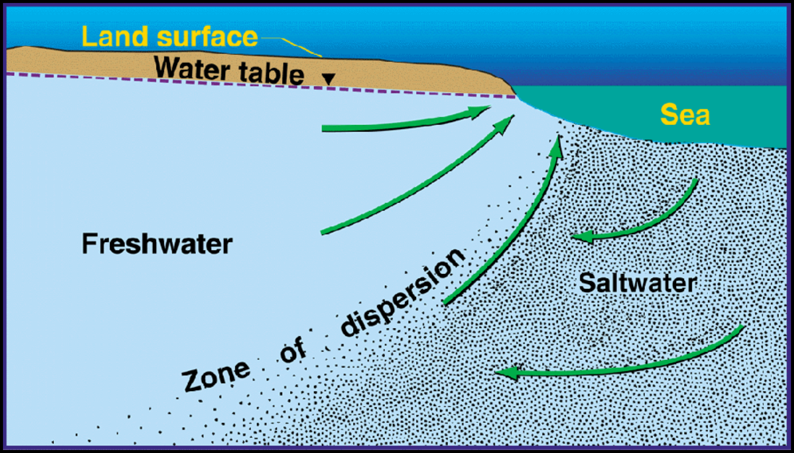
Saltwater Intrusion in Southeast Florida

The past, present, and future of saltwater intrusion studies in Southeast Florida



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

Outline

- The problem and southeast Florida's role in understanding saltwater intrusion
- The basics – flow and transport
- Benchmark southeast Florida studies
- Recent southeast Florida studies
- The future of salt water intrusion studies

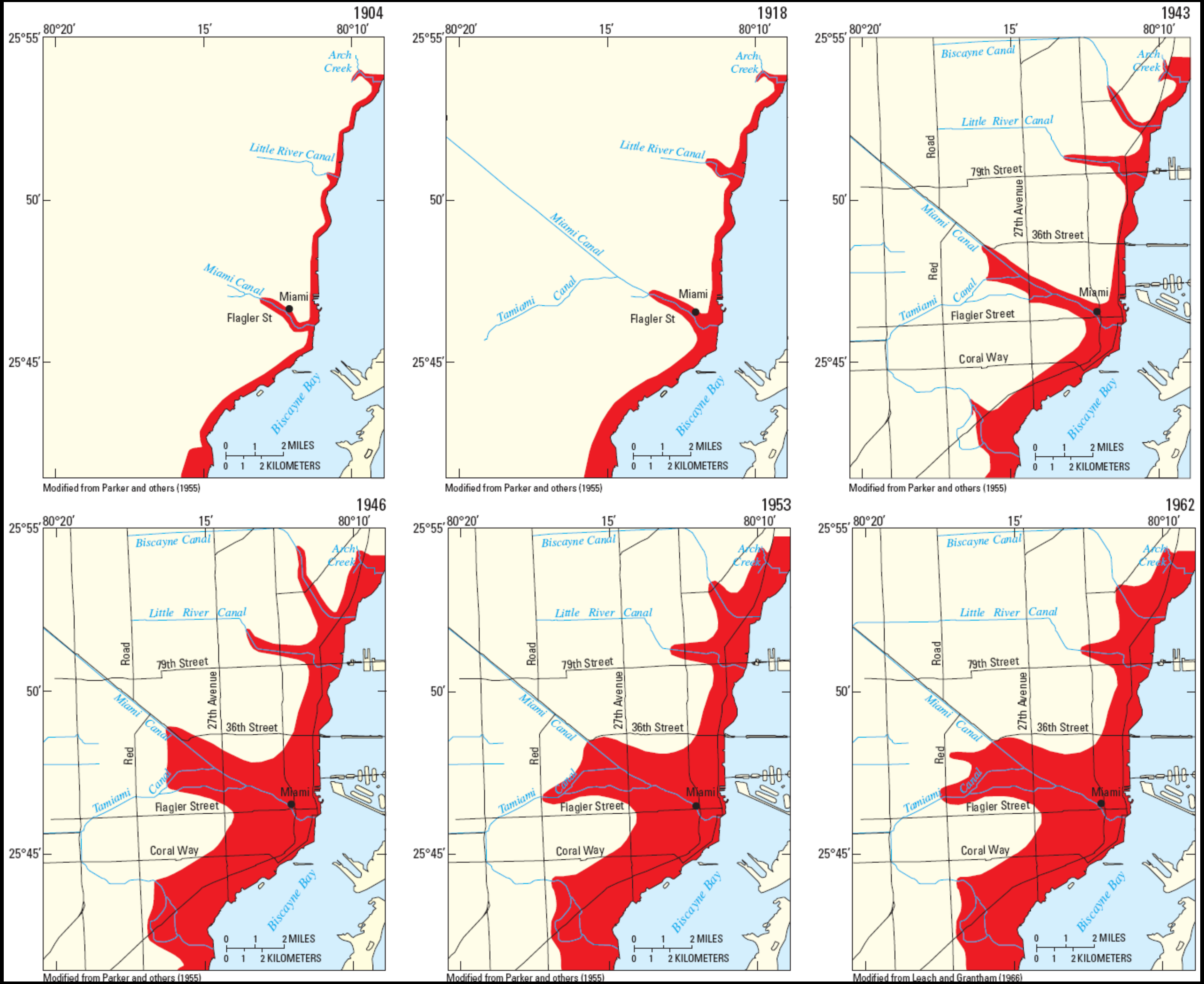
THE PROBLEM

Saltwater Intrusion in SE Florida

- H.H. Cooper (1964)
    - Over a period of about 35 years the seawater in the Biscayne aquifer of southeastern Florida advanced progressively inland, owing to a lowering of the fresh-water head.
    - Drainage of the Everglades was the principle cause of the lowering of the fresh-water head.
    - Applying the Gyben-Herzberg relation, Parker predicted saltwater at the base of the Biscayne aquifer would continue to advance and come to rest in equilibrium with the freshwater at the average annual 2.5 ft water table contour

Cooper, H. H., 1964, Sea water in coastal aquifers: U.S. Geological Survey Water-Supply Paper 1613-C, p. ii-v

Saltwater Intrusion in SE Florida



Modified from Parker and others (1955)

Modified from Leach and Grantham (1966)

Renken et al. (2005)

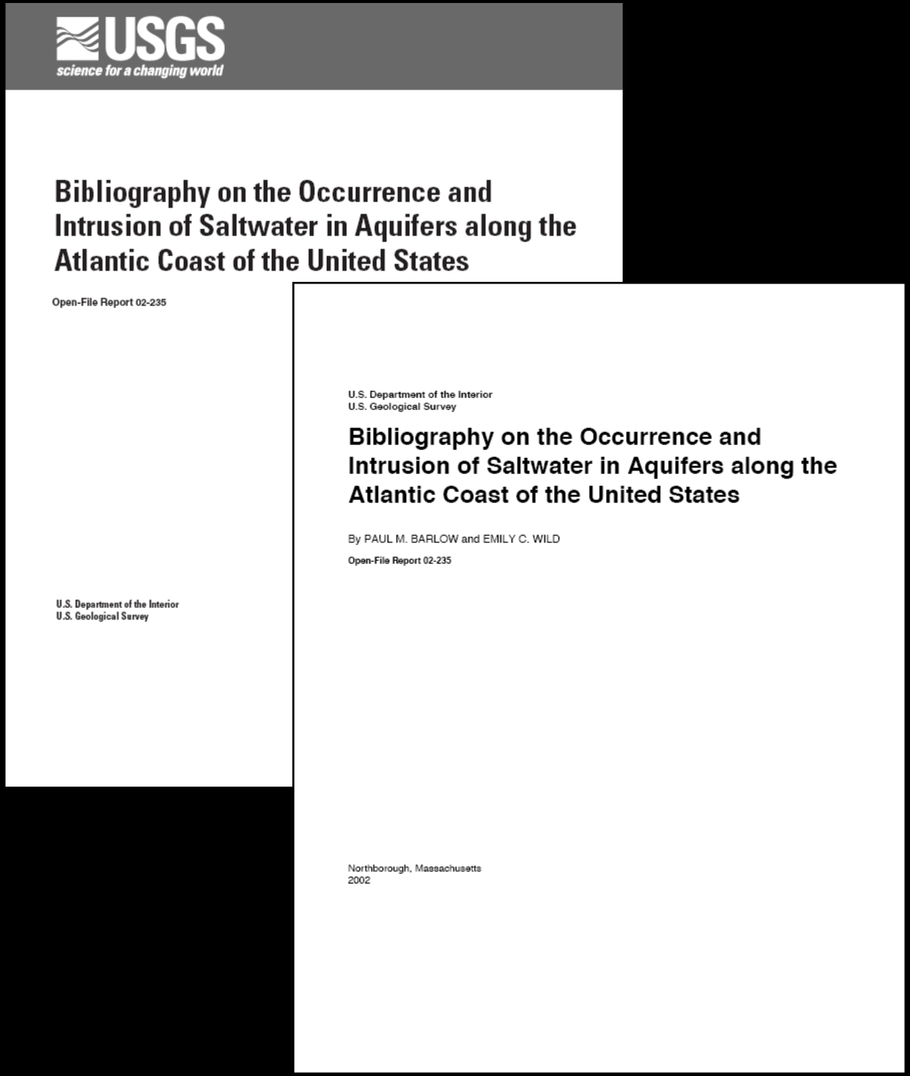
Saltwater Intrusion in SE Florida

- **H.H. Cooper (1964)**
    - **Advancement of the salt water wedge was of concern because it was predicted to eventually envelop numerous water-supply wells, including those of the Miami municipal supply in the Miami Springs well field.**
    - **The advancement of the salt water appeared to cease in the 1950's as much as 8 miles seaward of the predicted position.**
    - **Whether the front had stabilized or its advance had merely slowed was not only a matter of economic importance but of scientific interest because the premature stabilization could not be explained by any known theory.**
    - **The USGS began to investigate the phenomenon of saltwater circulation in 1957.**

Cooper, H. H., 1964, Sea water in coastal aquifers: U.S. Geological Survey Water-Supply Paper 1613-C, p. ii-v

Florida saltwater intrusion studies

- **>200 published studies as of 2002**
- **Earliest known study evaluating salt water intrusion**
  - **Stringfield, V.T., 1936, Artesian water in the Florida peninsula: U.S. Geological Survey Water-Supply Paper 773-C, p. 115–195.**



USGS
science for a changing world

Bibliography on the Occurrence and Intrusion of Saltwater in Aquifers along the Atlantic Coast of the United States

Open-File Report 02-235

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

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

Bibliography on the Occurrence and Intrusion of Saltwater in Aquifers along the Atlantic Coast of the United States

By PAUL M. BARLOW and EMILY C. WILD

Open-File Report 02-235

Northborough, Massachusetts
2002

Open-File Report 02-235
http://pubs.usgs.gov/of/2002/ofr02235/

THE BASICS

Flow in porous media

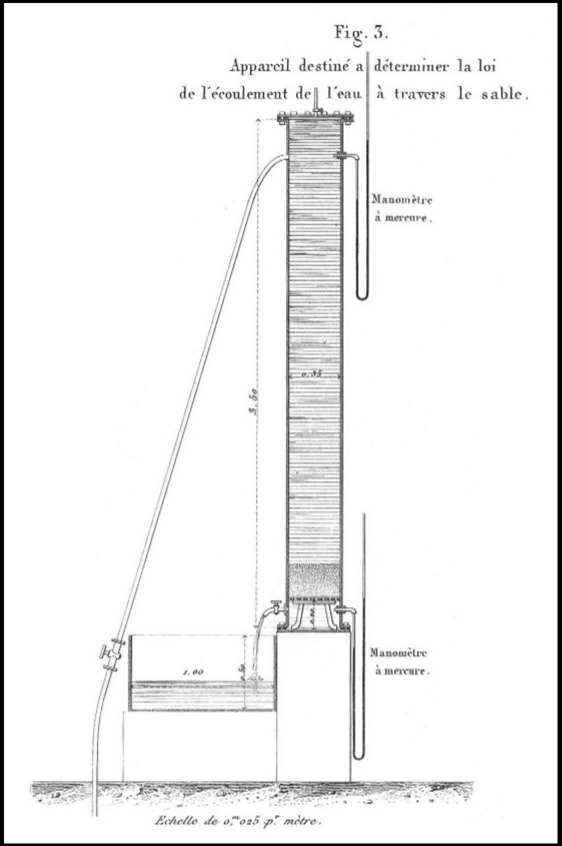
Henry Philibert Gaspard Darcy

http://en.wikipedia.org/wiki/Henry_Darcy

$$q = k\frac{s}{e}\left(h + e \pm h_o\right)$$

$$\Downarrow$$

$$q = KA\frac{\left(h + e \pm h_o\right)}{e}$$



Darcy H (1856) Les Fontaines Publiques de la Ville de Dijon [The Public Fountains of the City of Dijon]. Dalmont, Paris

Were not out of the woods yet

Pressure vs. fluid/force potential

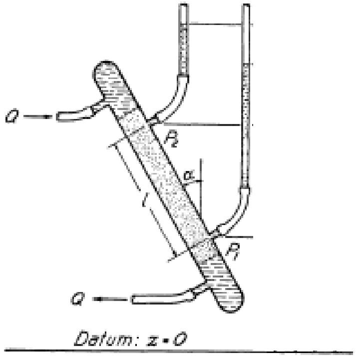
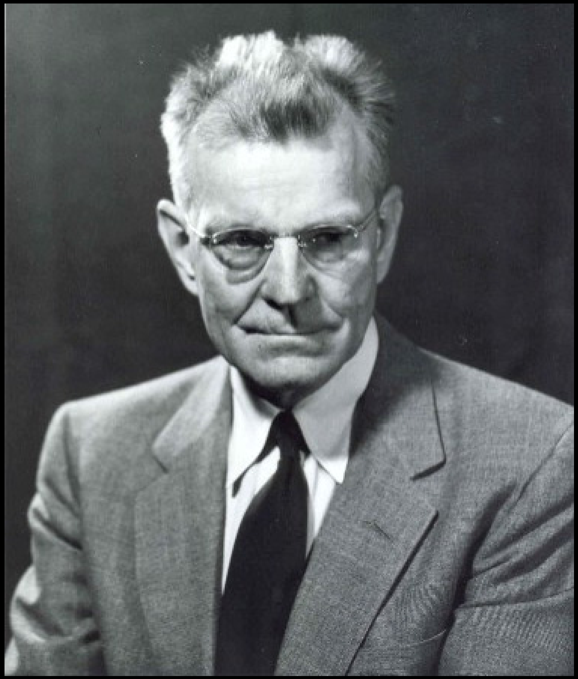


FIG. 1.—Apparatus for studying the flow of liquid through a permeable material.

INCOMPLETE

$$q = -K \cdot \frac{dp}{dl}$$



M. King Hubbert
http://www.hubbertpeak.com/hubbert/

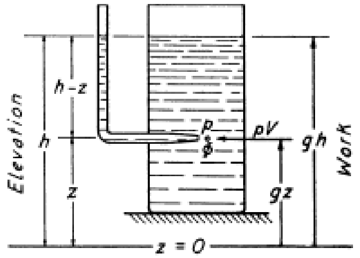
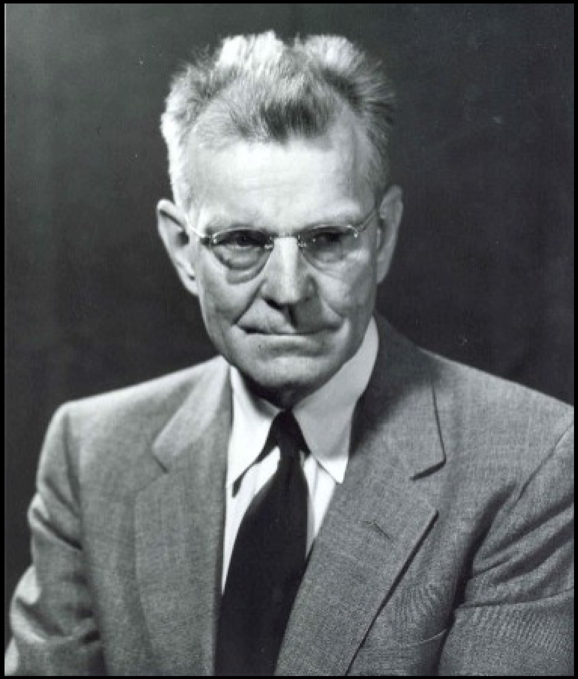


FIG. 5.—Fluid potential at any point inside a body of static liquid

$$q = -K \cdot \frac{dh}{dl} = -K \cdot \frac{1}{g} \cdot \frac{d\Phi}{dl}$$

Hubbert, M. K. (1940) The theory of ground-water motion. Journal of Geology 48, 785-944. Excerpts: p. 785-803, 924-930, 941-944.

Immiscible and miscible fluids



M. King Hubbert
http://www.hubbertpeak.com/hubbert/

$$\Phi_i = gz + \frac{\rho - \rho_o}{\rho_i}$$

$$\frac{\partial \Phi_i}{\partial s} = g \cdot \frac{\partial z}{\partial s} + \frac{1}{\rho_i} \frac{\partial p}{\partial s}$$

$$-\nabla \Phi_i = +\mathbf{g} - \frac{1}{\rho_i} \nabla p$$

Hubbert, M. K. (1940) The theory of ground-water motion. Journal of Geology 48, 785-944. Excerpts: p. 785-803, 924-930, 941-944.

Diffusion/Dispersion

$$D = Mv^n \text{ (Rifai et al., 1956)}$$

$$D = \alpha v + D_m$$

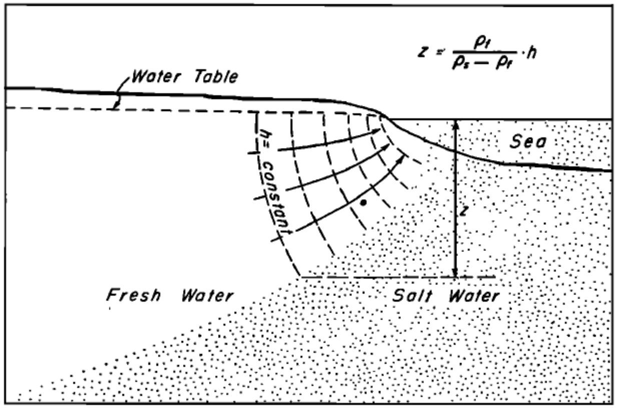


Fig. 1—Balance between fresh water and salt water in a coastal aquifer, with the salt water static

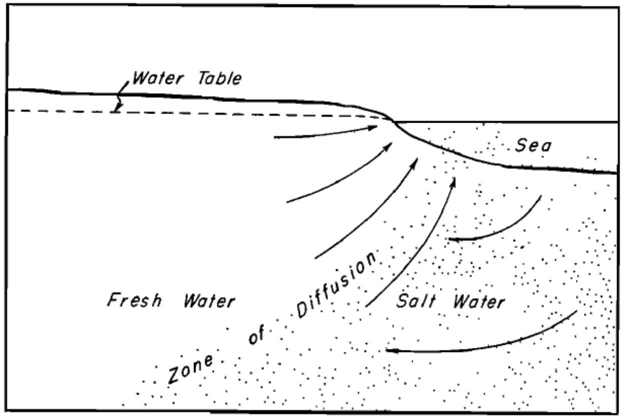


Fig. 2—Circulation of salt water from the sea to the zone of diffusion and back to the sea

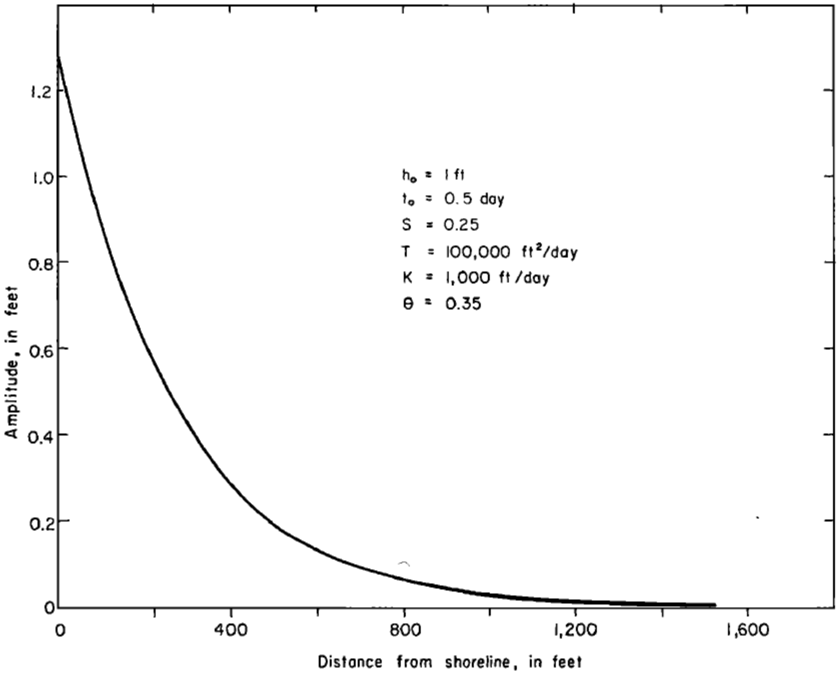


Fig. 6. Amplitude of tide-produced motion of water in a coastal aquifer

Cooper, H.H. (1959), A hypothesis concerning the dynamic balance of fresh water and salt water in a coastal aquifer: Journal of Geophysical Research, v. 64, no. 4, p. 461–467

Flow and Transport Equations

Groundwater Flow:

$$(S_w \rho S_{op} + \varepsilon \frac{\partial S_w}{\partial p}) \frac{\partial p}{\partial t} + \varepsilon S_w \left(\sum_{k=1}^{NS} \frac{\partial p}{\partial C_k} \frac{\partial C_k}{\partial t} + \frac{\partial p}{\partial T} \frac{\partial T}{\partial t} \right) - \nabla \cdot \left[\left(\frac{\mathbf{k} k_r}{\mu} \right) \cdot (\nabla p - \rho \mathbf{g}) \right] = Q_p$$

Storage

Mass

Pressure Forces

Buoyant Forces

Total Mass Change

Mass Flux

Mass Source/Sink

Groundwater Transport:

$$\left[\varepsilon S_w \rho c_{wk} + (1-\varepsilon) \rho_s c_{sk} \right] \frac{\partial U_k}{\partial t} + \varepsilon S_w \rho c_{wk} \mathbf{v} \cdot \nabla U_k - \nabla \cdot \left\{ \rho c_{wk} \left[\varepsilon S_w \left(\sigma_{wk} \mathbf{I} + \mathbf{D}_k \right) + (1-\varepsilon) \sigma_{sk} \mathbf{I} \right] \cdot \nabla U_k \right\} = Q_p c_{wk} \left(U_k^* - U_k \right)$$

Solute

Matrix Sorption

Velocity

Fluid Molecular

Matrix Diffusivity

Solute Change

Advective Solute Flux

Dispersive Solute Flux

Solute Source/Sink

Solute- Temperature-density/viscosity relation:

$$u = u_o + \sum_{k=1}^{NS} \frac{\partial u}{\partial C_k} \left(C_k - C_{k_o} \right) + \frac{\partial u}{\partial T} \left(T - T_o \right) + \frac{\partial u}{\partial p} \left(p - p_o \right), \quad u = \rho \text{ or } \mu$$

BENCHMARK SOUTHEAST FLORIDA STUDIES

Hilton H. Cooper, Jr.

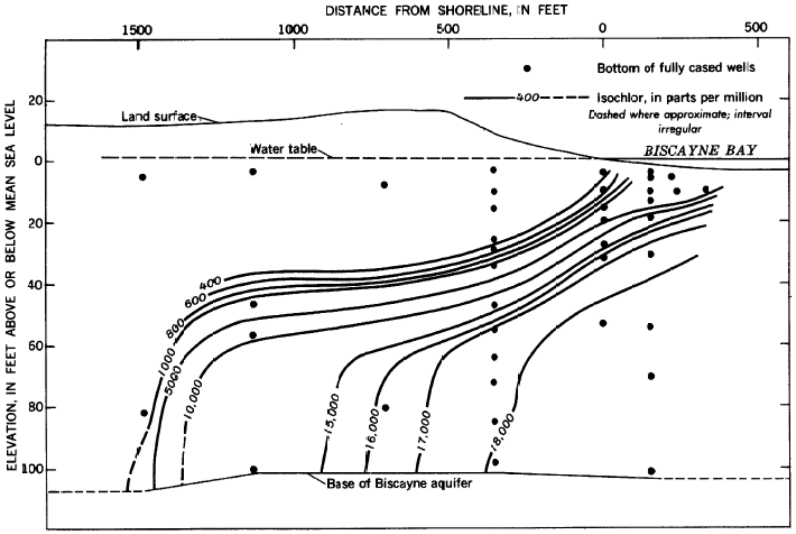


FIGURE 5.—Section through the Cutler area, near Miami, Fla., showing the zone of diffusion, September 8, 1958.

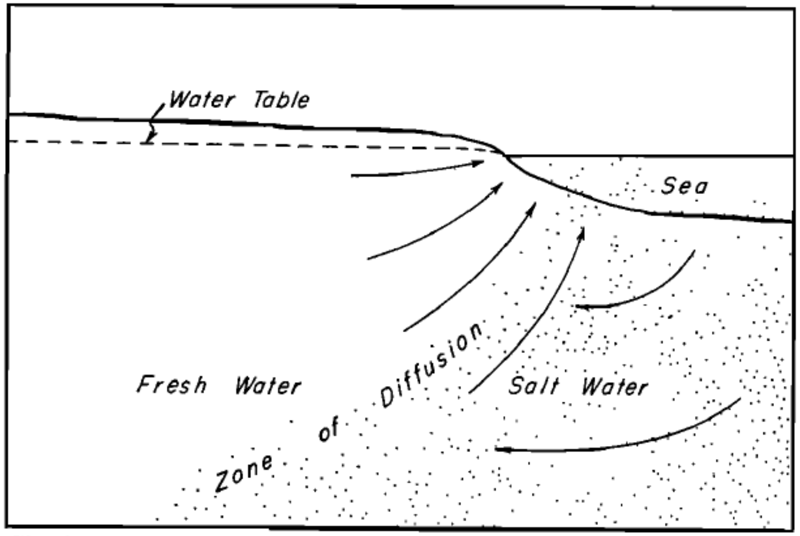


FIG. 2—Circulation of salt water from the sea to the zone of diffusion and back to the sea

Cooper, H.H. (1964), A hypothesis concerning the dynamic balance of fresh water and salt water in a coastal aquifer: U.S. Geological Survey Water-Supply Paper 1613-C, p. 1-12

Francis A. Kohout

F.A. Kohout (on left)
http://sofia.usgs.gov/projects/index.php?project_url=grndwtr_disch/

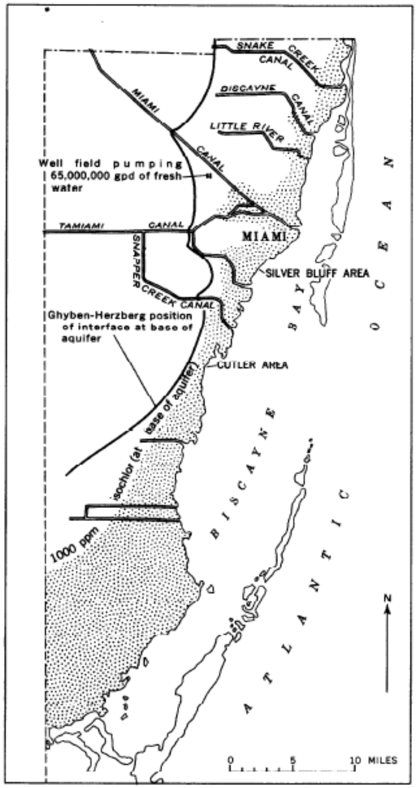


FIGURE 7.—Map of the eastern part of Dade County, Fla., showing the theoretical Ghyben-Herzberg position and the actual position of salt water at the base of the Biscayne aquifer.

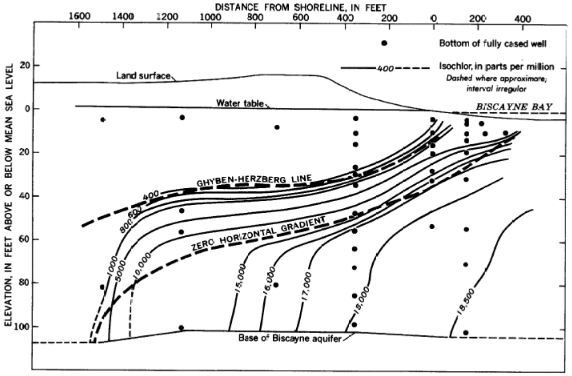


FIGURE 9.—Cross section through the Cutler area, near Miami, Fla., showing the position of the line of zero horizontal gradient (traced from fig. 17) within the zone of diffusion, September 18, 1958.

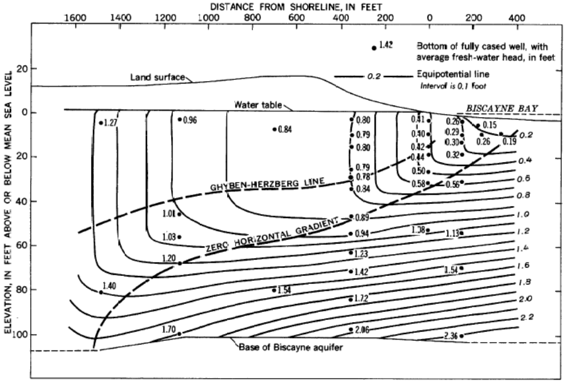
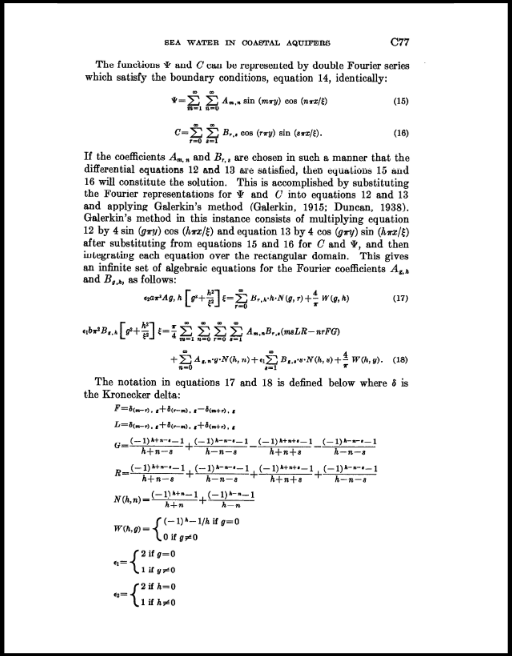


FIGURE 17.—Cross section through the Cutler area, near Miami, Fla., showing lines of equal fresh-water potential for a low-head condition; average for September 18, 1958.

Kohout, F.A., 1964, The flow of fresh water and salt water in the Biscayne aquifer of the Miami area, Florida: U.S. Geological Survey Water-Supply Paper 1613-C, p. 12-32

Harold R. Henry



SEA WATER IN COASTAL AQUIFERS C77

The functions Ψ and C can be represented by double Fourier series which satisfy the boundary conditions, equation 14, identically:

$$\Psi=\sum_{m=1}^{\infty}\sum_{n=0}^{\infty} A_{m,n}\sin(m\pi y)\cos(n\pi x/\xi) \qquad (15)$$

$$C=\sum_{r=0}^{\infty}\sum_{s=1}^{\infty} B_{r,s}\cos(r\pi y)\sin(s\pi x/\xi). \qquad (16)$$

If the coefficients $A_{m,n}$ and $B_{r,s}$ are chosen in such a manner that the differential equations 12 and 13 are satisfied, then equations 15 and 16 will constitute the solution. This is accomplished by substituting the Fourier representations for Ψ and C into equations 12 and 13 and applying Galerkin's method (Galerkin, 1915; Duncan, 1938). Galerkin's method in this instance consists of multiplying equation 12 by 4 sin $(g\pi y)$ cos $(h\pi x/\xi)$ and equation 13 by 4 cos $(g\pi y)$ sin $(h\pi x/\xi)$ after substituting from equations 15 and 16 for C and Ψ, and then integrating each equation over the rectangular domain. This gives an infinite set of algebraic equations for the Fourier coefficients $A_{g,h}$ and $B_{g,h}$, as follows:

$$\epsilon_2 a\pi^2 Ag,h\left[g^2+\frac{h^2}{\xi^2}\right]\xi=\sum_{r=0}^{\infty} B_{r,h}\cdot h\cdot N(g,r)+\frac{4}{\pi}W(g,h) \qquad (17)$$

$$\epsilon_1 b\pi^2 B_{g,h}\left[g^2+\frac{h^2}{\xi^2}\right]\xi=\frac{\pi}{4}\sum_{m=1}^{\infty}\sum_{n=0}^{\infty}\sum_{r=0}^{\infty}\sum_{s=1}^{\infty} A_{m,n}B_{r,s}(msLR-nrFG)$$
$$+\sum_{n=0}^{\infty} A_{g,n}\cdot g\cdot N(h,n)+\epsilon_1\sum_{s=1}^{\infty} B_{g,s}\cdot s\cdot N(h,s)+\frac{4}{\pi}W(h,y). \qquad (18)$$

The notation in equations 17 and 18 is defined below where δ is the Kronecker delta:

$$F=\delta_{(m-r),s}+\delta_{(r-m),s}-\delta_{(m+r),s}$$

$$L=\delta_{(m-r),s}+\delta_{(r-m),s}+\delta_{(m+r),s}$$

$$G=\frac{(-1)^{h+n-s}-1}{h+n-s}+\frac{(-1)^{h-n-s}-1}{h-n-s}-\frac{(-1)^{h+n+s}-1}{h+n+s}-\frac{(-1)^{h-n-s}-1}{h-n-s}$$

$$R=\frac{(-1)^{h+n-s}-1}{h+n-s}+\frac{(-1)^{h-n-s}-1}{h-n-s}+\frac{(-1)^{h+n+s}-1}{h+n+s}+\frac{(-1)^{h-n-s}-1}{h-n-s}$$

$$N(h,n)=\frac{(-1)^{h+n}-1}{h+n}+\frac{(-1)^{h-n}-1}{h-n}$$

$$W(h,g)=\begin{cases}(-1)^h-1/h \text{ if } g=0\\ 0 \text{ if } g\neq 0\end{cases}$$

$$\epsilon_1=\begin{cases}2 \text{ if } g=0\\ 1 \text{ if } y\neq 0\end{cases}$$

$$\epsilon_2=\begin{cases}2 \text{ if } h=0\\ 1 \text{ if } h\neq 0\end{cases}$$

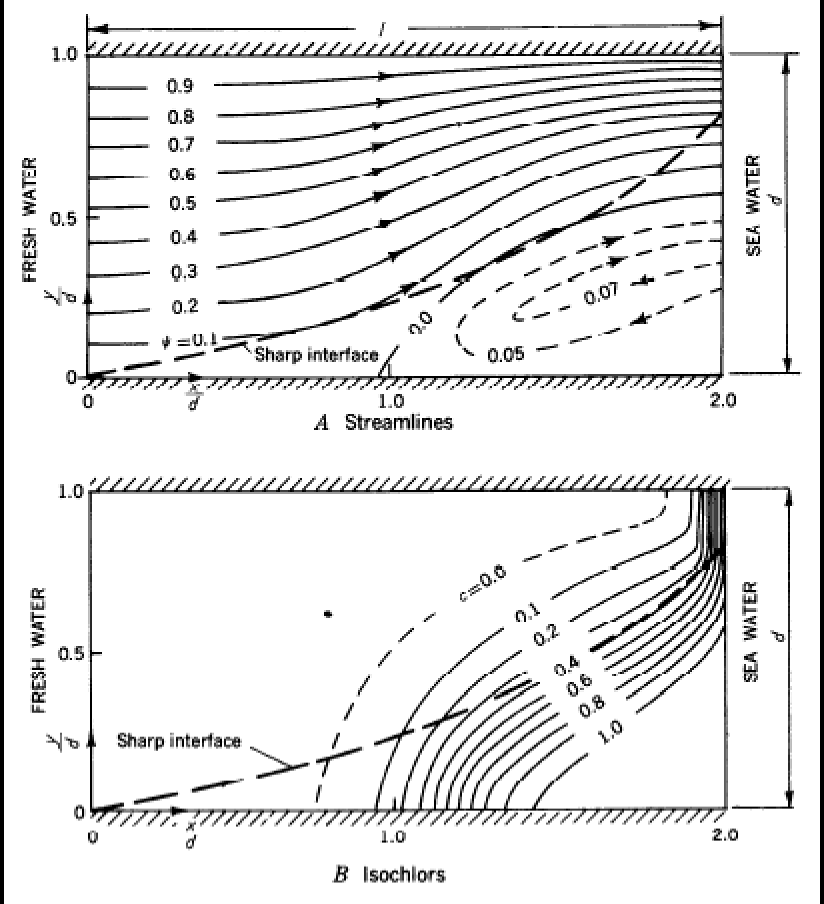


FIGURE 34.—Flow and salt concentration patterns in an idealized mathematical model.

Harold R. Henry

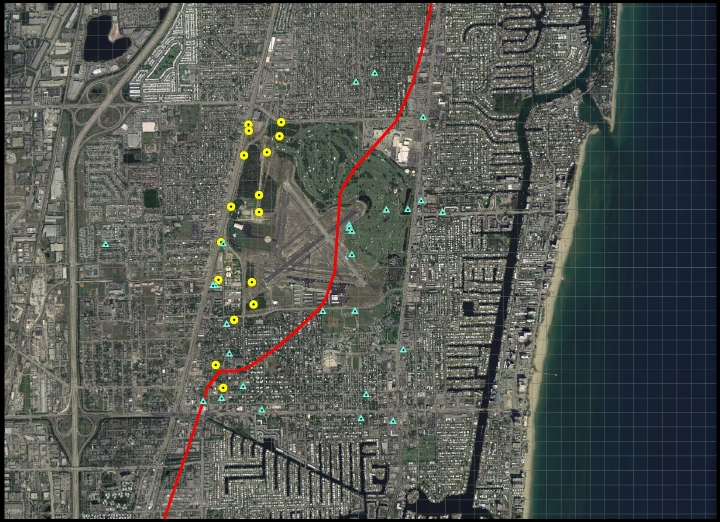
http://www.icr.org/index.php?module=articles&action=view&ID=163/

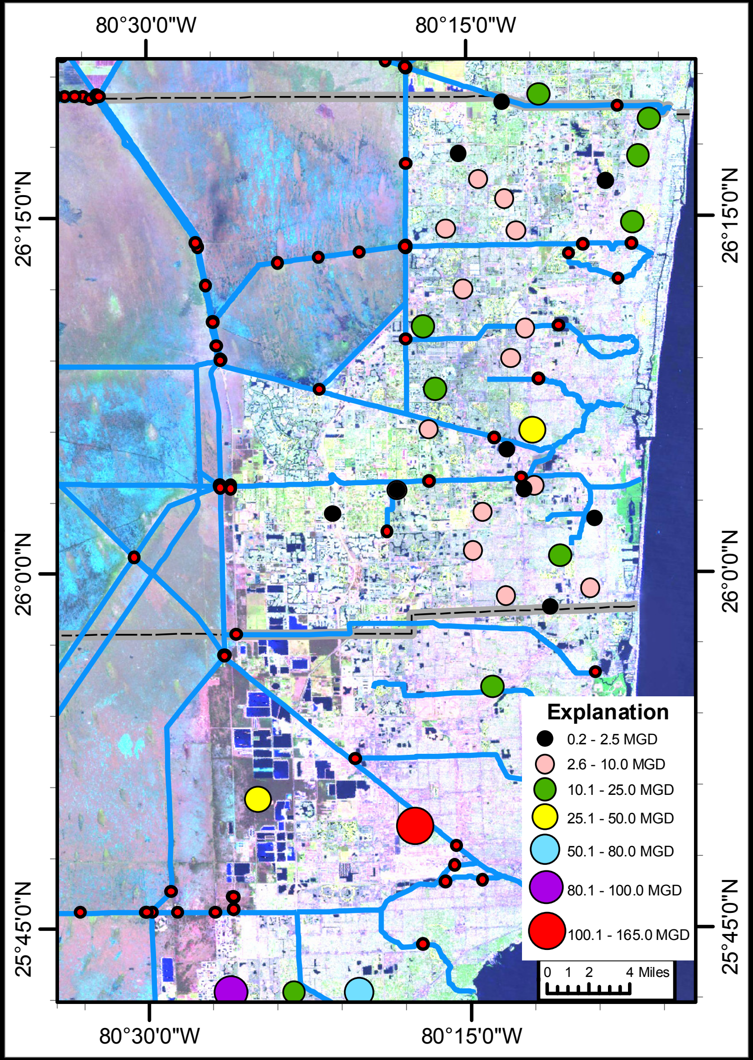
Henry, H. R., 1964, Effects of dispersion on salt encroachment in coastal aquifers: U.S. Geological Survey Water-Supply Paper 1613-C, p. 70-82

RECENT STUDIES

Broward County

- Historic evaluation of saltwater intrusion at a municipal well field

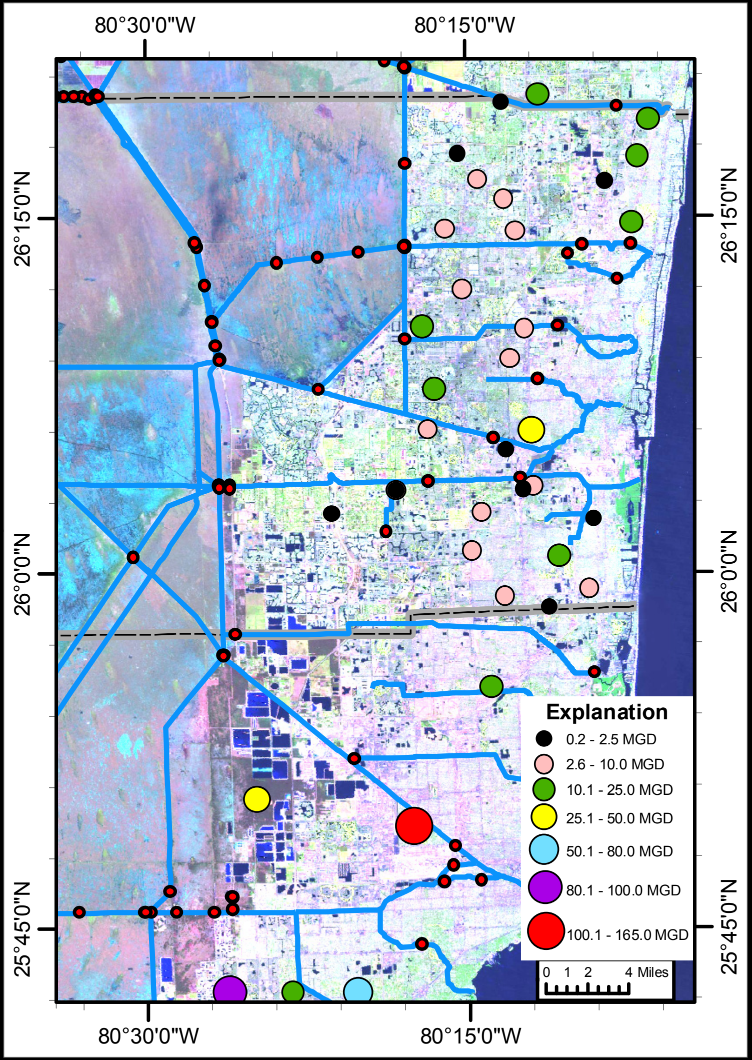




Data from Renken et al. (2005)

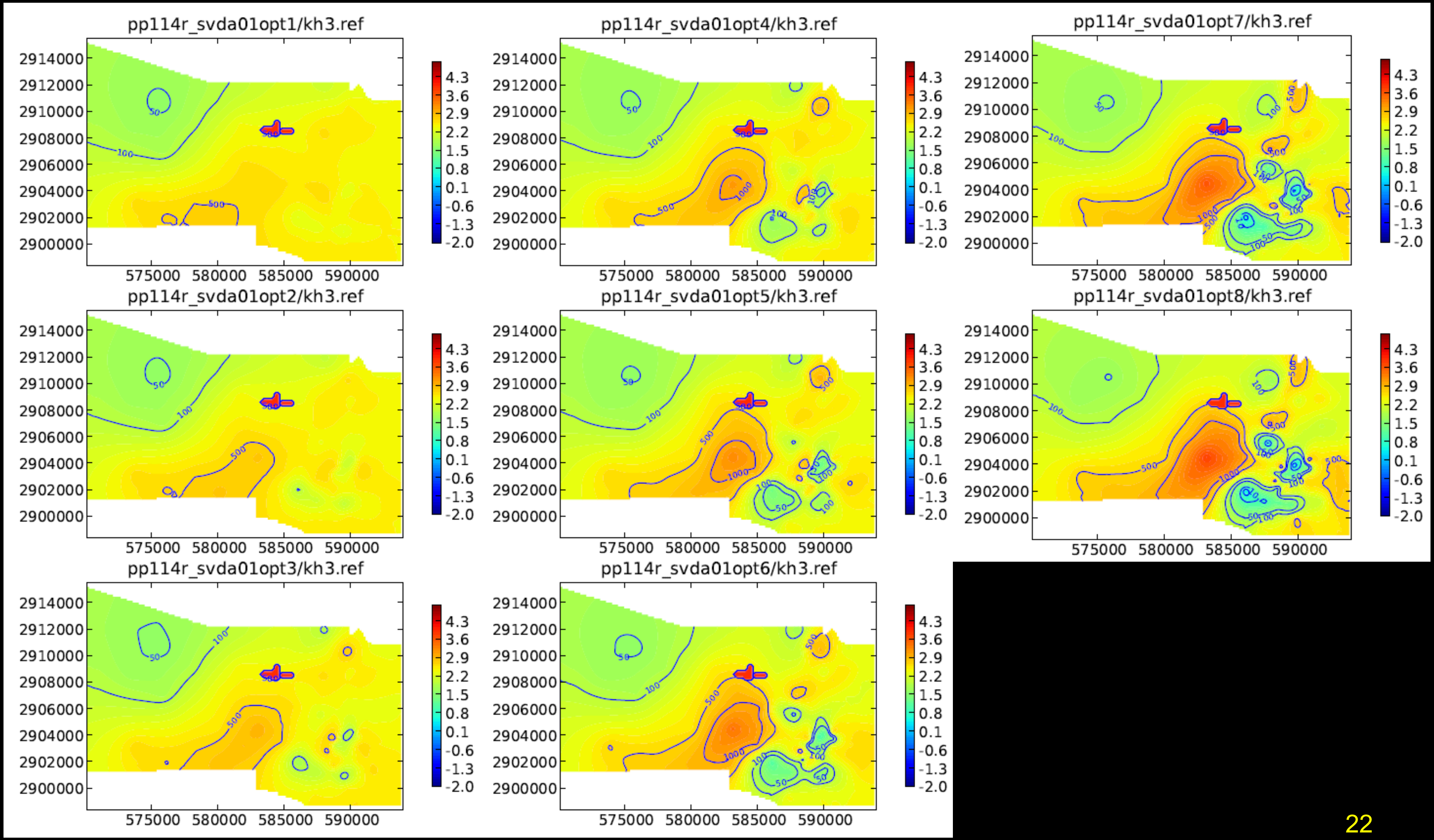
Broward County

- Highly urbanized in eastern Broward
- Water Conservation Areas west of urbanized areas
- Extensive and highly-managed canal drainage system
    - Water supply
    - Flood control
    - Saltwater intrusion control

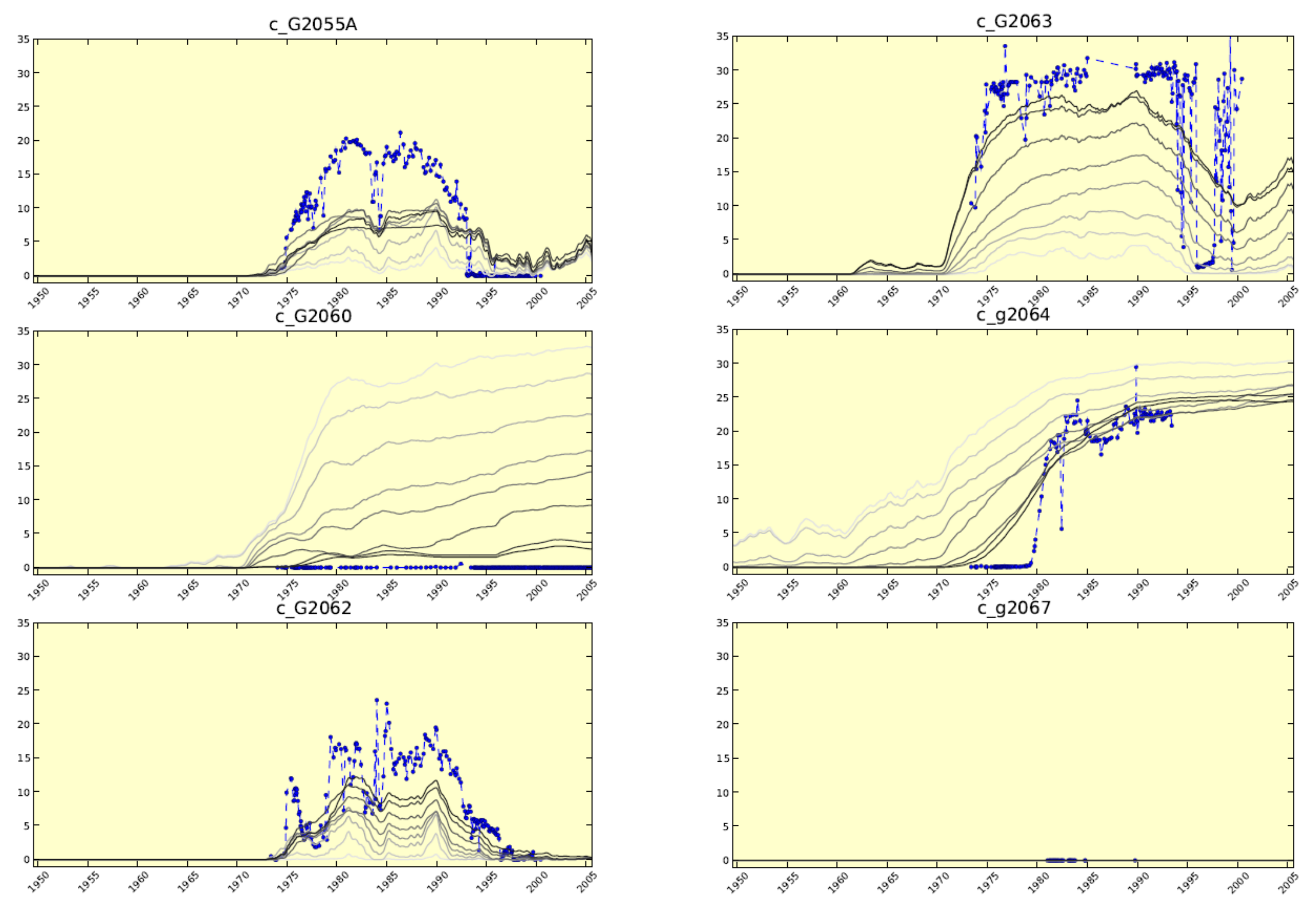


Data from Renken et al. (2005)

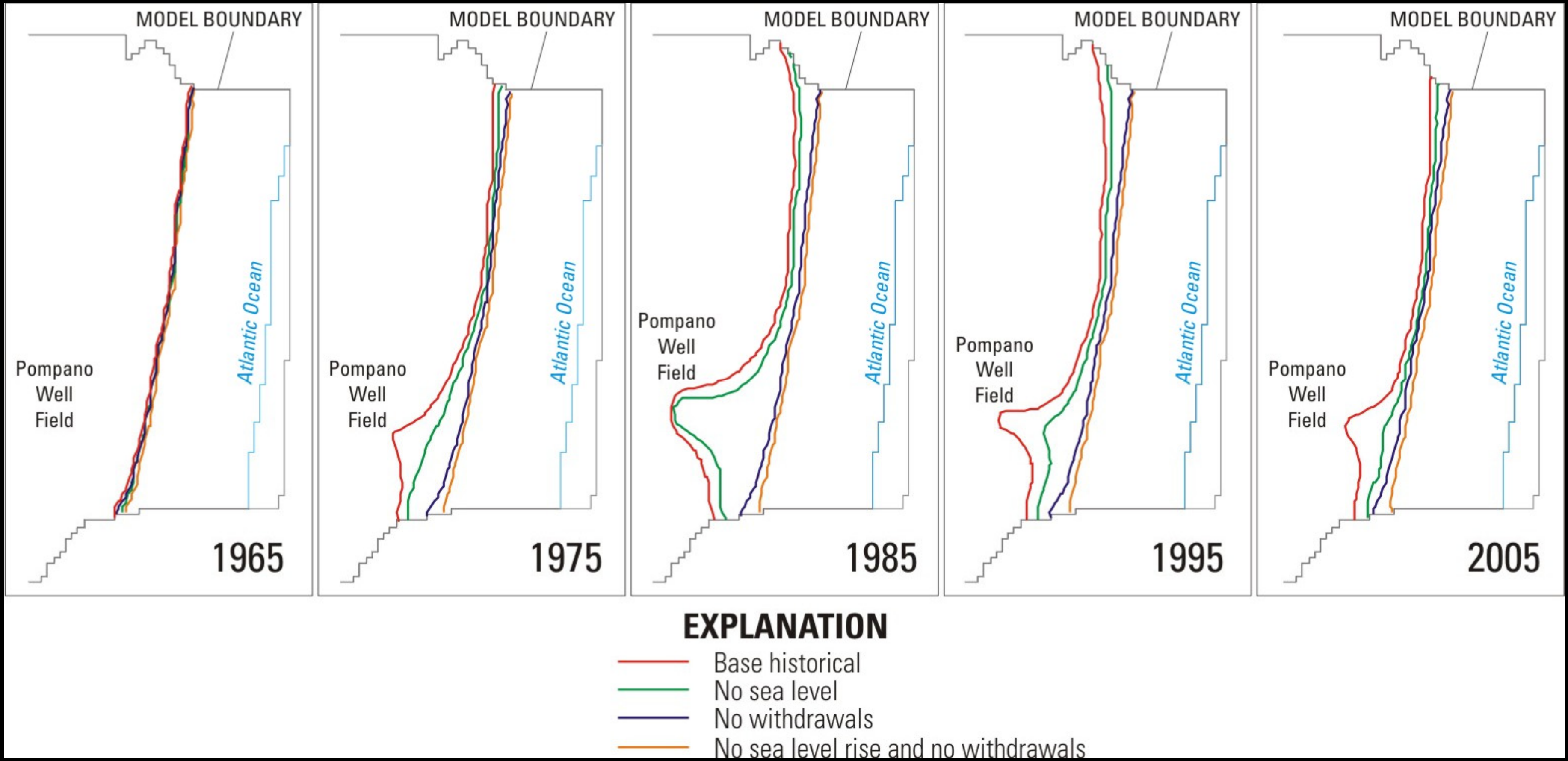
Broward County Hydraulic Conductivity



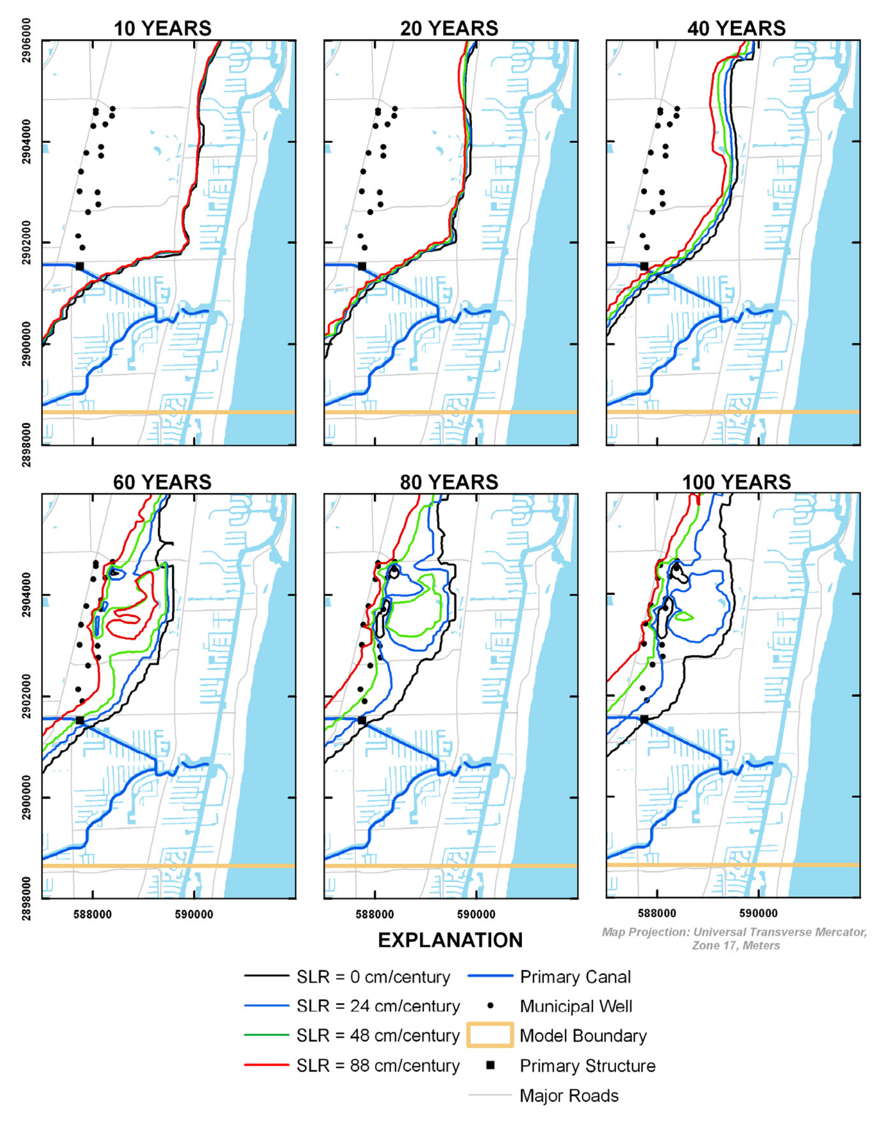
Broward County TDS Concentration

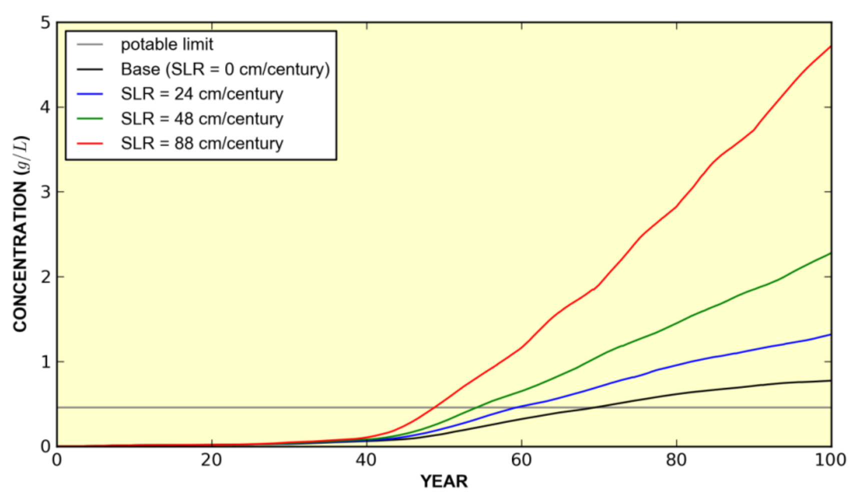


Broward County – well field impacts



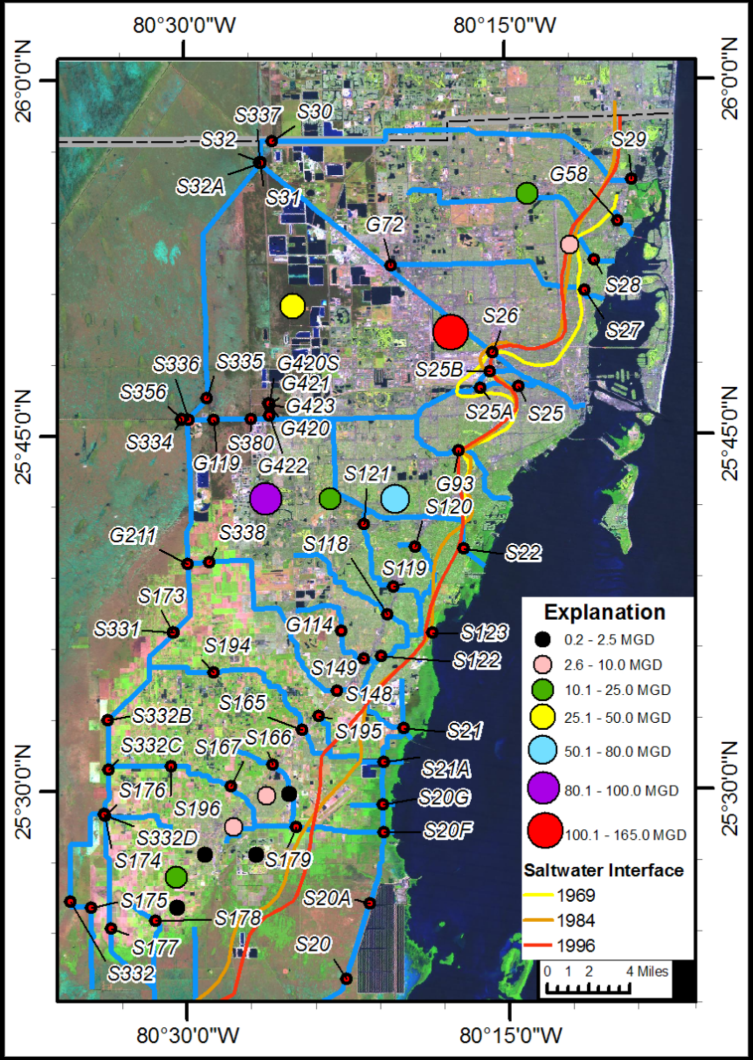
Broward County – sea-level rise analysis





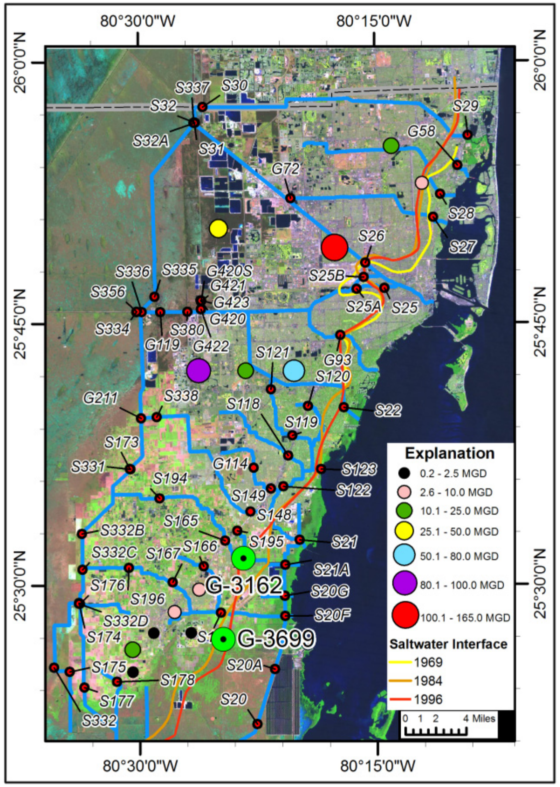
Miami-Dade County

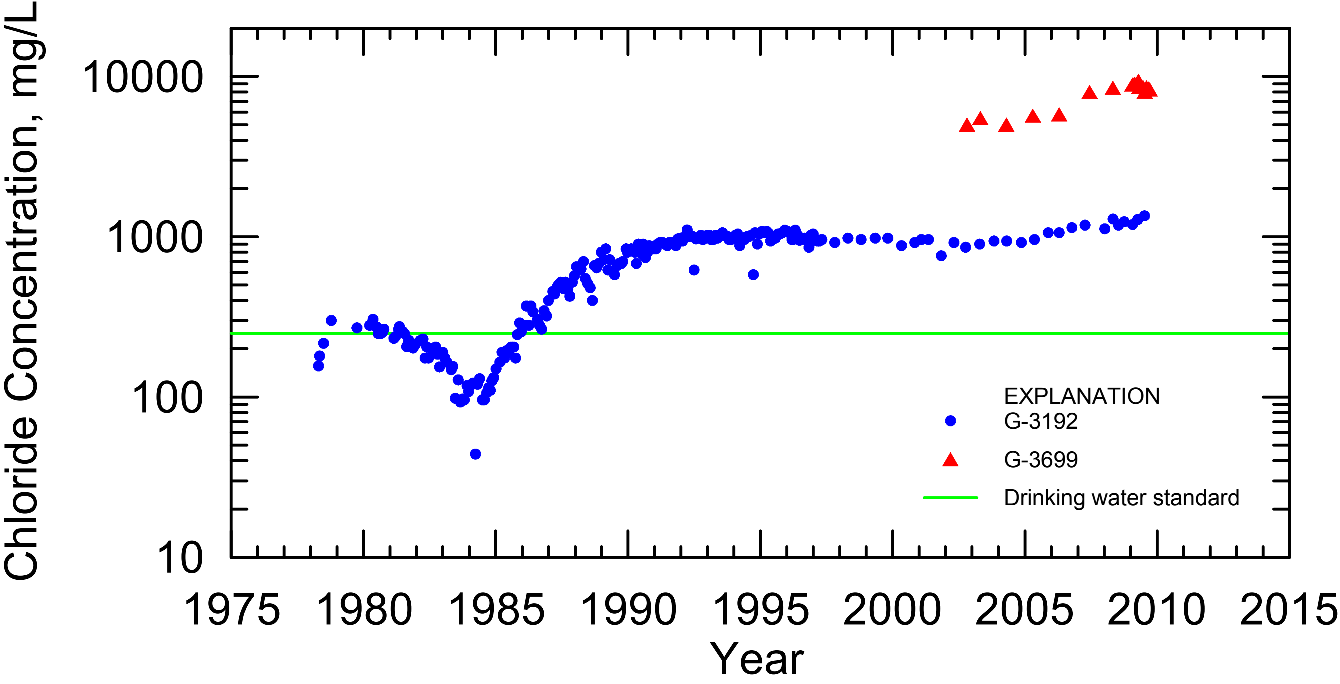
- **Highly urbanized in eastern Miami-Dade**
- **Everglades west and south of urbanized areas**
- **Extensive and highly-managed canal drainage system**
  - **Water supply**
  - **Flood control**
  - **Saltwater intrusion control**
- **Extensive groundwater use**
  - **770 MGD in 1996**



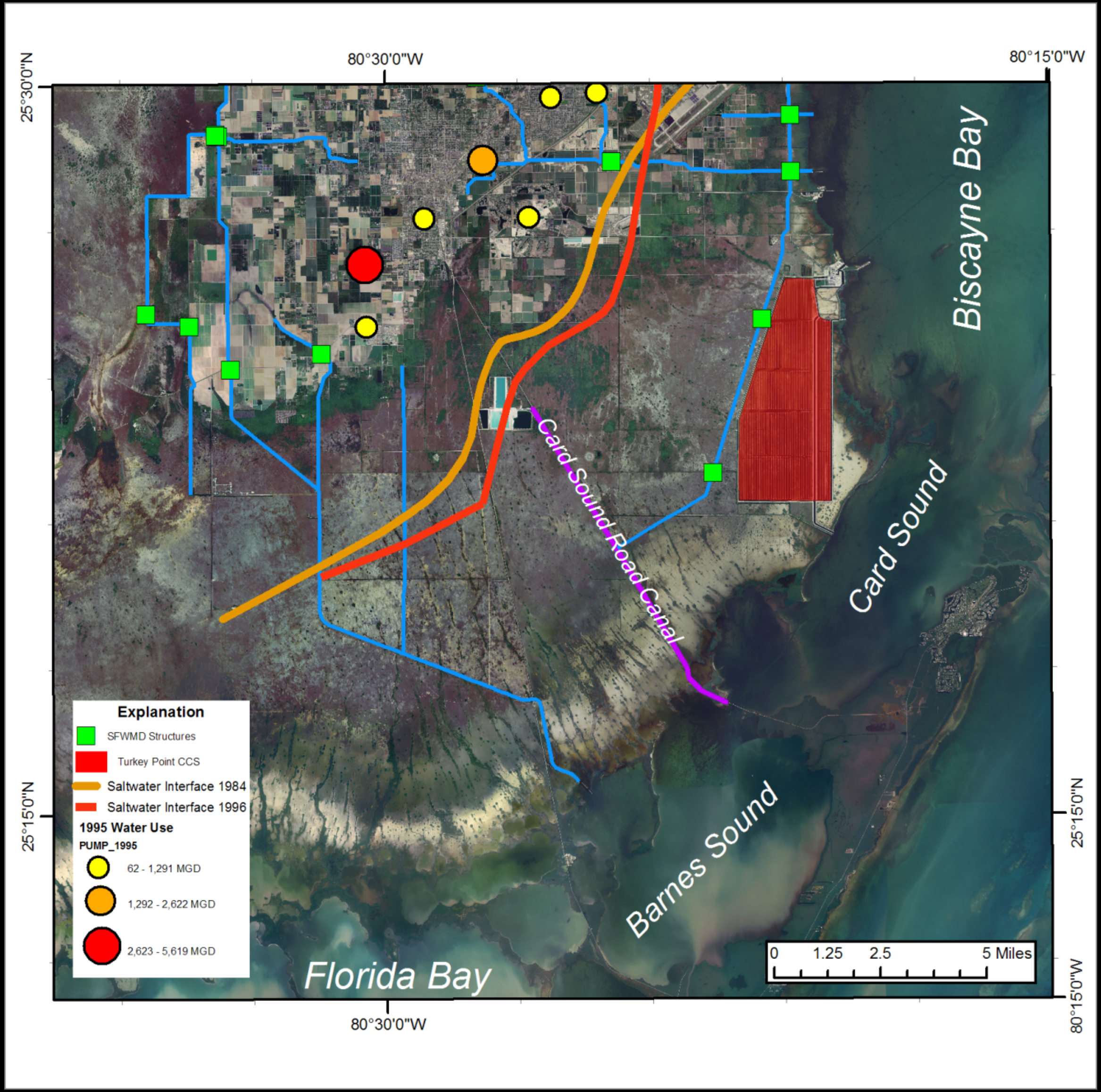
Data from Renken et al. (2005)

South Miami-Dade County Issues

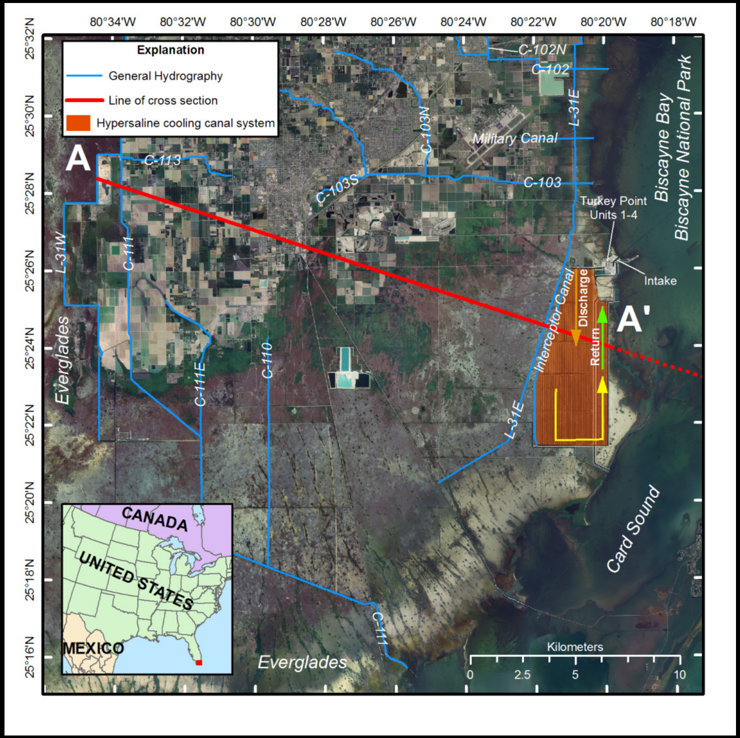


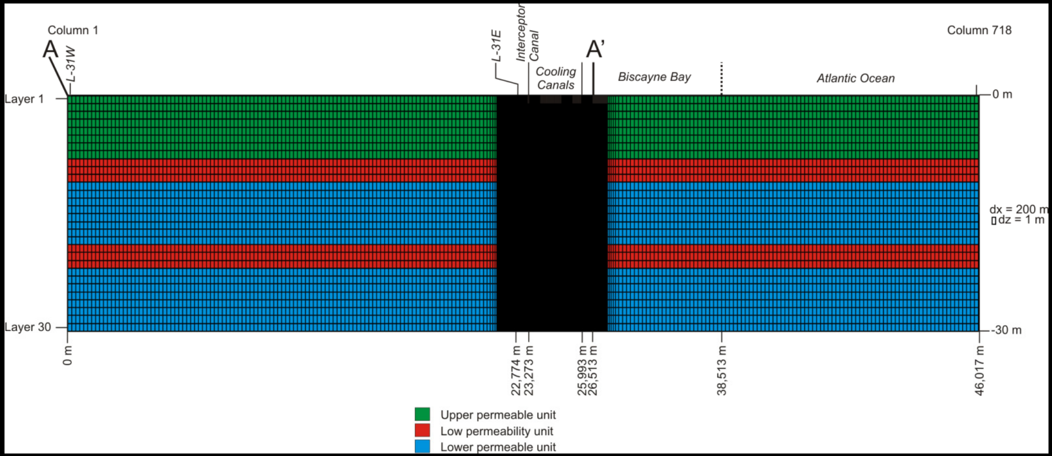


South Miami-Dade County Issues



Turkey Point Numerical Model

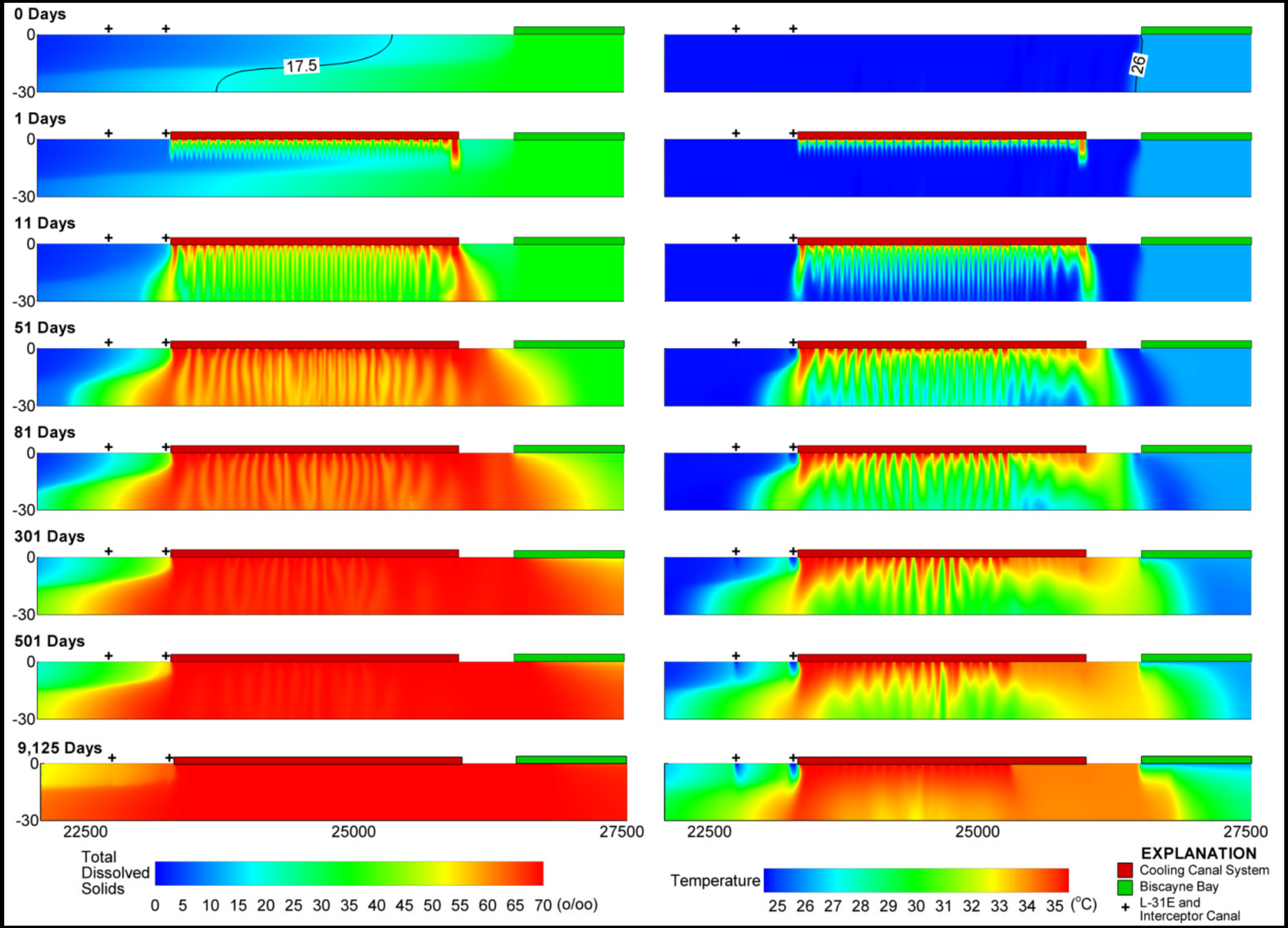




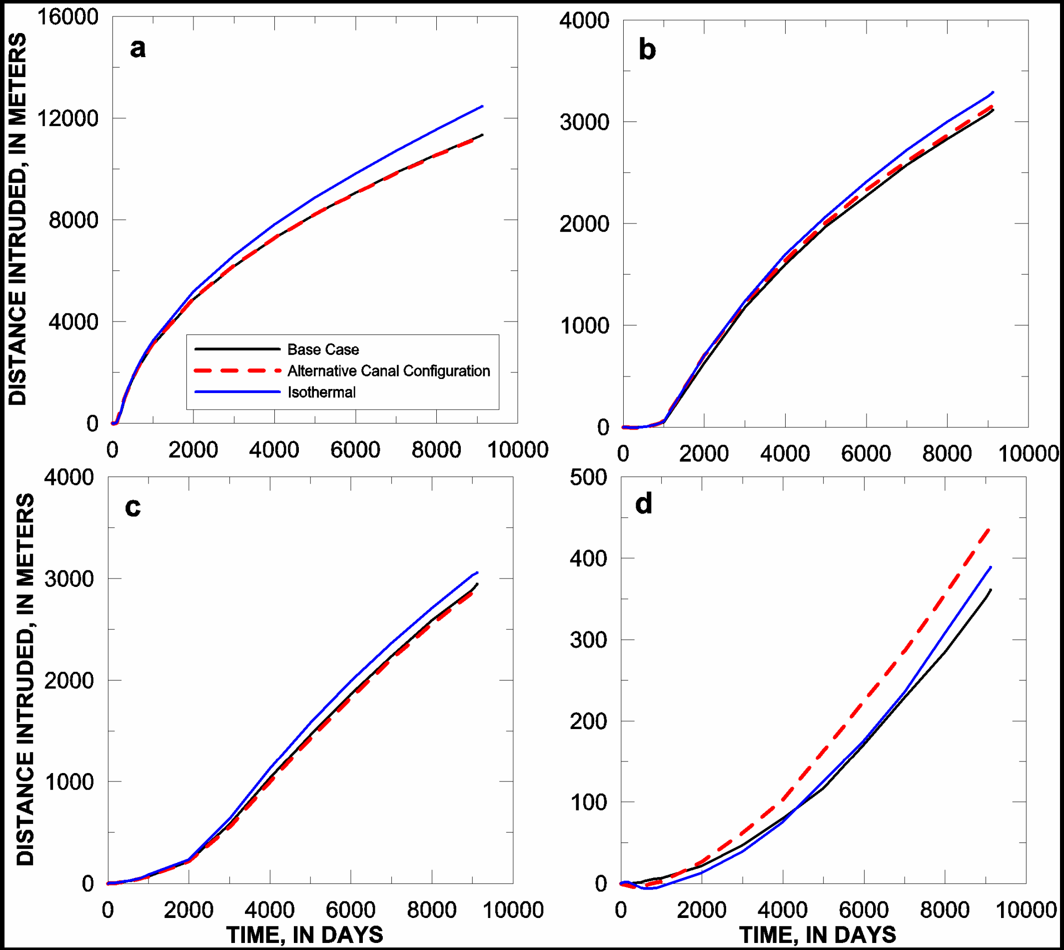
Hydraulic Unit	Case A	Case B	Case C	Case D
Upper permeable unit	K_h = 10,000 K_v = 100	K_h = 1,000 K_v = 10	K_h = 1,000 K_v = 10	K_h = 1 K_v = 0.1
Low permeability unit	K_h = 10,000 K_v = 100	K_h = 1,000 K_v = 10	K_h = 1 K_v = 1	K_h = 1 K_v = 1
Lower permeable unit	K_h = 10,000 K_v = 100	K_h = 1,000 K_v = 10	K_h = 1,000 K_v = 10	K_h = 1,000 K_v = 10

Non-Isothermal Hypersaline CCS

CASE A



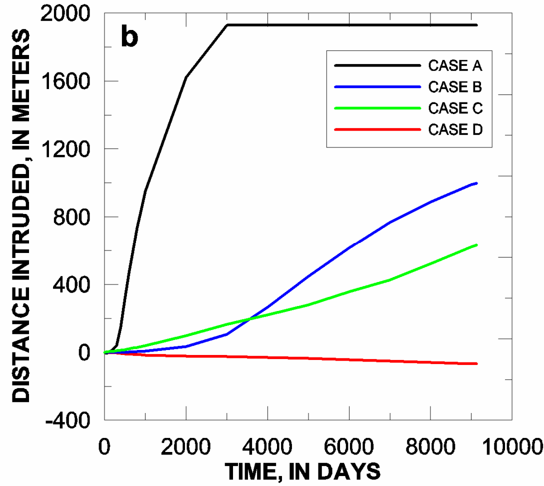
Aquifer Response – saltwater intrusion



$$\Delta\rho_{35} = \quad 26.3 \left[\mathrm{kg}/\mathrm{m}^3\right]$$

$$\Delta\rho_{70} = \quad 52.5 \left[\mathrm{kg}/\mathrm{m}^3\right]$$

$$\Delta\rho_{T} = -4.20 \left[\mathrm{kg}/\mathrm{m}^3\right]$$

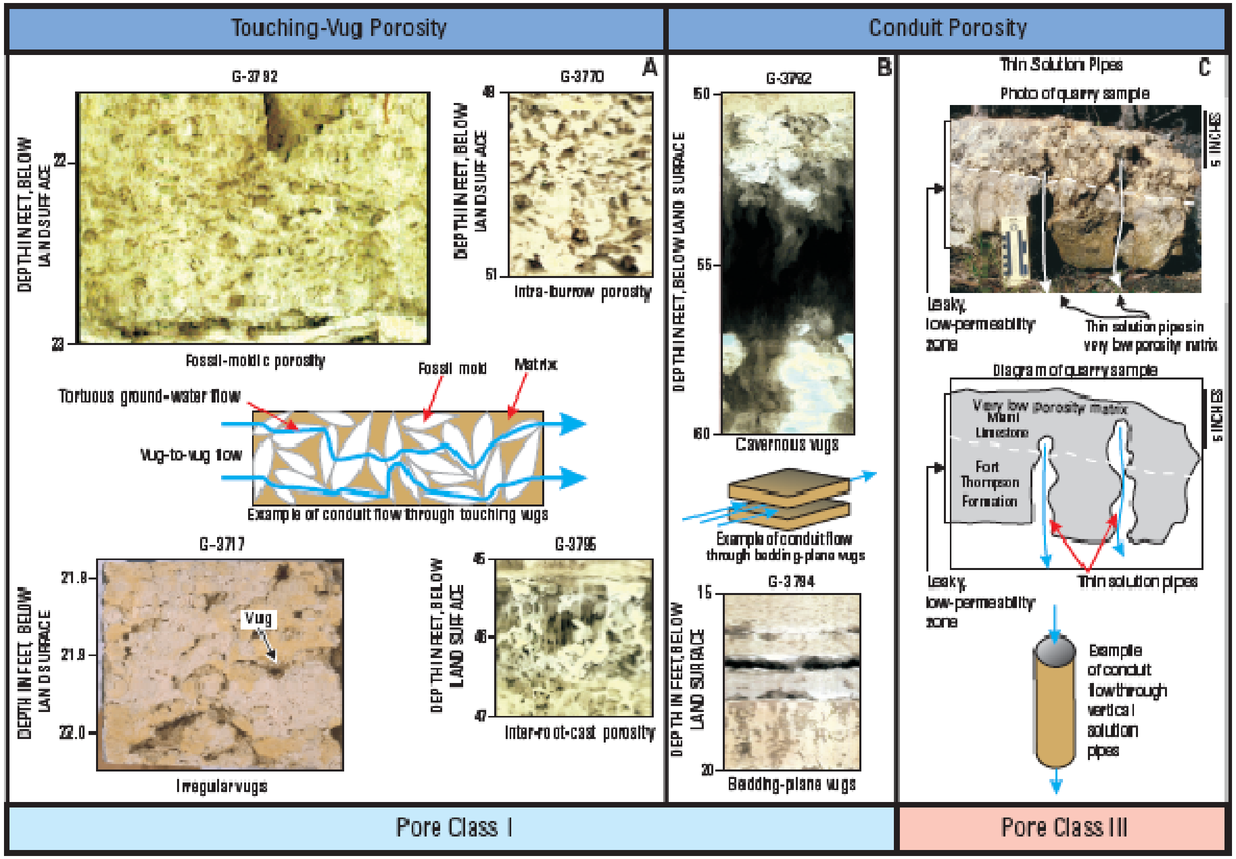


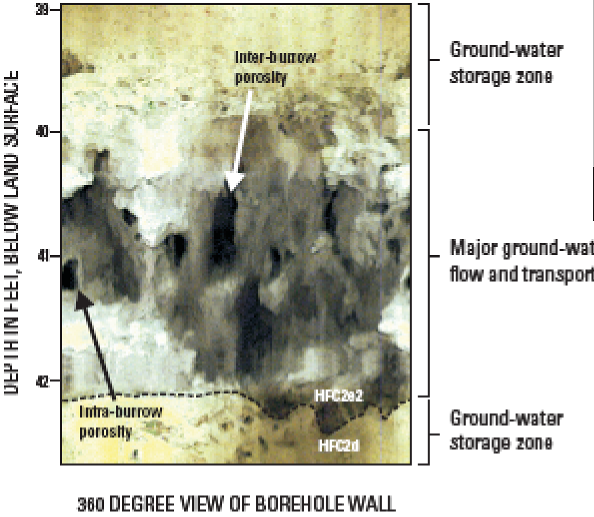
CCS TDS = 35‰

FUTURE CHALLENGES

Improved Aquifer Characterization

Cunningham and others, 2006

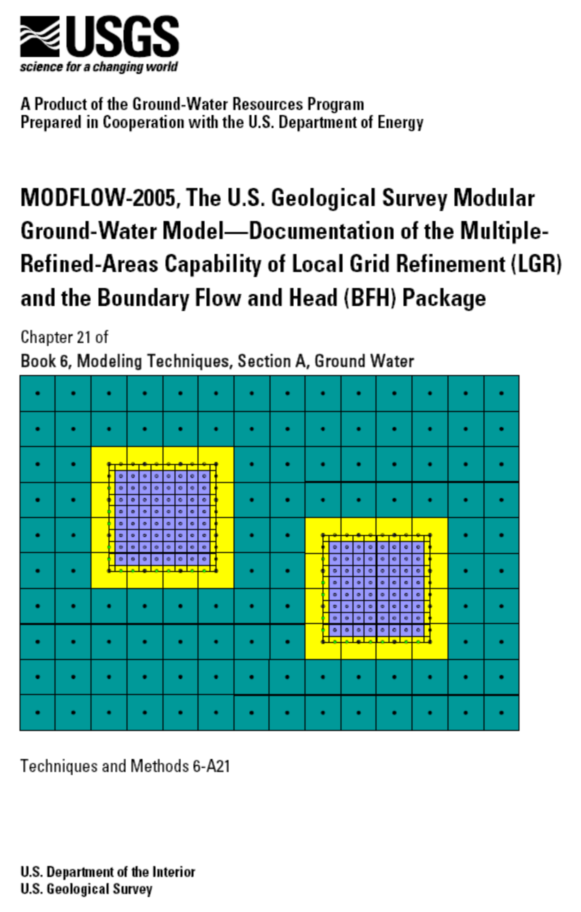




360 DEGREE VIEW OF BOREHOLE WALL

Improving Model Predictions

- Local Grid Refinement
  - Parent and child models
  - Irregularly shaped child models
  - Improved ability to represent heterogeneity in areas of interest



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A Product of the Ground-Water Resources Program
Prepared in Cooperation with the U.S. Department of Energy

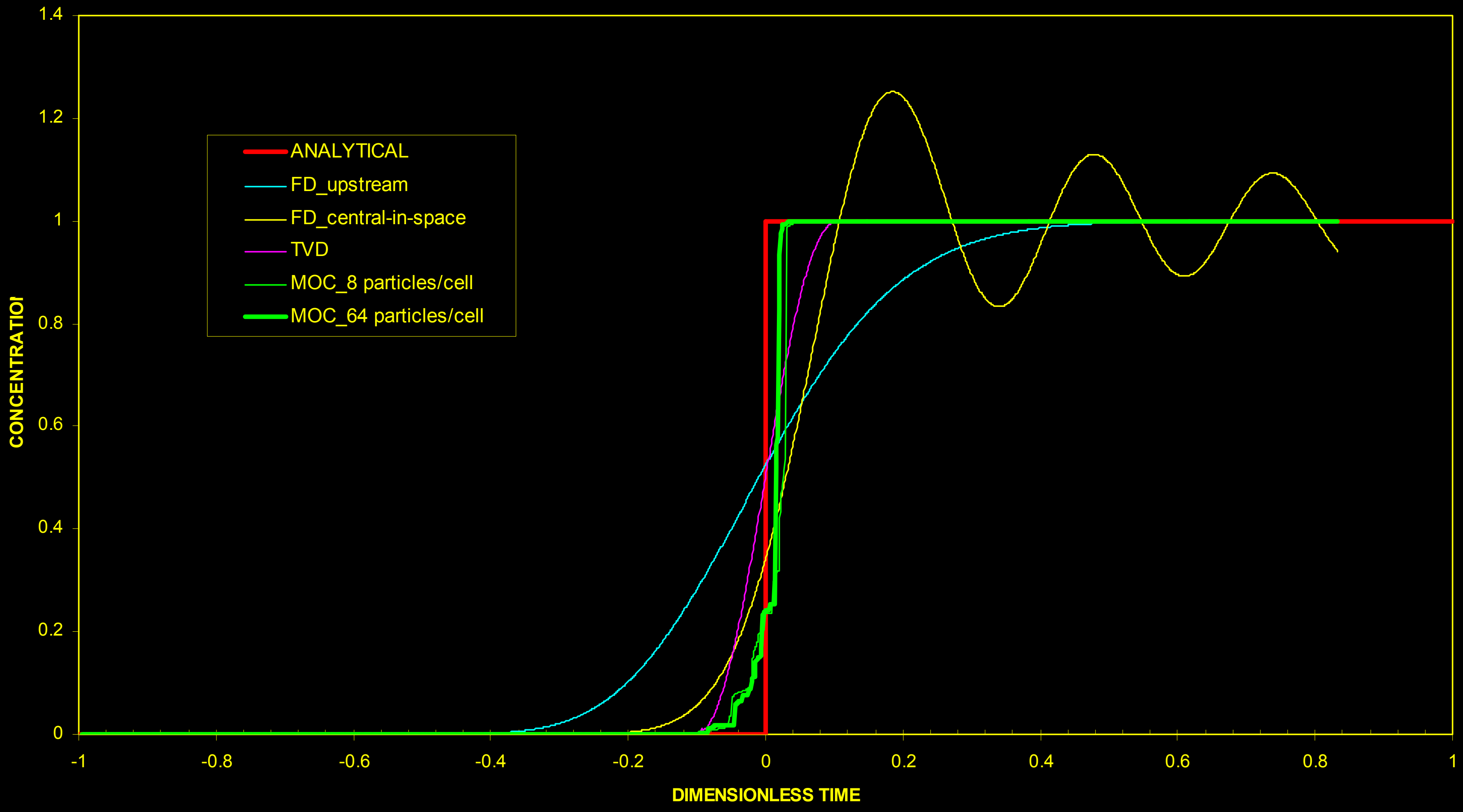
MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—Documentation of the Multiple-Refined-Areas Capability of Local Grid Refinement (LGR) and the Boundary Flow and Head (BFH) Package

Chapter 21 of
Book 6, Modeling Techniques, Section A, Ground Water

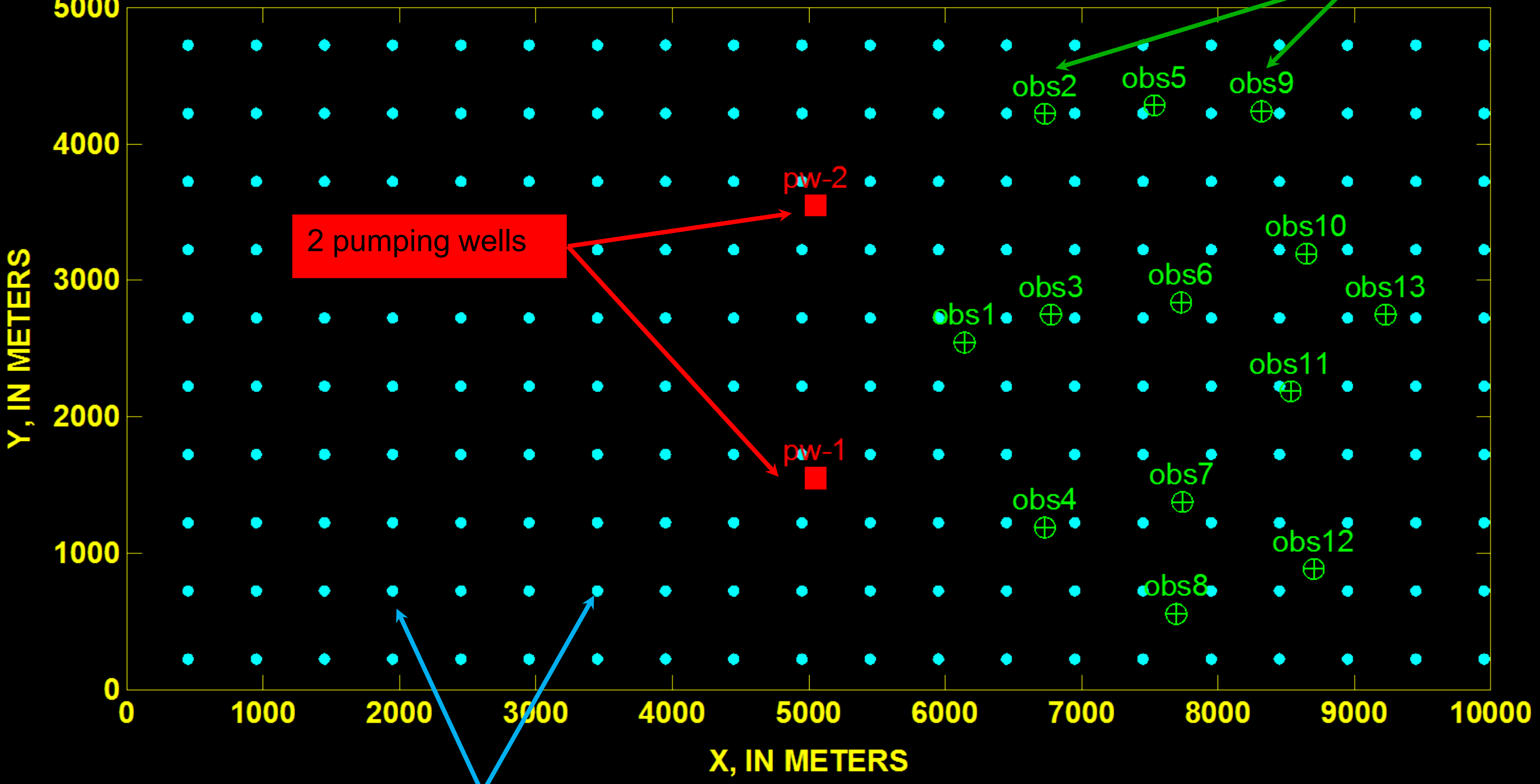
Techniques and Methods 6-A21

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

Improving Model Predictions



Improving Model Predictions



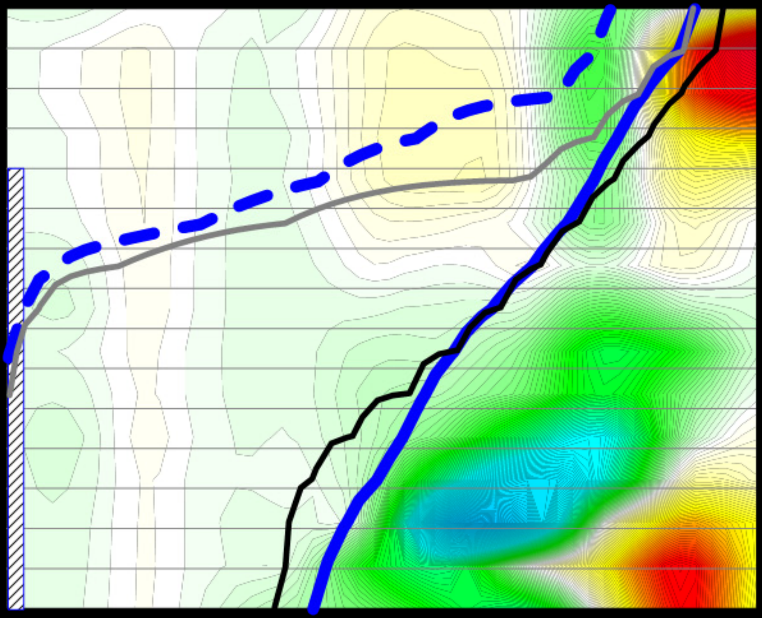
13 multi-layer observation locations

2 pumping wells

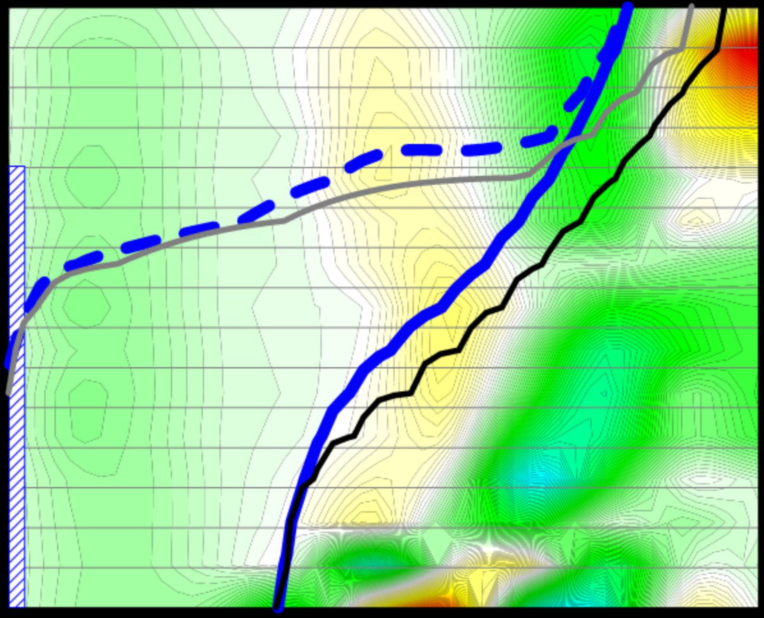
500-m spaced pilot point grid

Improving Model Predictions

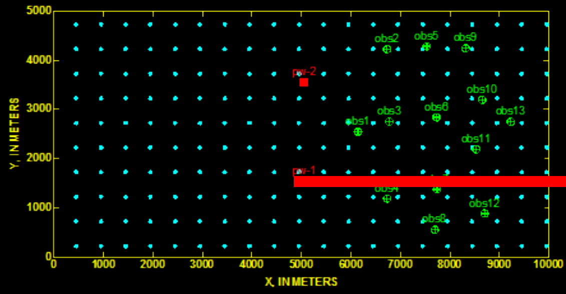
UNIFORM WEIGHTING



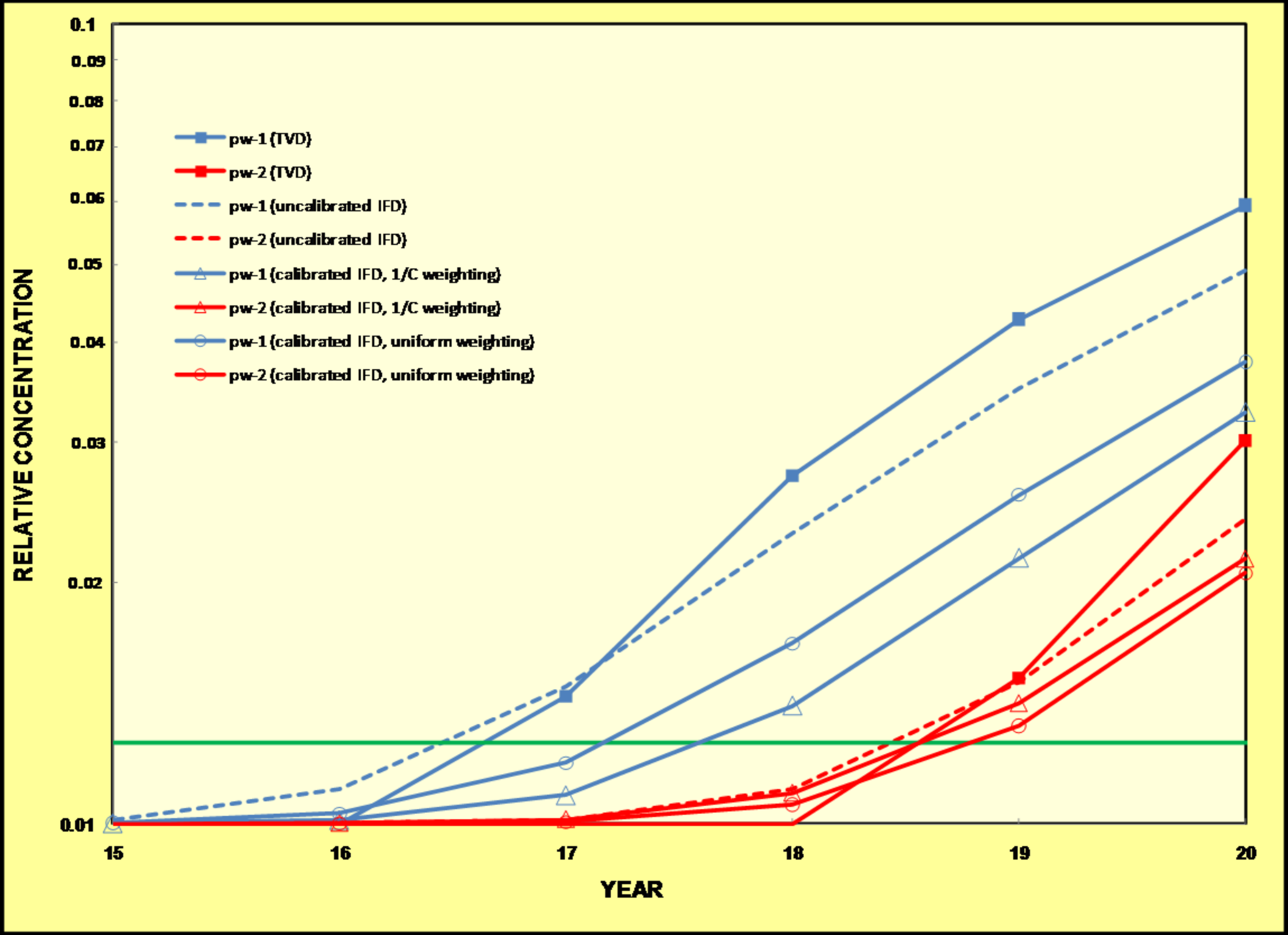
1/C WEIGHTING



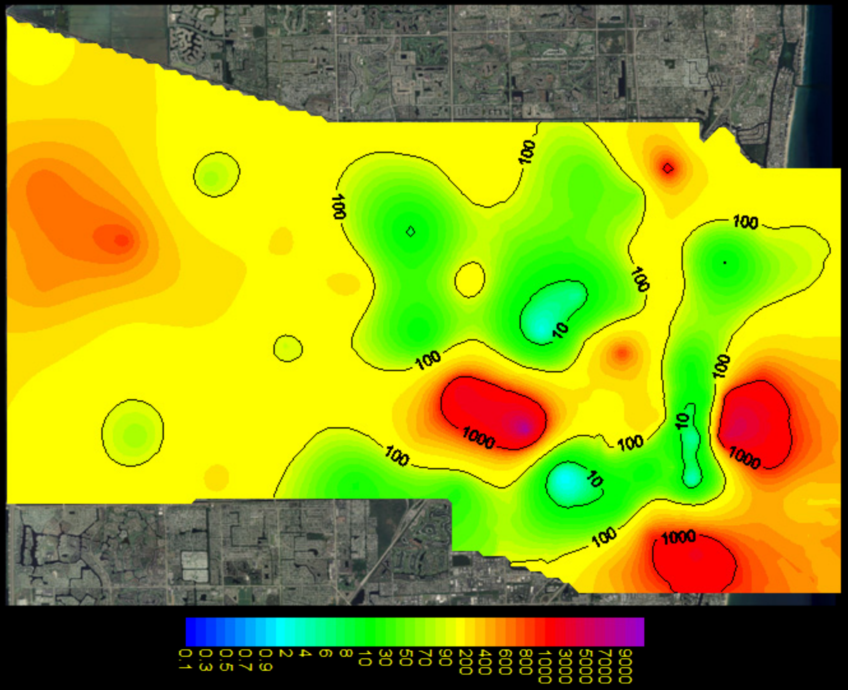
Blue line – FD
Black line – TVD



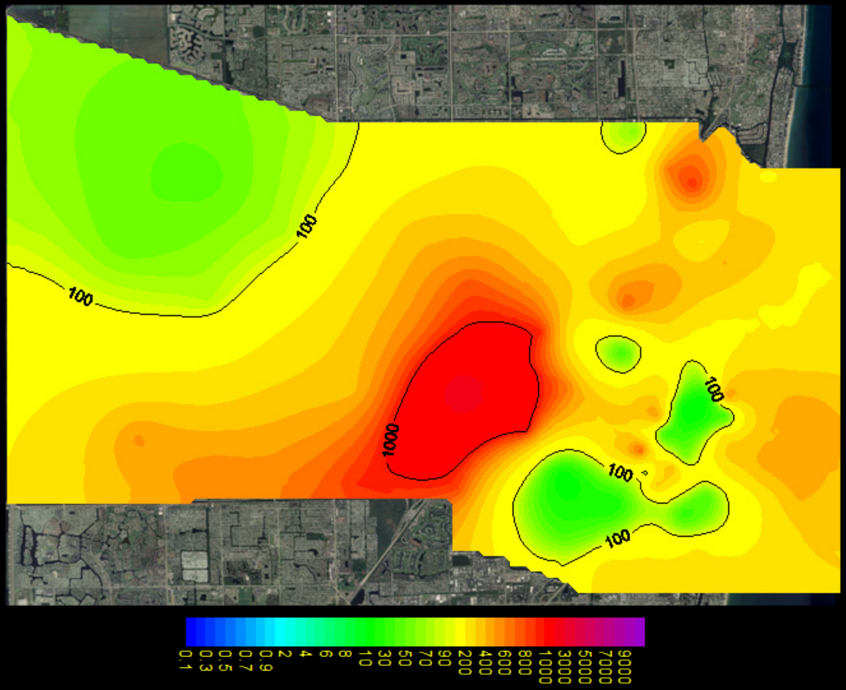
Improving Model Predictions



It’s not just academic…



FD



TVD