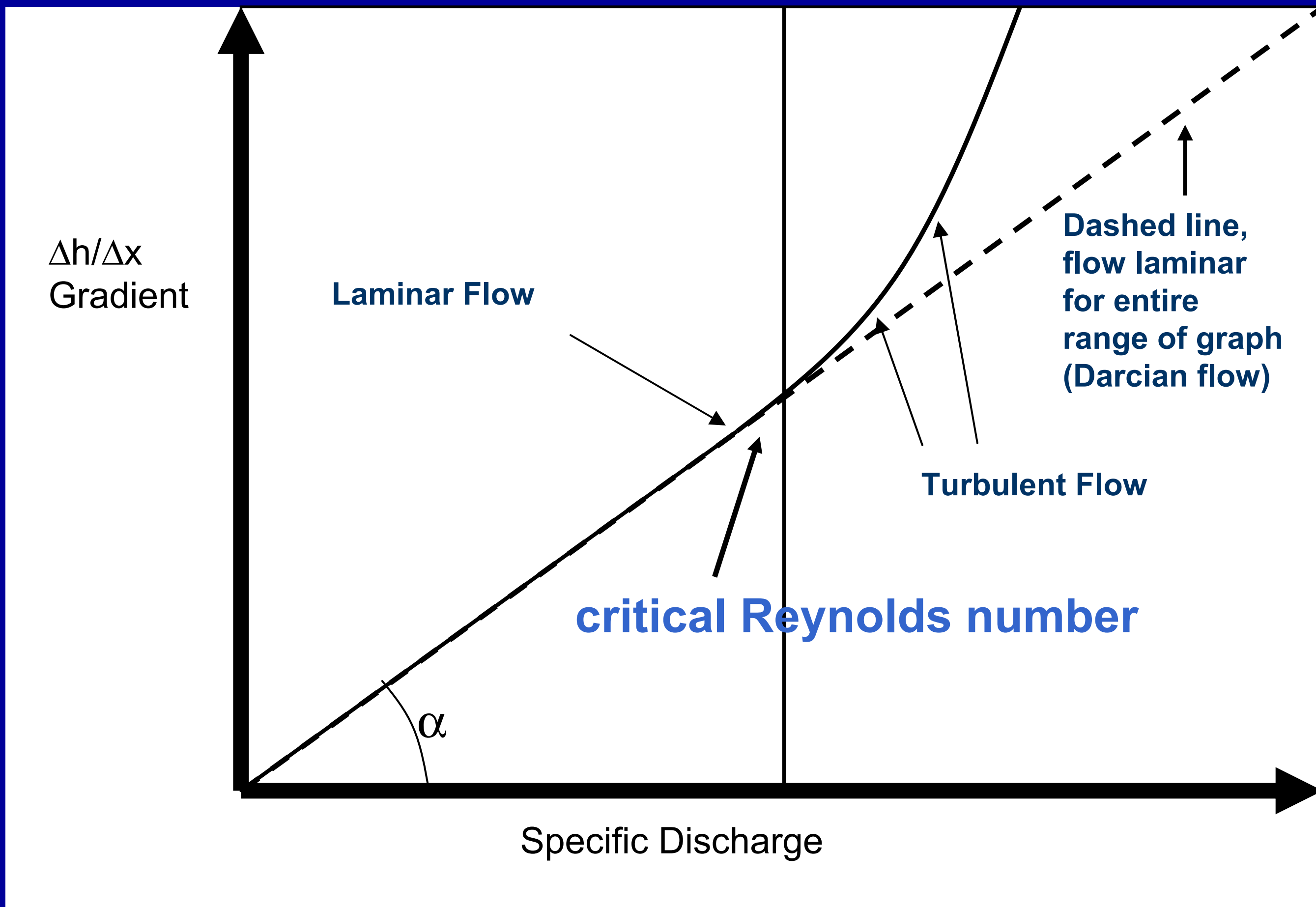
Reynolds numbers indicate whether flow is laminar or turbulent

$$R_e = \frac{\rho q d}{\mu} = \frac{inertial\ \ forces}{viscous\ \ forces}$$

Flow is turbulent when the critical Reynolds number (N_{Re}) is exceeded

$$R_e > N_{\mathrm{Re}},\ flow\ is\ turbulent$$

WHAT IS TURBULENT GROUND-WATER FLOW ?

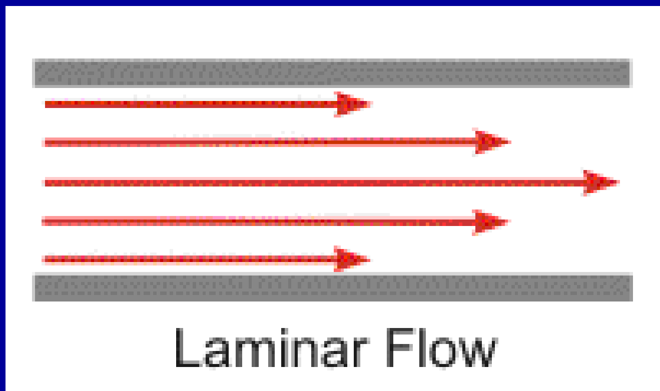


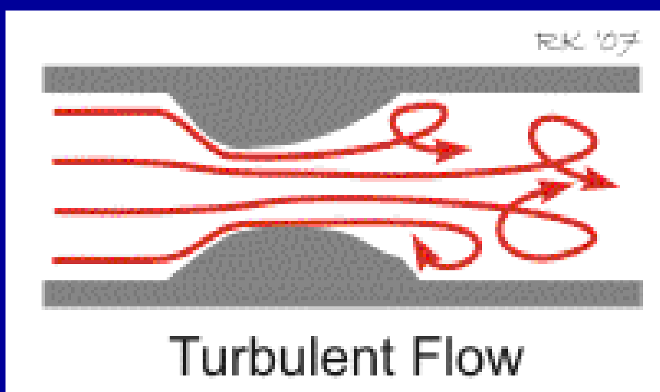
Notice turbulence decreases Specific Discharge, energy is lost to eddies

Darcy's Law is not valid for turbulent flow

WHY STUDY TURBULENT FLOW ?

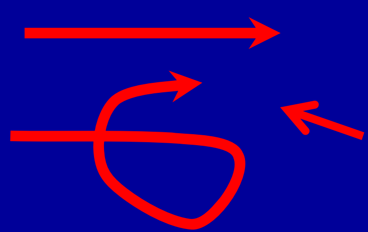
- **It's fundamental hydrology**





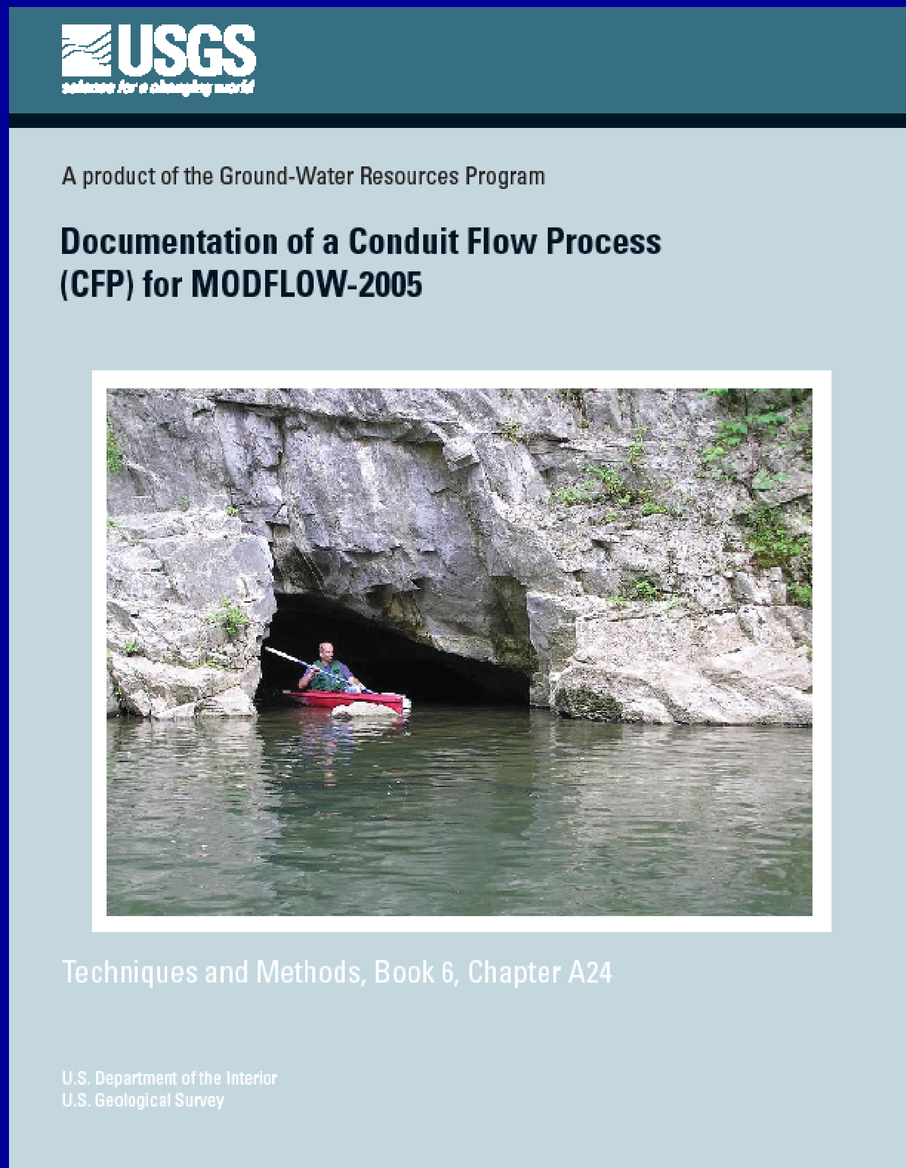
- **Could explain most groundwater movement in karst**

- **Implications for:**
  - **Fate of injected waters**
    - **ASR**
    - **Wastewater**
  - **Saltwater intrusion**
  - **Nutrient loading (from submarine groundwater discharge)**
  - **Contaminate transport**



Streamlines trace out the path of a 'mass-less' particle moving within the ground-water flow system.

Conduit Flow Process Mode 2 (CFPM2)



A product of the Ground-Water Resources Program

Documentation of a Conduit Flow Process (CFP) for MODFLOW-2005

Techniques and Methods, Book 6, Chapter A24

U.S. Department of the Interior
U.S. Geological Survey

CFPM2 Governing Flow Equation

Traditional MODFLOW with Darcy's Law and
laminar hydraulic conductivity

$$\frac{\partial}{\partial x}\left(Klam_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Klam_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Klam_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

CFP Mode 2 computes horizontal turbulent flow using
turbulent hydraulic conductivity.

$$\frac{\partial}{\partial x}\left(Kturb_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kturb_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Klam_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

CFPM2 Turbulent K

Turbulent horizontal hydraulic conductivity (K_{turb}) is a non-linear function of the Reynolds Number (Re) after critical Reynolds number (N_{Re}) is exceeded.

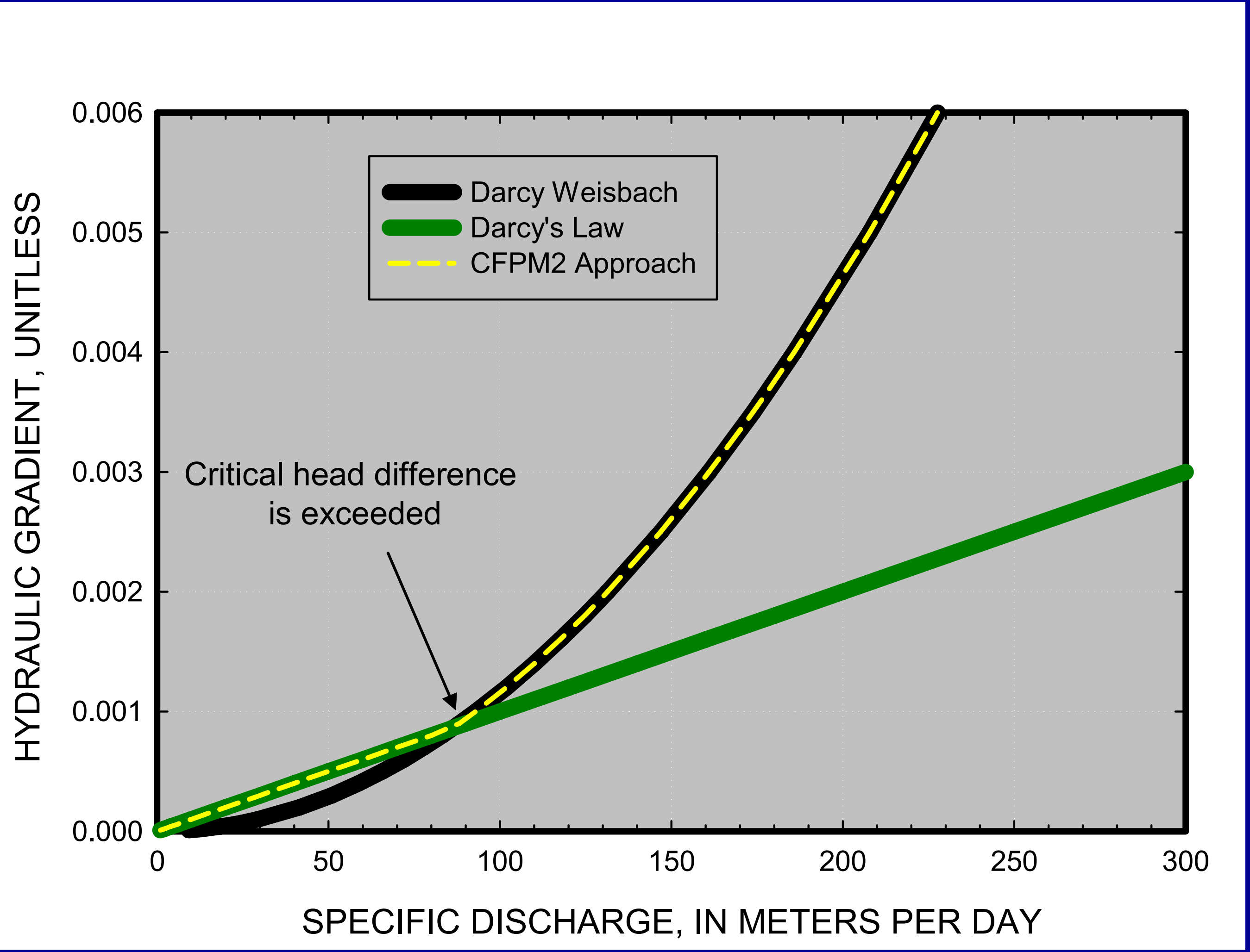
$$K_{turb} = F_{adj} K_{lam}$$

$$F_{adj\,kiter} = \sqrt{\frac{K_{lam} \Delta h_{crit}}{K_{turb\,kiter-1} \Delta h_{kiter-1}}}$$

Derived by Kuniansky and Halford, 2008

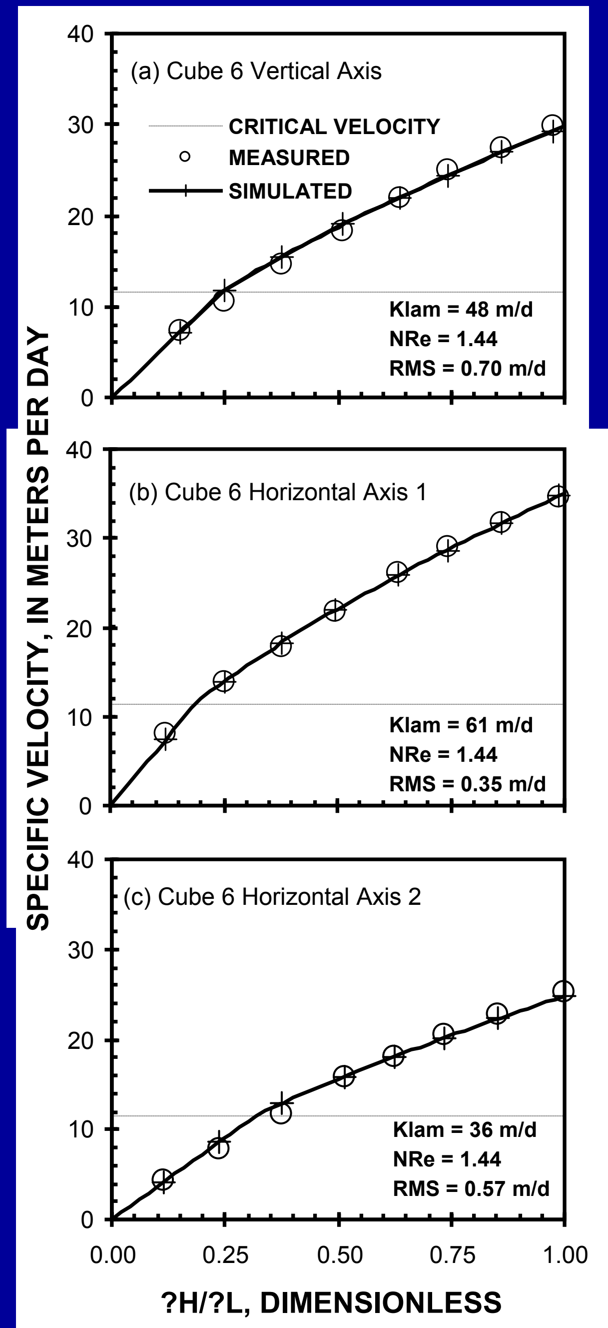
$$\Delta h_{crit} = \frac{N_{\mathrm{Re}} \Delta l v}{K_{lam} d_{pore}}$$

CFPM2 Benchmark Testing

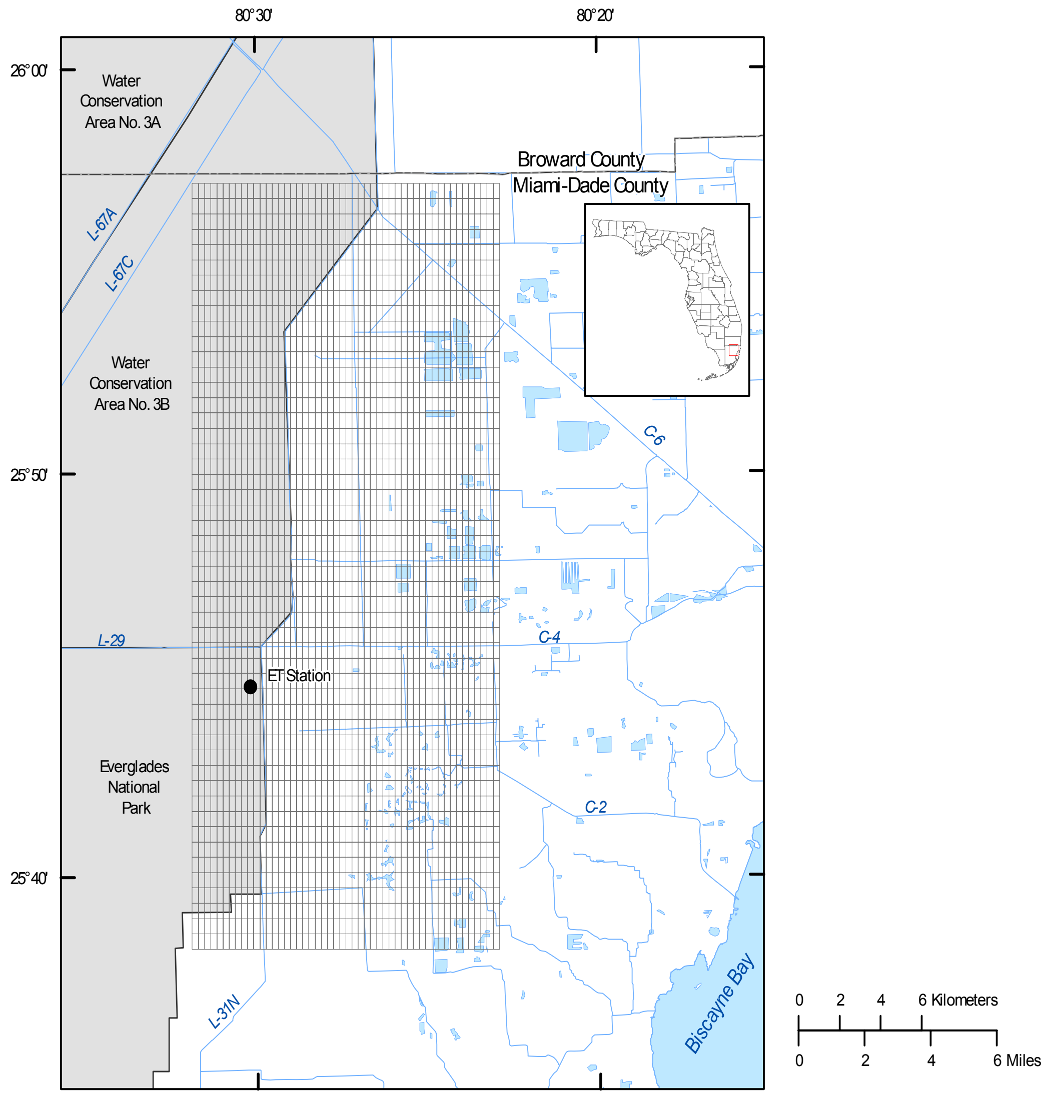


CFPM2 Testing

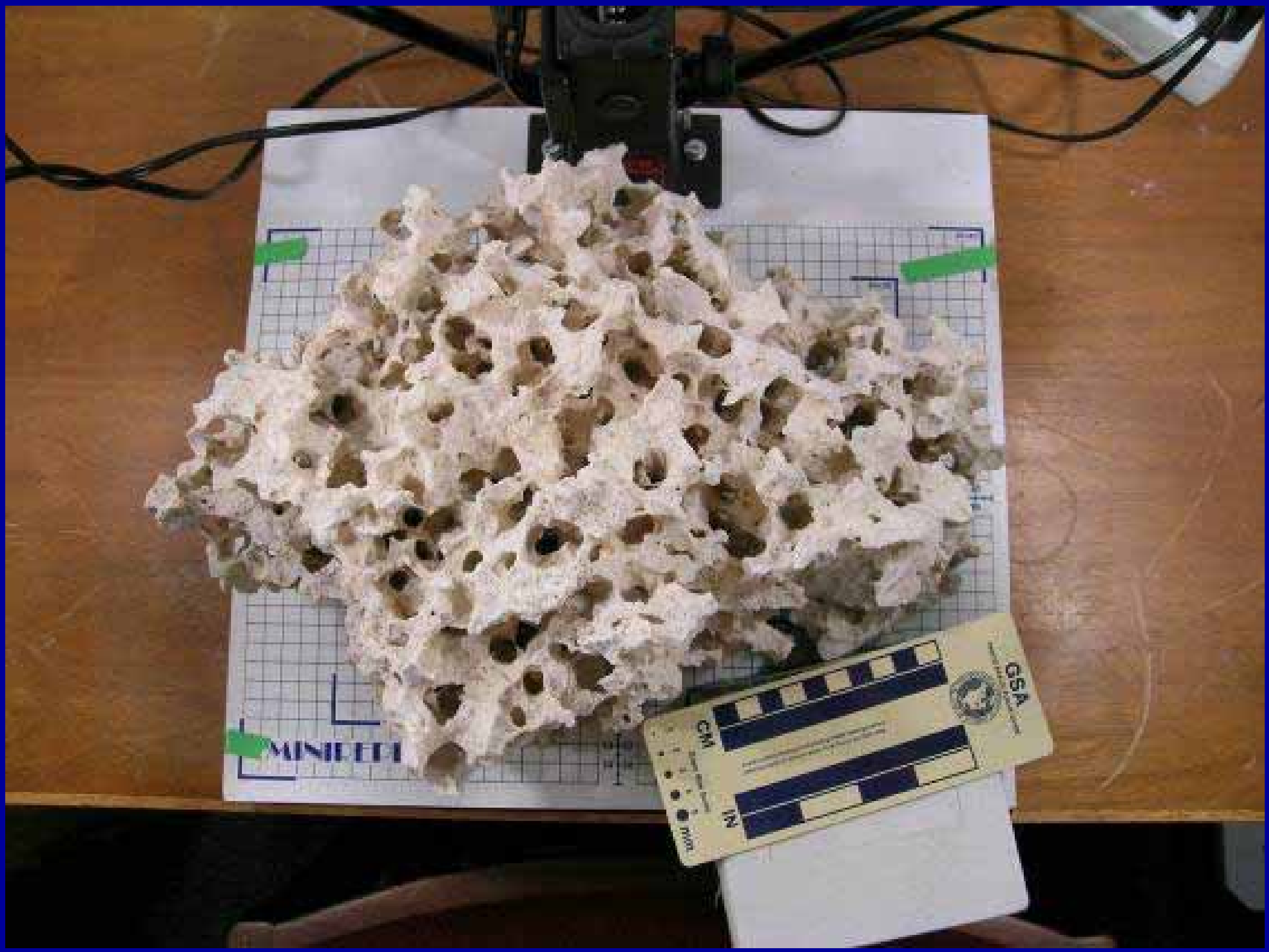
Permeameter Data Verify New Turbulence Process for MODFLOW By Eve L. Kuniansky and others.



CFPM2 APPLICATION TO BISCAYNE AQUIFER

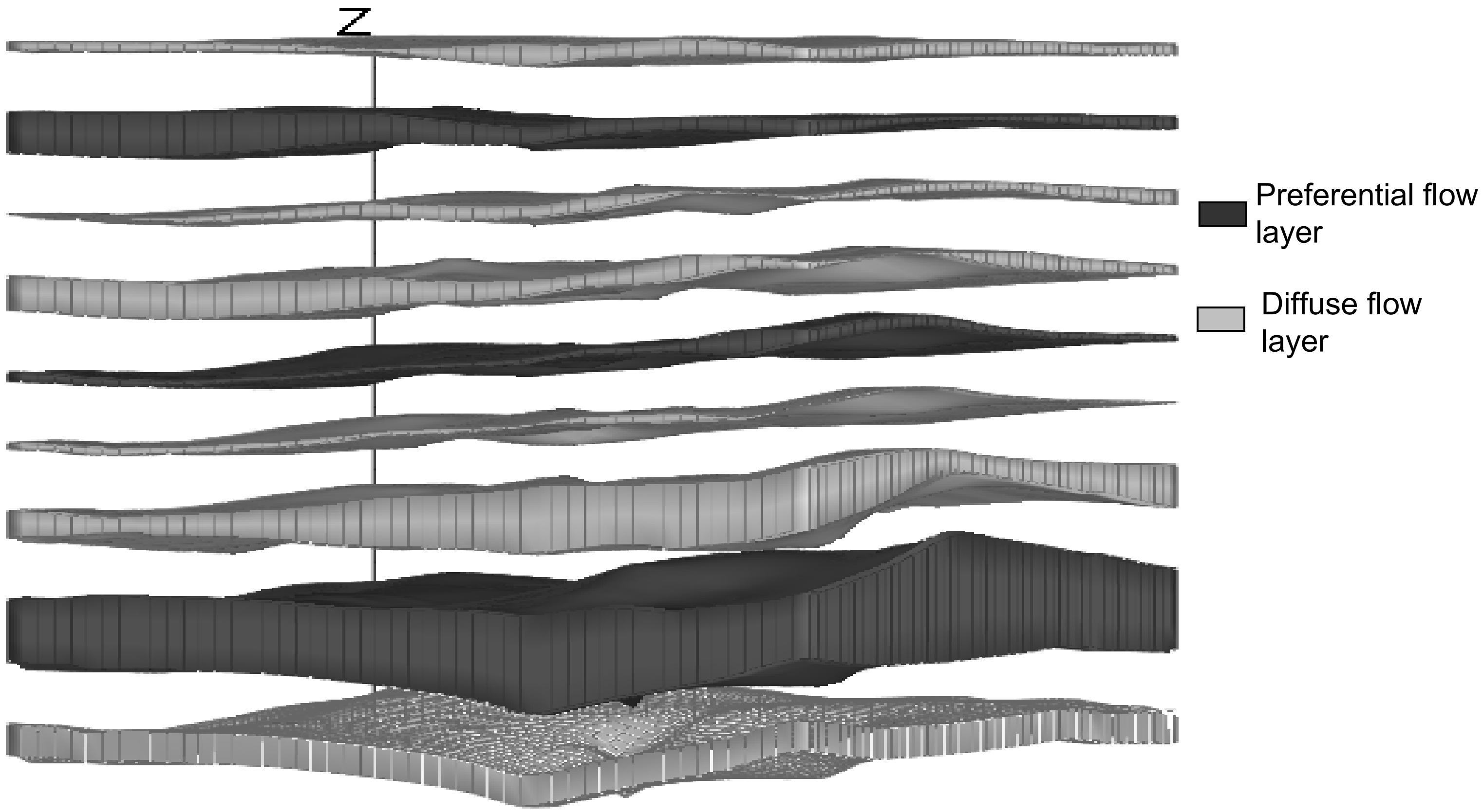


CFPM2 APPLICATION TO BISCAYNE AQUIFER



Picture from Kevin Cunningham, USGS

CFPM2 APPLICATION TO BISCAYNE AQUIFER



Hydrogeologic conceptualization of Lake Belt area from: Cunningham and Dixon, written communication

CFPM2 APPLICATION TO BISCAYNE AQUIFER

To estimate K_{lam}, one could use the resistance terms in the Darcy-Weisbach equation, limited by effective porosity. Limiting by effective porosity accounts for the resistance offered by "dead end" voids.

$$K_{lam} = \left(\frac{gd^2}{32v} \right) \theta$$

Derived by Eve Kuniansky, 2008

Table 1. Initial estimates of laminar horizontal hydraulic conductivity for preferential flow layers

Layer	Source Data	Number Wells	Mean Effective Porosity (%)	Number of Measurement On cores or images	Mean Vug Diameter (cm)	Laminar Horizontal Hydraulic Conductivity (meters per day)
2	Direct Measurement on cores	23	11.8	240	0.9	200,000
5	Direct Measurement on cores	6	18.3	65	0.8	300,000
8	Mostly Measurements from digital borehole wall images	22	14.8	438	3.5	5,000,000

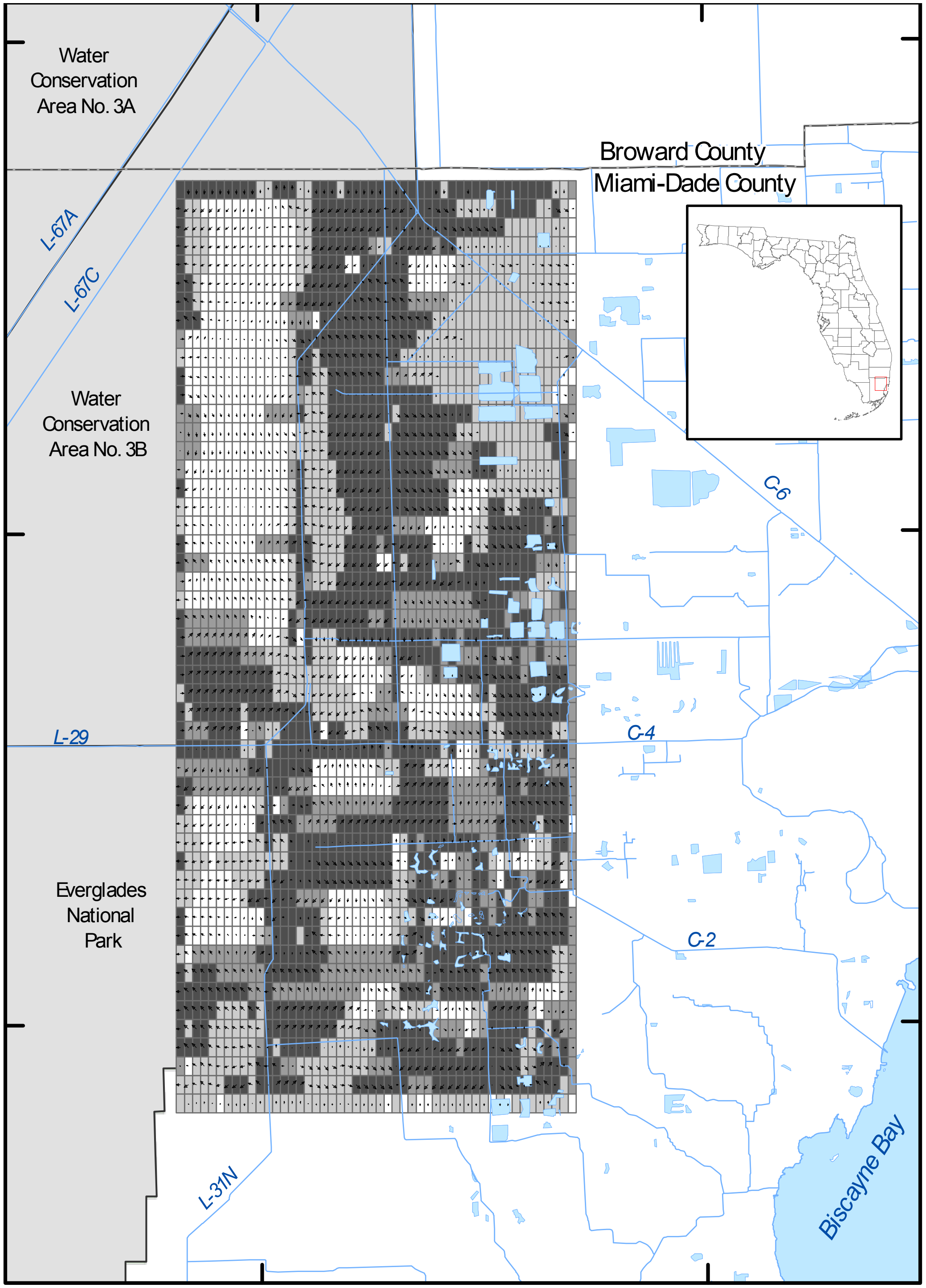
Data from Kevin Cunningham and others, 2006

CFPM2 APPLICATION TO BISCAYNE AQUIFER

Table 3. Critical Reynolds Numbers Assigned for Turbulent Model Scenarios

Scenario	N_{Re}
S1	11
S2	55
S3	440
S4	1100
S5	2200

Critical reynolds numbers are uncertain



Preliminary Run—layer 8

Upper critical Reynolds Number equals 55

Explanation

Flow vector

Canal or stream

Turbulence Codes

1 Flow to right and front are laminar

2 Flow to right is turbulant

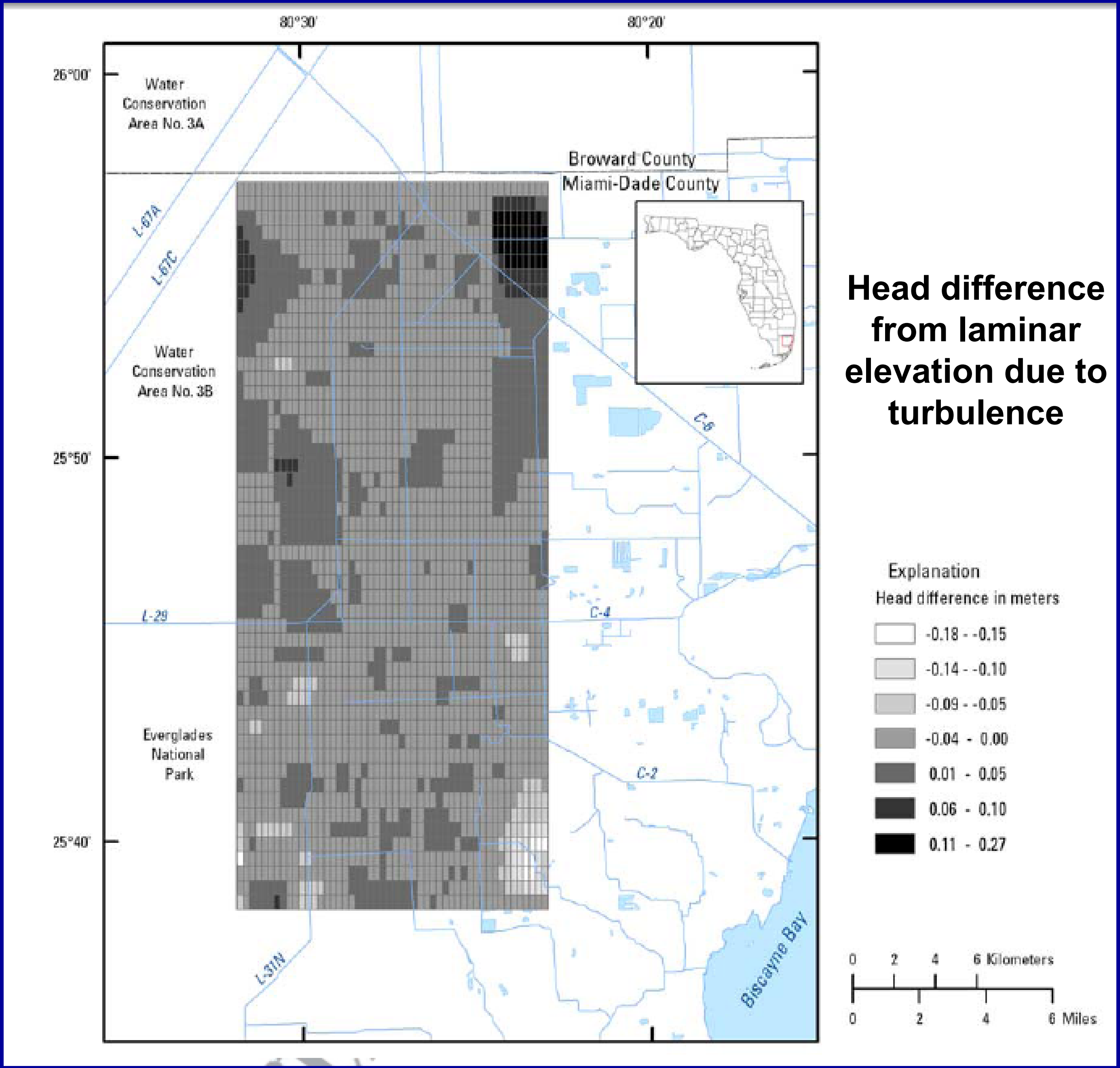
3 Flow to front is turbulant

4 Flow to right and front are turbulant

0 2 4 6 Kilometers

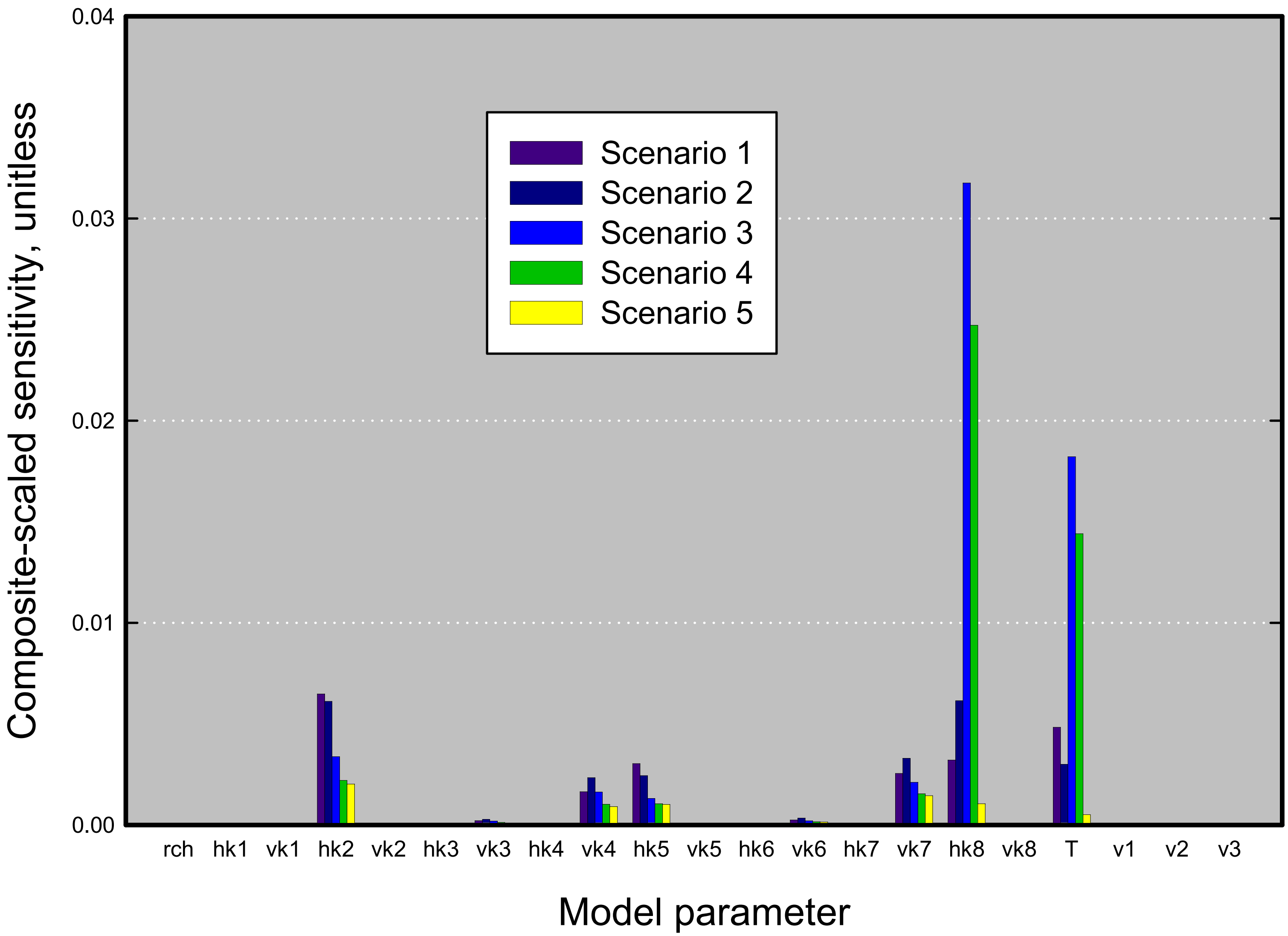
0 2 4 6 Miles

USGS



Head difference from laminar elevation due to turbulence

CFPM2 APPLICATION TO BISCAYNE AQUIFER



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Summary

1. Extent of turbulent flow increases with increasing hydraulic conductivity, mean void diameter, groundwater temperature, and decreasing critical Reynolds numbers.

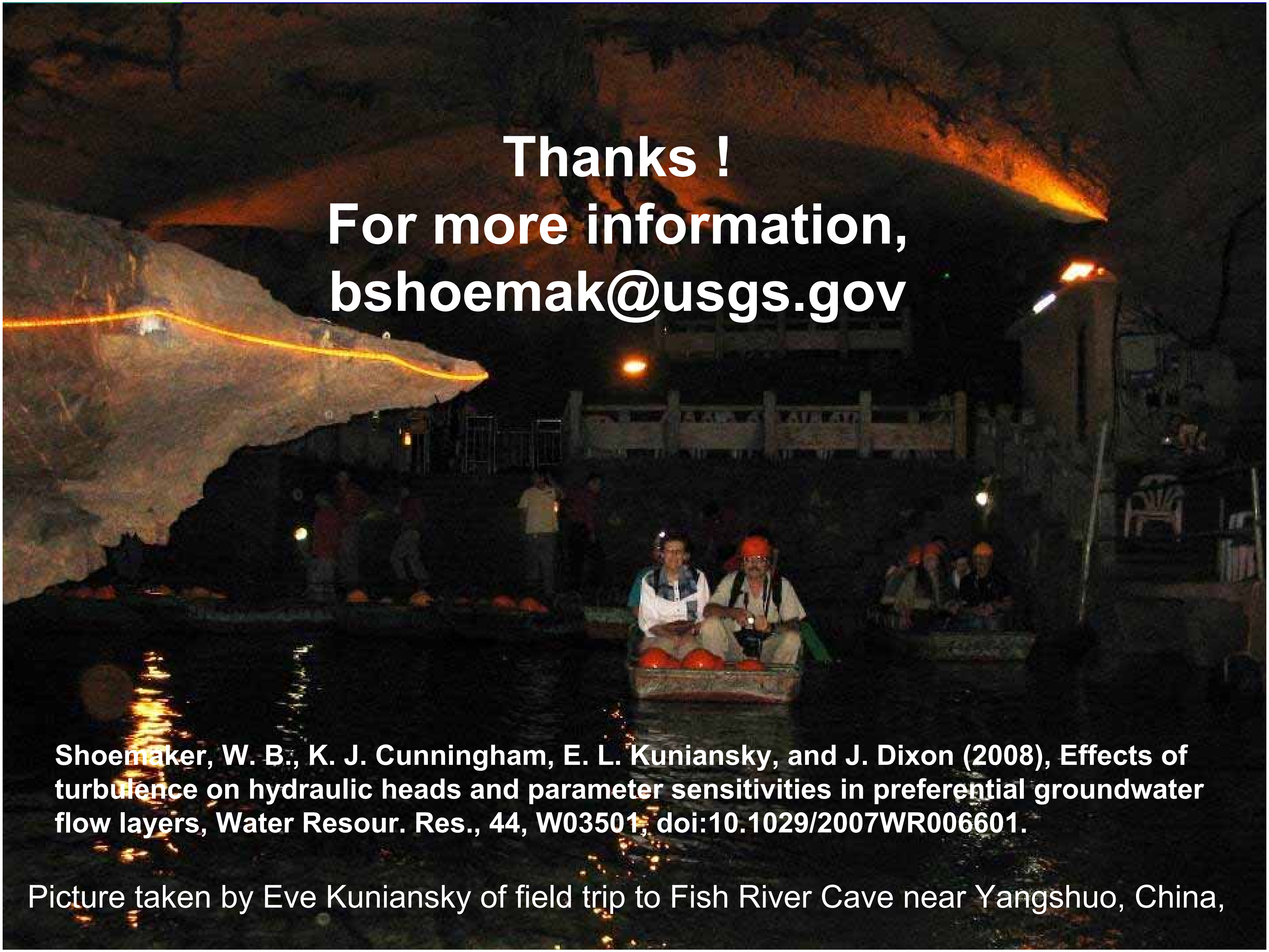
2. When turbulence was active (occurring in about 56% of preferential flow model cells), head differences from laminar elevations ranged from about 18 to +27 cm.

3. The composite-scaled sensitivities of horizontal hydraulic conductivities decreased by as much as 70% when turbulence was essentially removed.

4. This study highlights potential errors in model calculations based on the equivalent porous media assumption, which assumes laminar flow in uniformly distributed void spaces

Limitations

- Macro-scale simplification of impacts of turbulent flow
- Vast uncertainty in aquifer hydraulic properties and boundaries
- Theory is sound, but applications on systems with uncertainty may produce unreliable predictions



Thanks !

For more information,

bshoemak@usgs.gov

Shoemaker, W. B., K. J. Cunningham, E. L. Kuniansky, and J. Dixon (2008), Effects of turbulence on hydraulic heads and parameter sensitivities in preferential groundwater flow layers, Water Resour. Res., 44, W03501, doi:10.1029/2007WR006601.

Picture taken by Eve Kuniansky of field trip to Fish River Cave near Yangshuo, China,