Effect of conduit network geometry on predictions of flow and transport in springsheds

Wendy Graham, Rob de Rooij and Wes Henson, UF
Doug Hearn, SJRWMD

Background

- Currently groundwater flow and transport in Florida springsheds is simulated using equivalent porous medium models (MODFLOW)
- Models exist that could account for the presence of conduits in the subsurface (i.e. MODFLOW-USG, MODFLOW-CFP, FEFLOW, DisCo)

Thus questions arise:

- How does the inclusion of conduits change model parameters, model predictions?
- Does including conduits lead to a model that will improve management decisions?

Problem: We don’t know where they are!

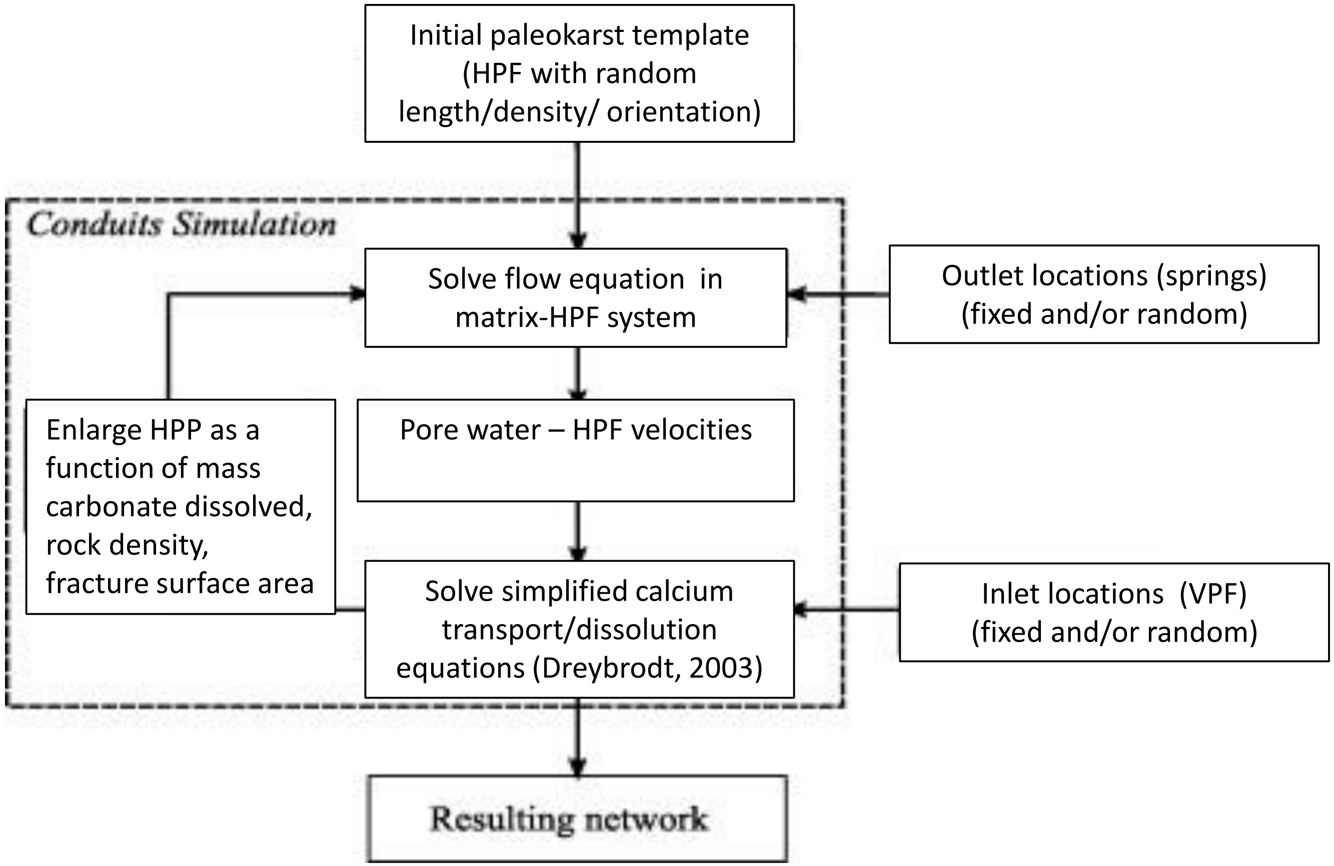
Project Objectives

Goal 1: Develop a conduit dissolution model to generate conduit networks that honor what is known about the topography, geology, hydrology and climate of the system

Goal 2: Conduct Morris Method Global Sensitivity Analysis to understand most important model parameters that influence how karst conduit networks evolve

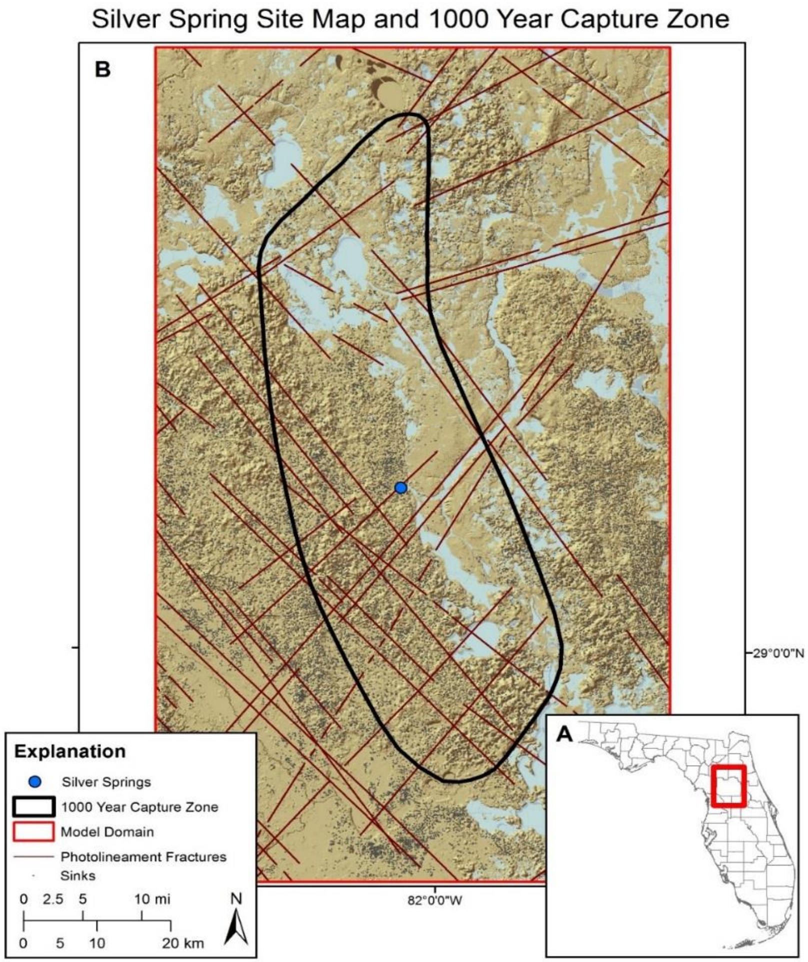
Goal 3: Conduct Monte Carlo simulation of conduit generation, groundwater flow and conservative solute transport for conditions representative of the Silver Springshed

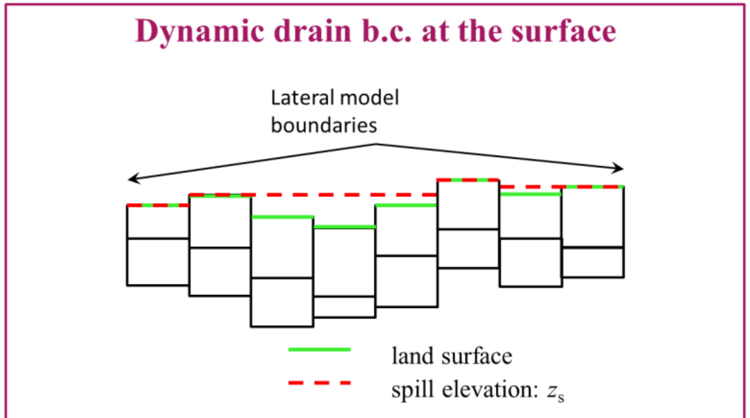
Conduit Generation Model



Conduit generation is simulated with DisCo (de Rooij et al , 2013)
Conduits are generated by dissolving horizontal and vertical preferential pathways within the porous matrix using a reactive-solute transport model.

Model Domain, Boundary Conditions and Set up





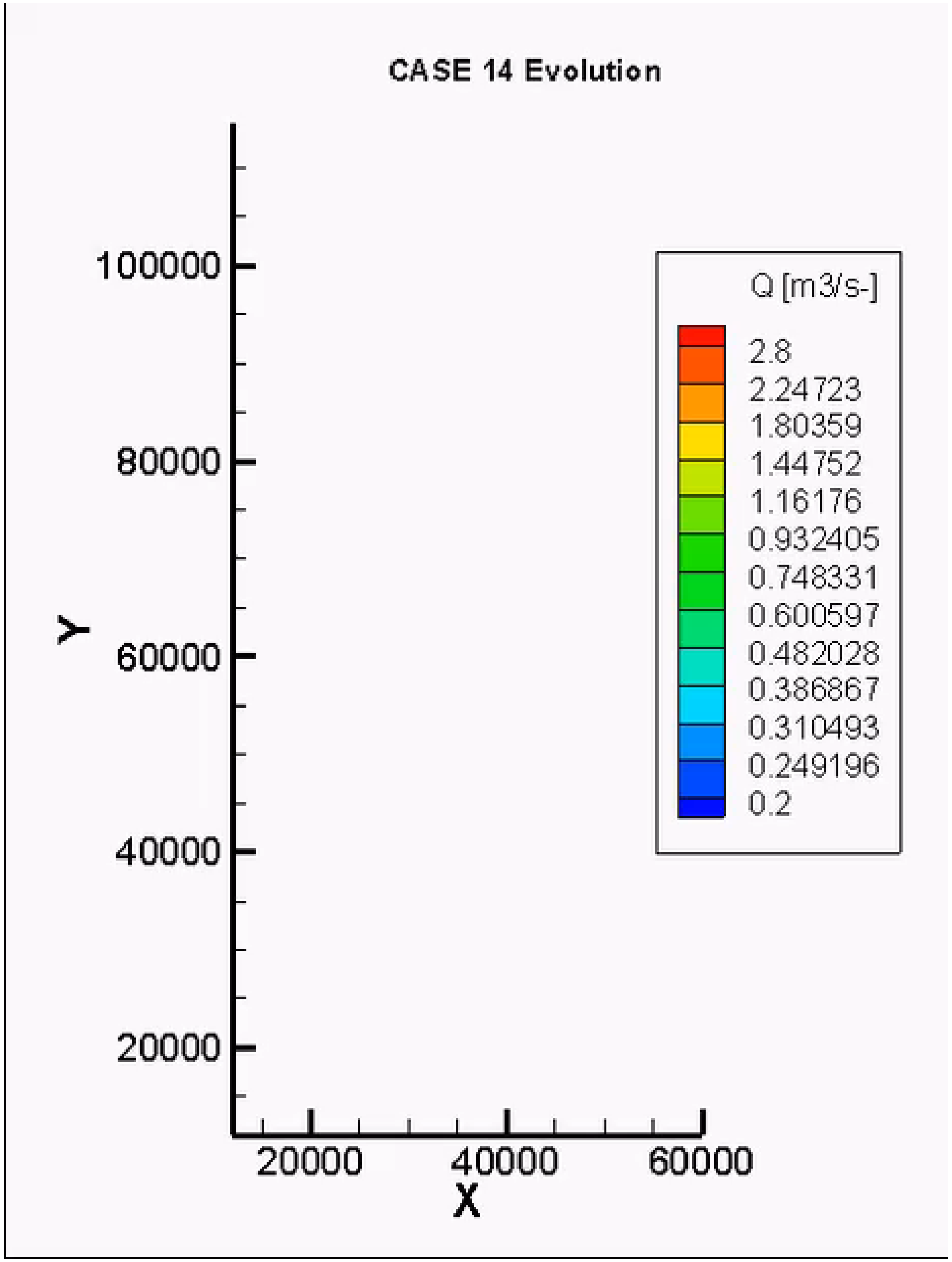
$$q_{OUT} = \begin{cases} \gamma\left(h_{cell} - z_s\right) & \text{if } h_{\text{topmost cell}} > z_s \\ 0 & \text{if } h_{\text{topmost cell}} \le z_s \end{cases}$$

Springshed Boundaries- No Flux

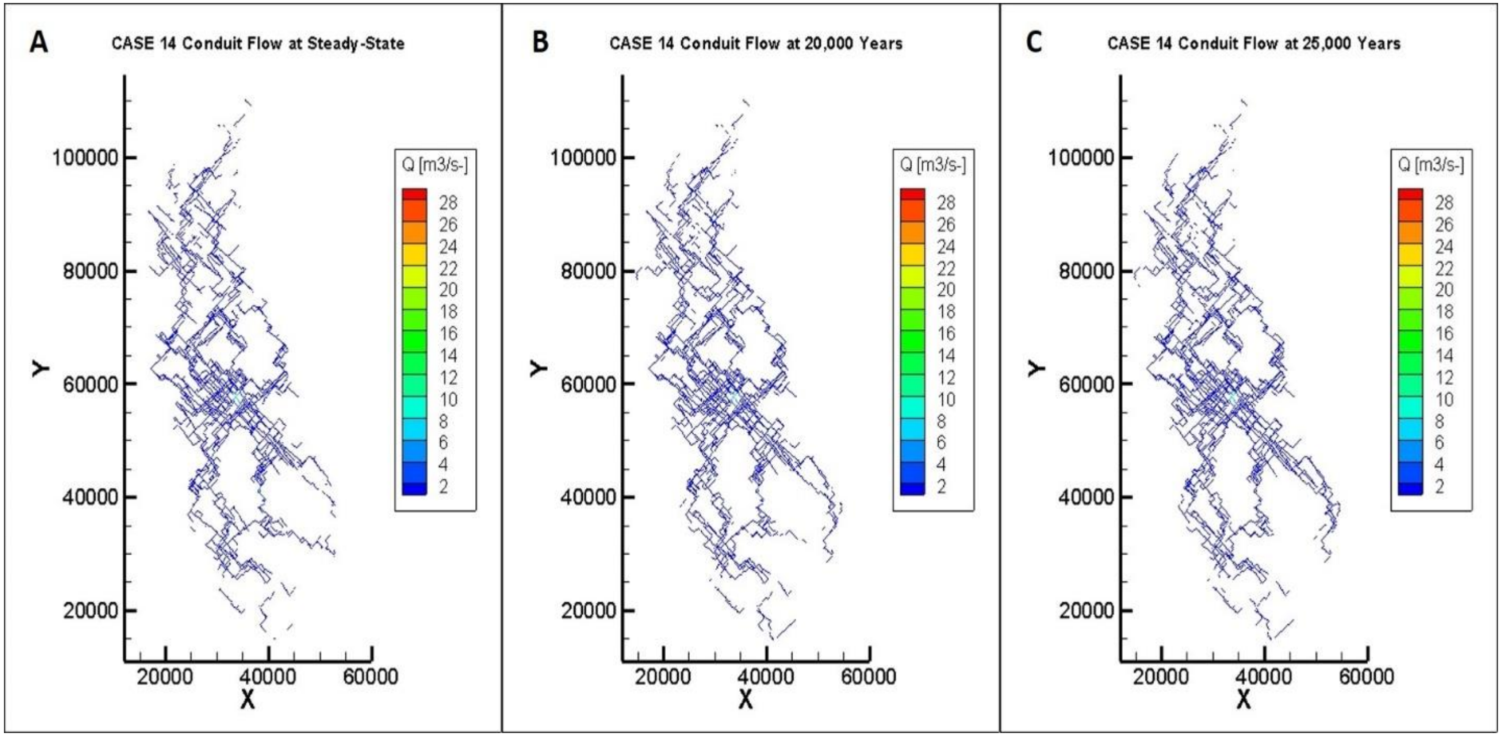
Steady state recharge : 1.18E-8 m s^{-1}

Total areal recharge ~28 m3/s

Evolution of Example Network



How long should we evolve networks?



Network and contributing area stabilize when steady spring flow is achieved. Compare networks at this point in time.

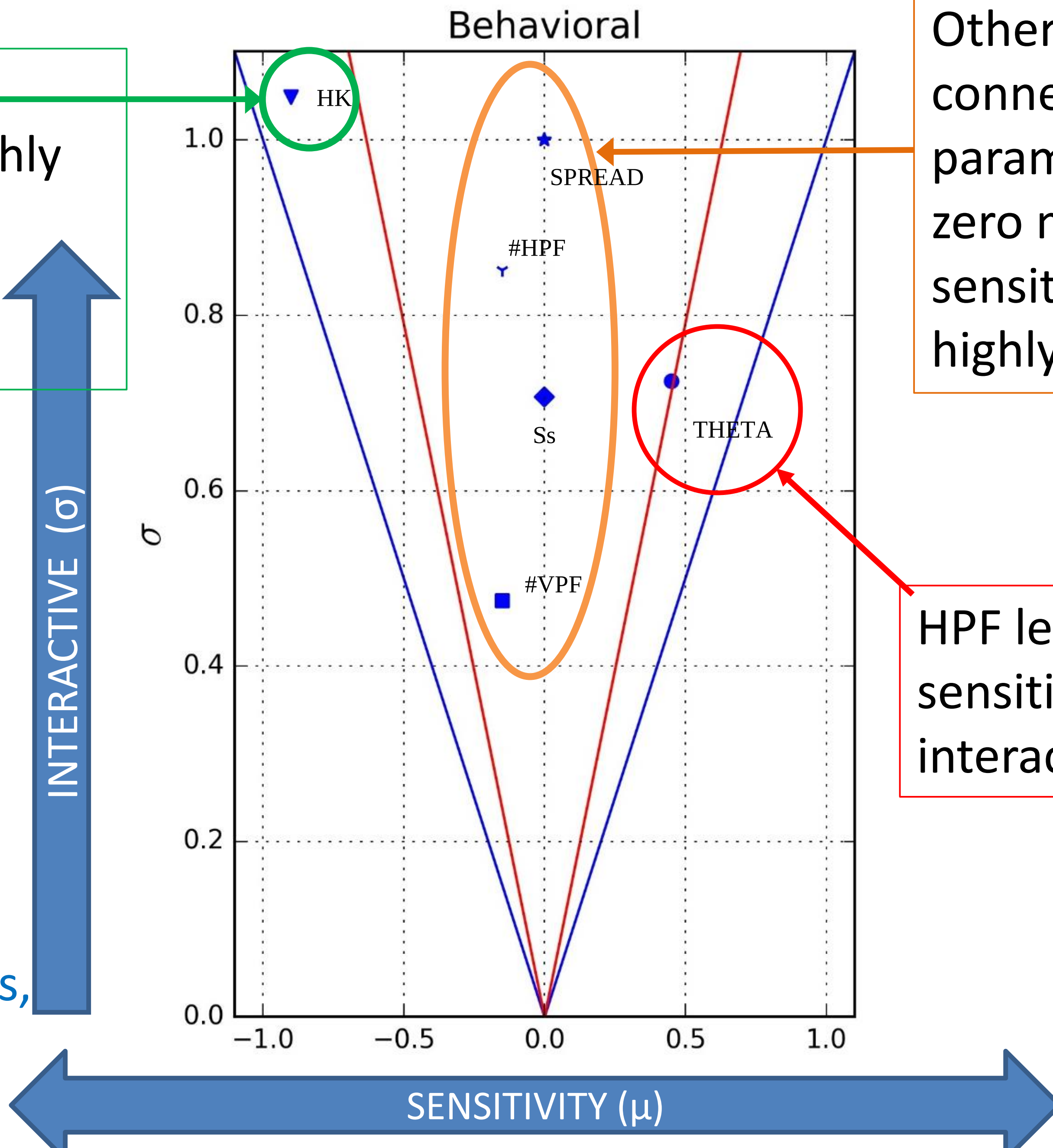
Morris Method Global Sensitivity Analysis Parameters

Parameter	Units	Probability Distribution*	Source
HPF Number	Count	U(2500, 4000)	[Vernon, 1951]
Northeast HPF Set 1 Orientation	Degrees	Fixed 45°	[Vernon, 1951]
Northwest HPF Set 2 Orientation	Degrees	Fixed 315°	[Vernon, 1951]
HPF Spread	Degrees	U(0°, 60°)	Estimated
HPF k	Unitless	U(0.75, 2.00)	Estimated
HPF theta	M	U(4000, 6000)	Estimated
VPF Number	count	U(250, 500)	[Denizman, 1998; Ford and Williams, 2013]
Matrix Porosity	unitless	U(0.25, 0.40)	[Langston et al., 2012b]
Matrix Hydraulic Cond.	$m\ s^{-1}$	LU(1E-4, 1E-8)	[Heath, 1983]
Matrix Specific Storage	m^{-1}	U(1E-4, 1.00E-6)	[Batu, 1998]
Epikarst Hydraulic Cond.	$m\ s^{-1}$	Fixed 1E-3	[Heath, 1983]
Epikarst Porosity	unitless	Fixed 0.3	[Langston et al., 2012b]
Epikarst Specific Storage	m^{-1}	Fixed 1E-4	[Batu, 1998]

Horizontal and vertical preferential flowpath (HPF and VPF) and matrix properties for Morris Method Global Sensitivity Analysis.
*U(minimum, maximum) uniform distribution probability range for GSA
LU(minimum, maximum) is log uniform distribution probability range for GSA

Morris Method Sensitivity Plot

Hydraulic conductivity: highly sensitive and moderately interactive

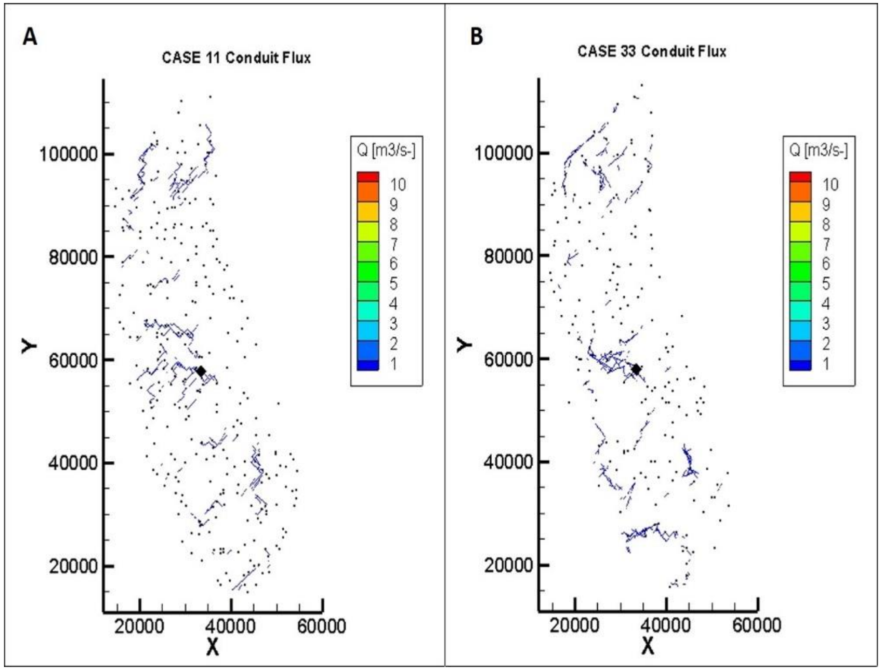


Other paleokarst connectivity parameters: near zero mean sensitivity and highly interactive

HPF length scale: sensitive and highly interactive

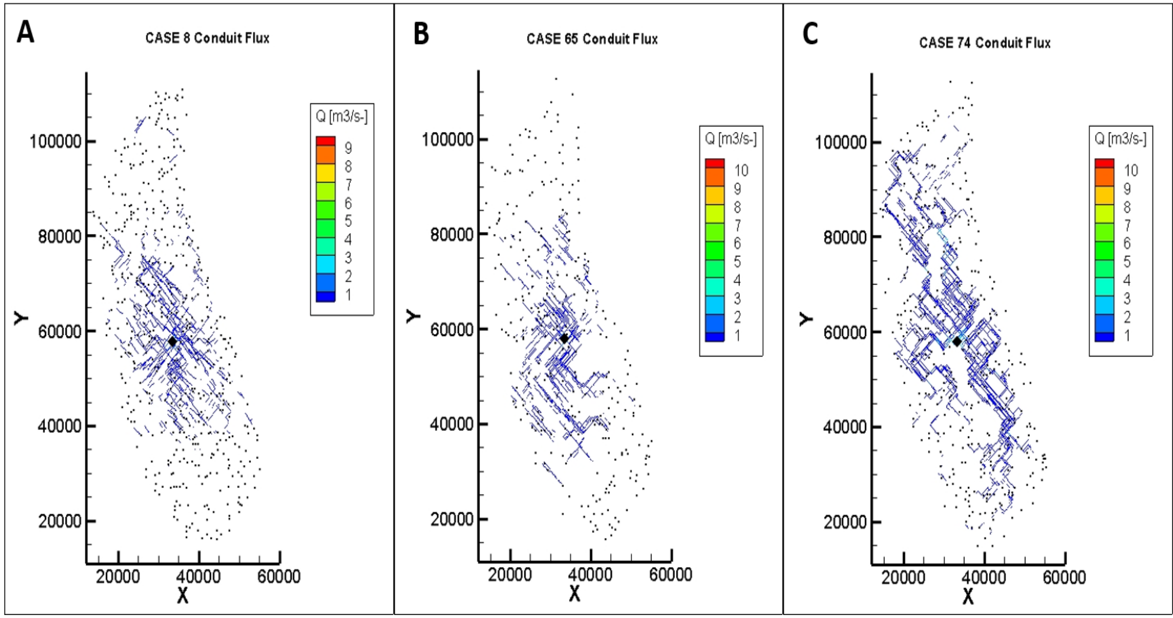
58 /90 reps generated 1st magnitude springs, i.e "behavioral"

Comparison of behavioral and non-behavioral networks

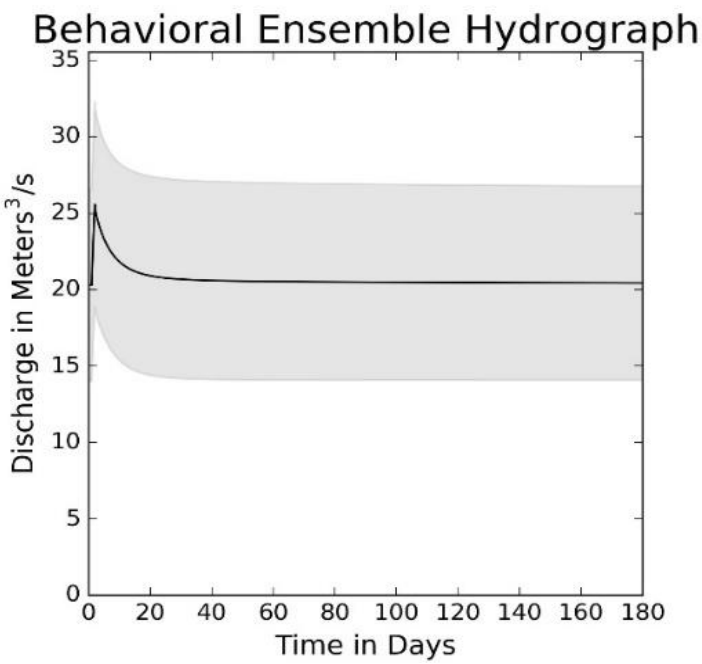


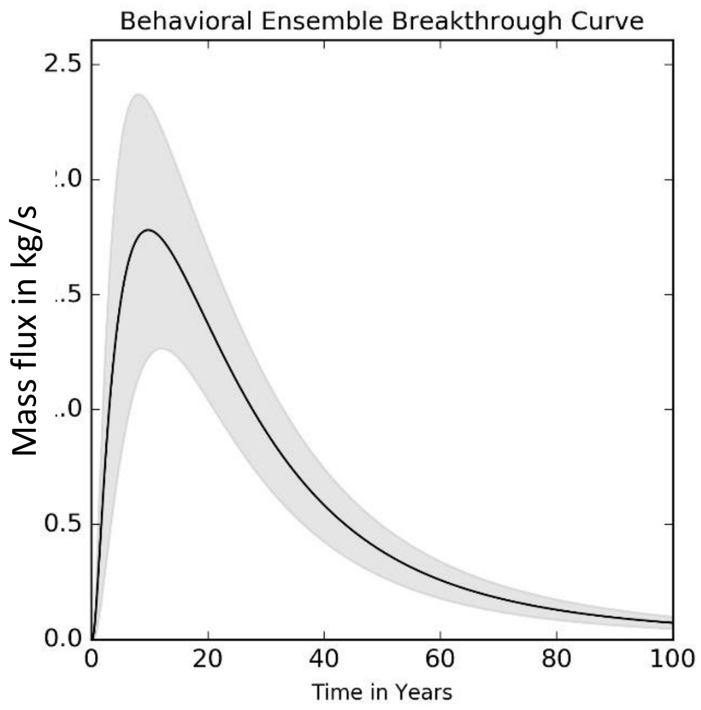
Non-Behavioral

Behavioral



Hydrographs and BTC for Behavioral Ensemble



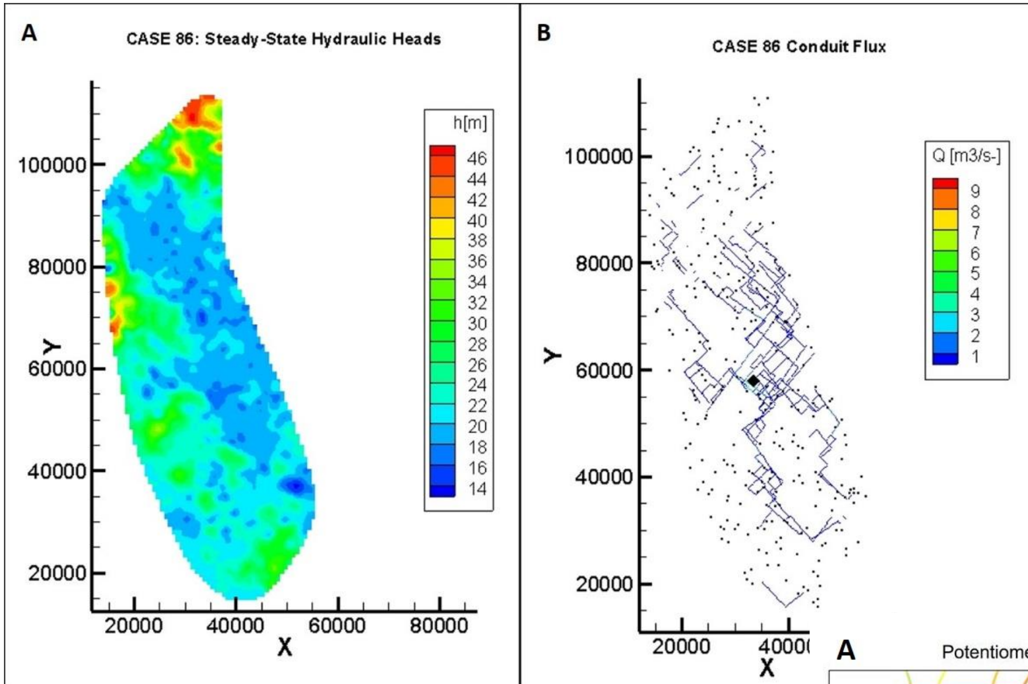


For Behavioral Replicates:
Mean steady spring flow 20 m3/s
Std Dev steady spring flow: 6.7 m3/s

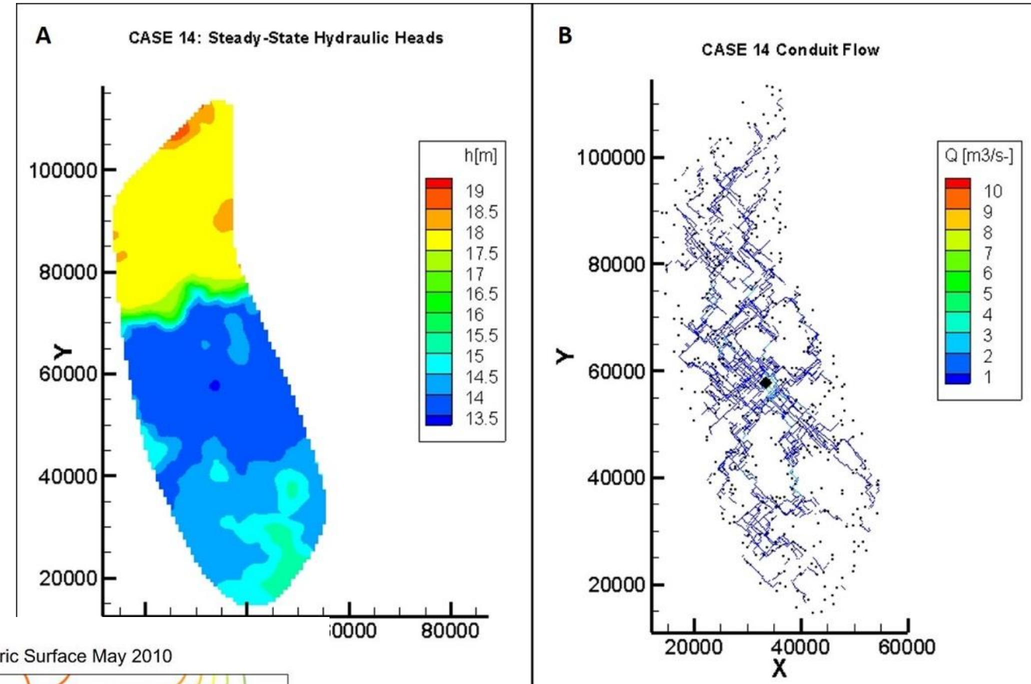
For Behavioral Replicates:
Mean Peak Travel Time= 16 yr
Std Dev Peak Travel Time = 1 yr

(Mean- Black line, Standard deviation- shaded gray envelope)

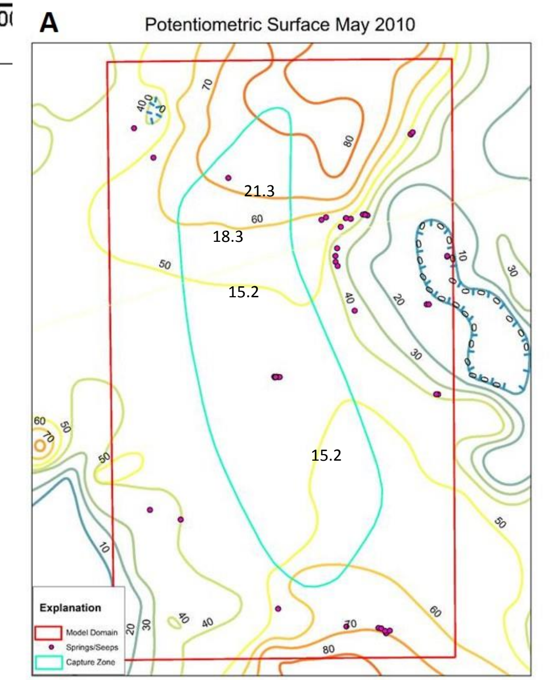
Behavioral networks showed significant variation in hydraulic heads and fluxes



Springflow= 9.93 m^3/s



Springflow= 28.65 m^3/s



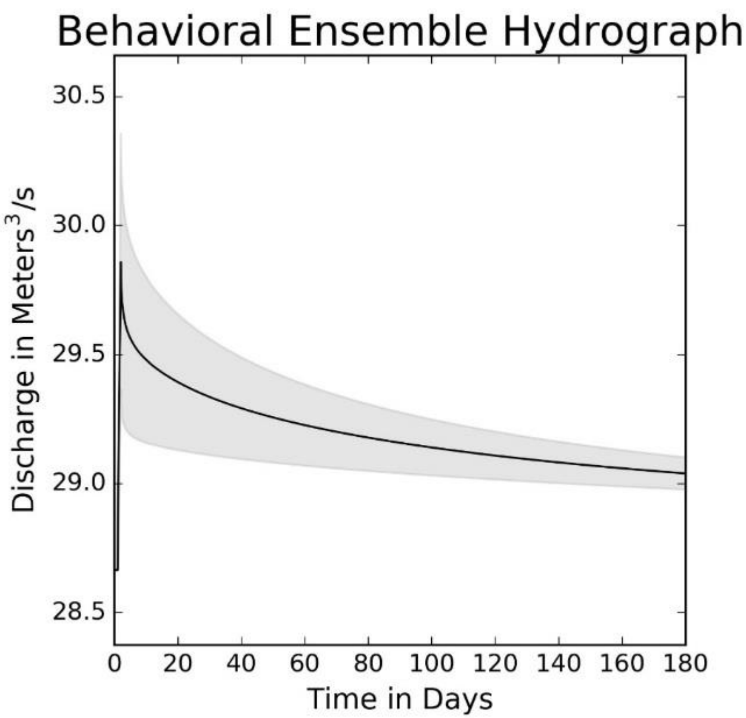
Desired behavior is not only a function of springflow…also need to reproduce head distribution

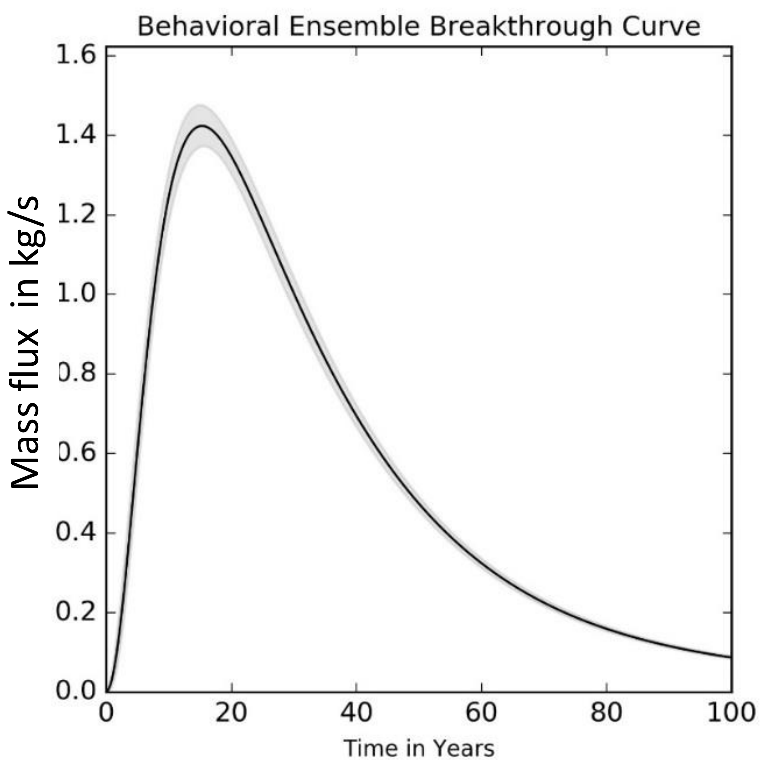
Monte Carlo Simulation

Fix conduit network statistics and porous matrix properties and evaluate the influence of uncertainty of random conduit configuration on flow and transport in an idealized Silver Springshed

	K	Theta	Number of VPF	Number of HPF	Hydraulic Conductivity (m s^{-1})	Spread (°)	Porosity	Specific Storage (m^{-1})
Case 14	1.17	6000	500	3000	0.0001	20	0.25	3.4E-05
Case 81	1.58	4000	200	3500	0.0001	40	0.35	6.7E-05
Average	1.375	5000	350	3250	0.0001	30	0.3	5.1E-05
Selected Parameters	**1.5**	**5000**	**350**	**3250**	**0.0001**	**30**	**0.3**	**1.0E-05**

Results for Behavioral Replicates





For Behavioral Replicates:
Mean steady spring flow 29.2 m3/s
Std Dev steady spring flow: 0.15 m3/s

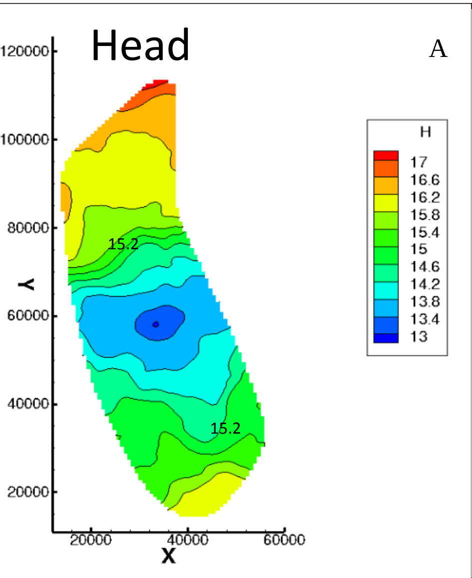
For Behavioral Replicates:
Mean Peak Travel Time= 16 yr
Std Dev Peak Travel Time = 1 yr

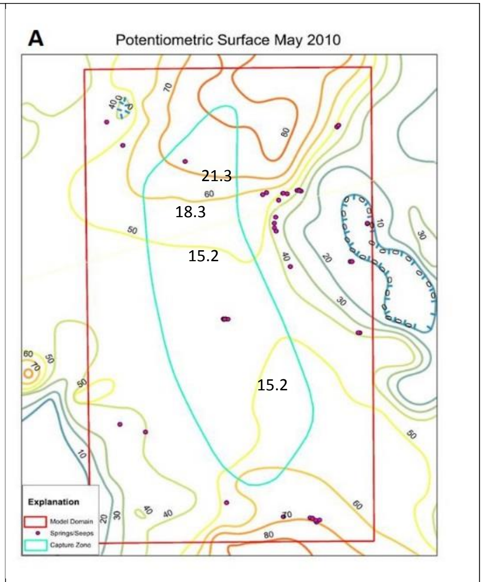
Only 37/400 were behavioral for both hydraulic heads and spring flows!

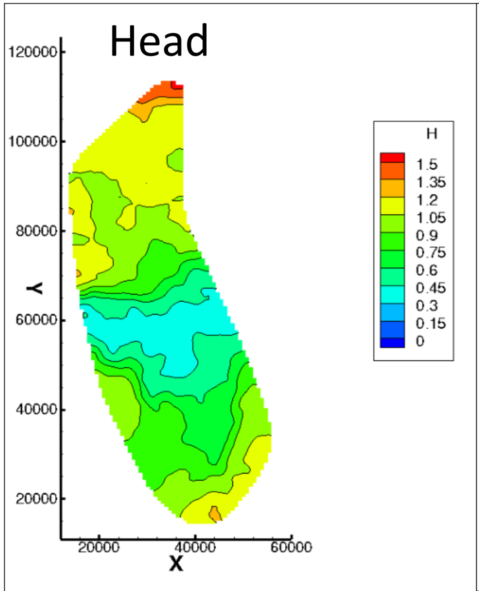
Backward Pulse Monte Carlo

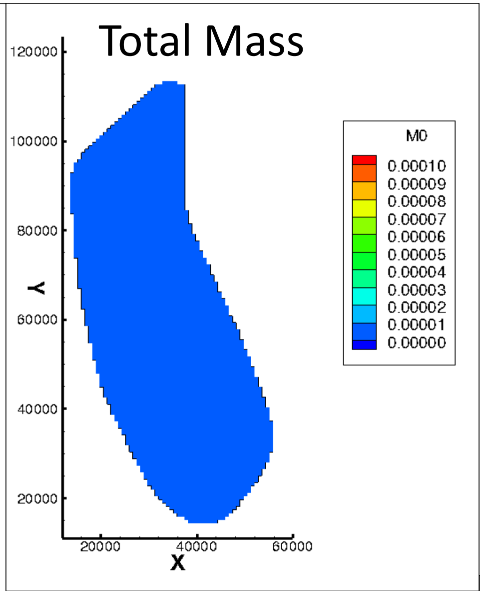
Mean

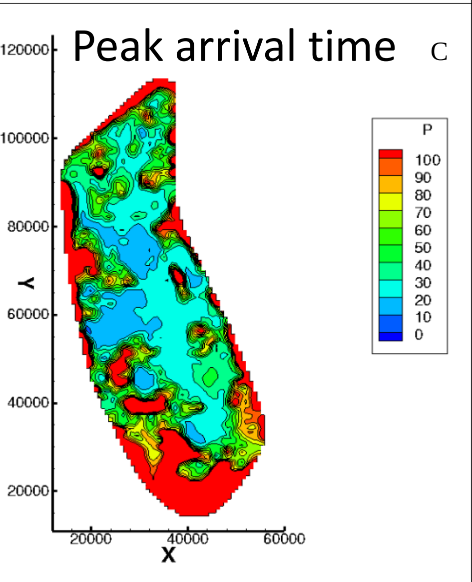
Std Dev

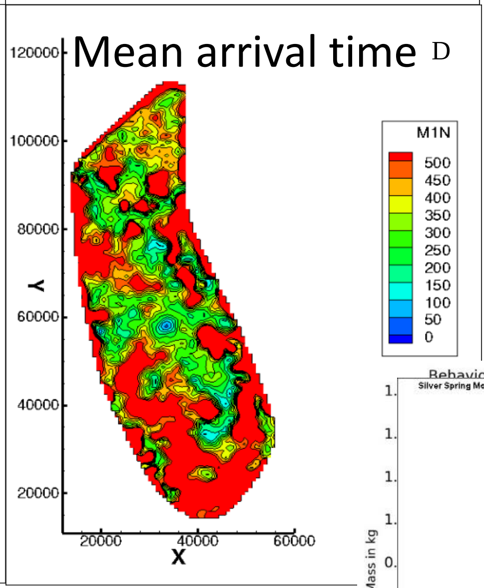


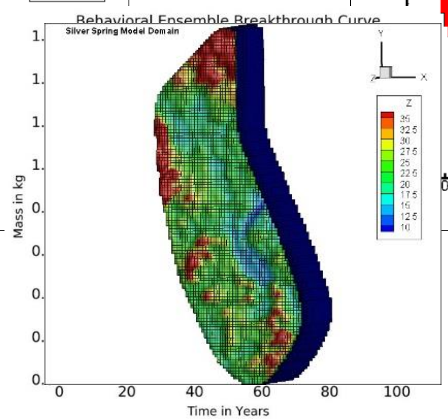


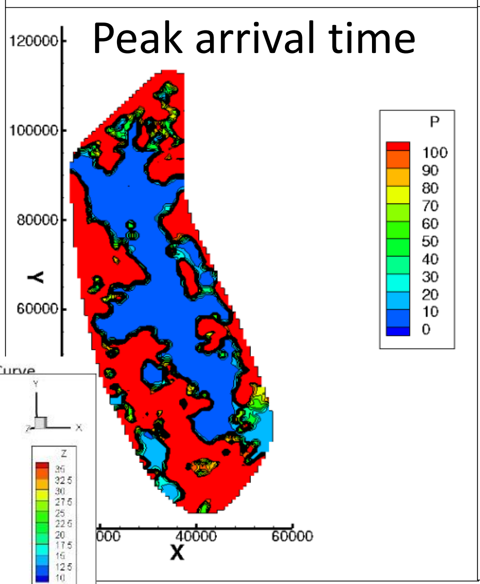


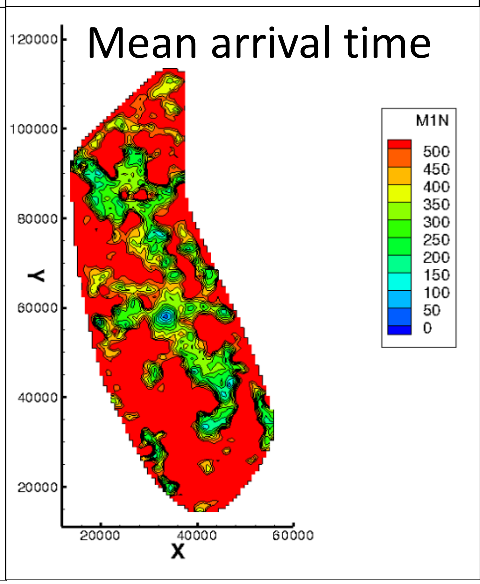




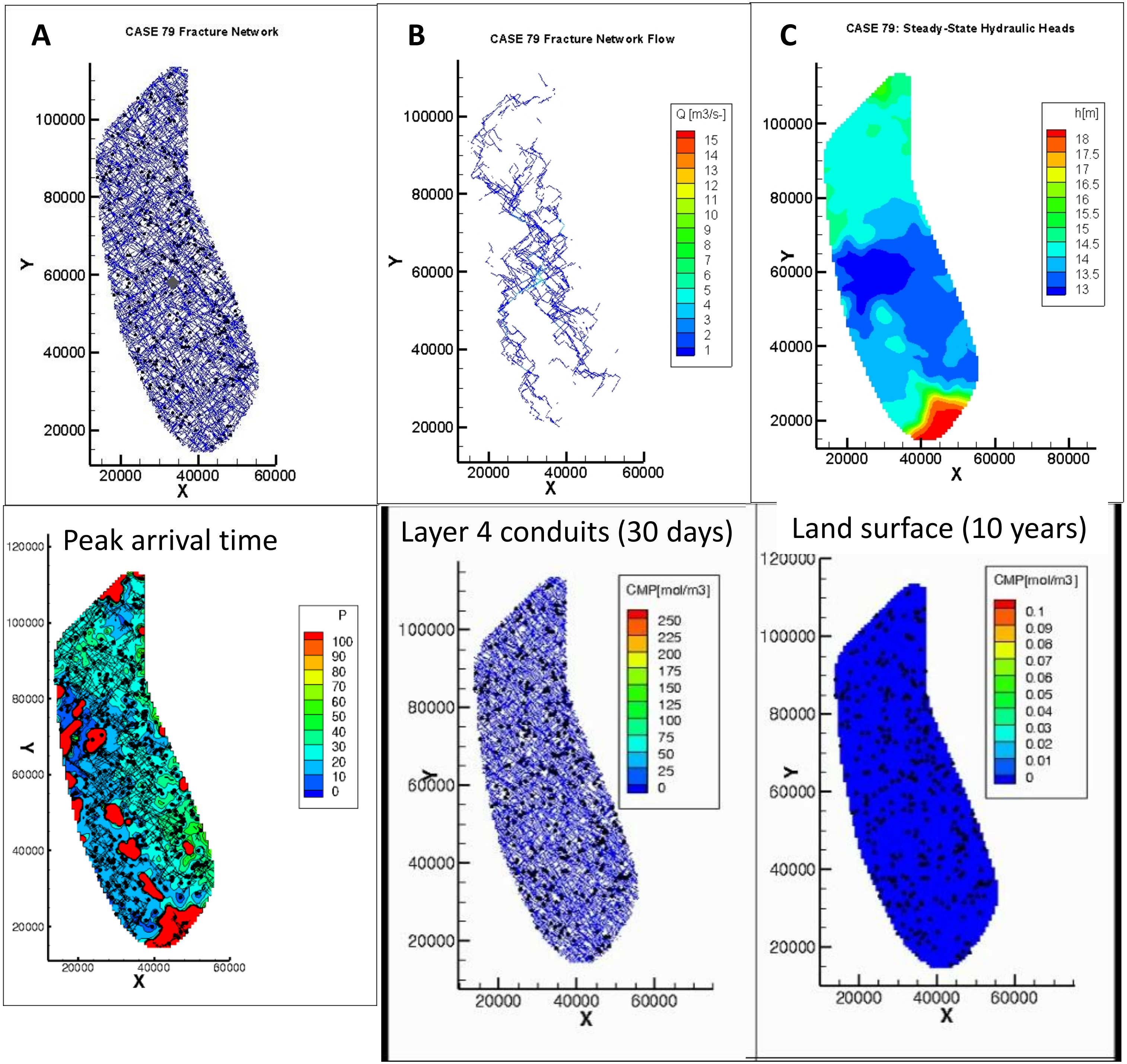




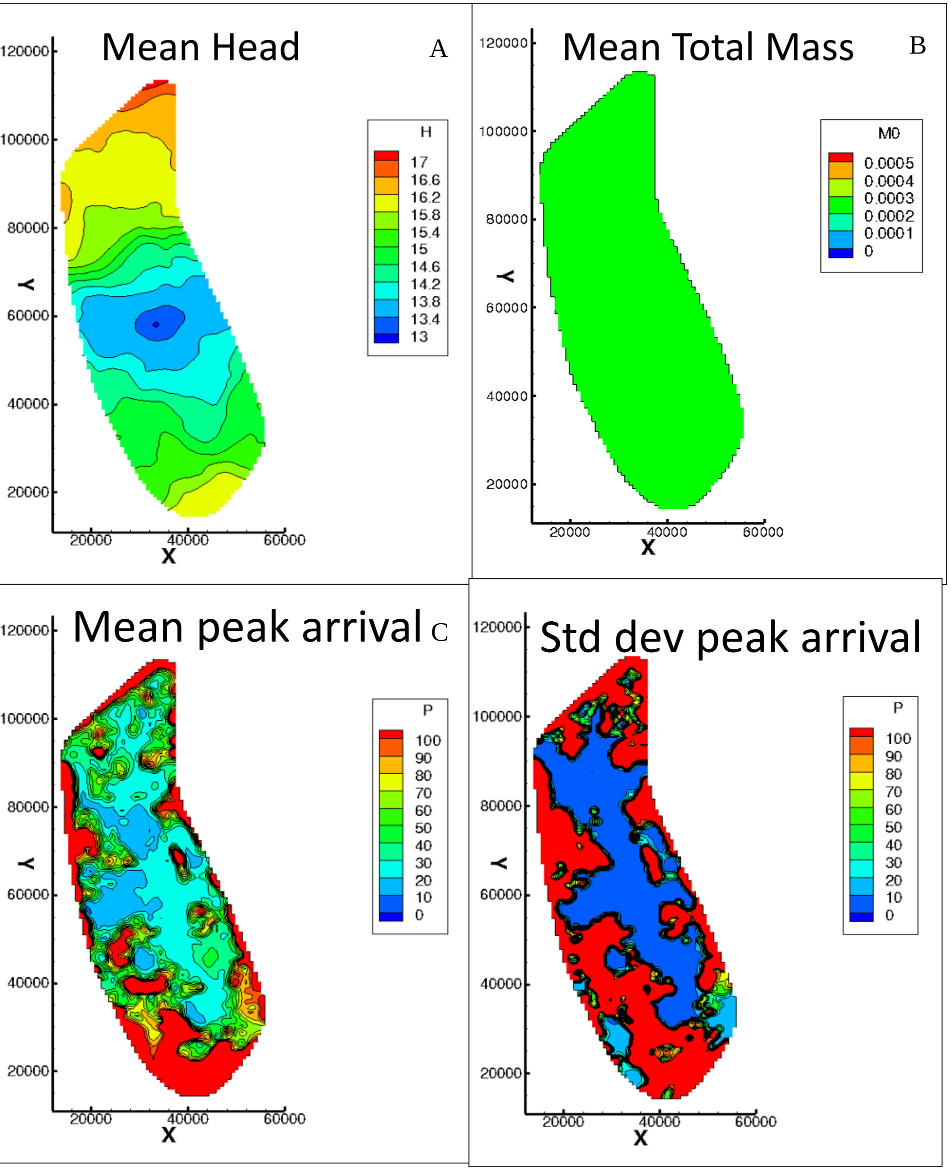




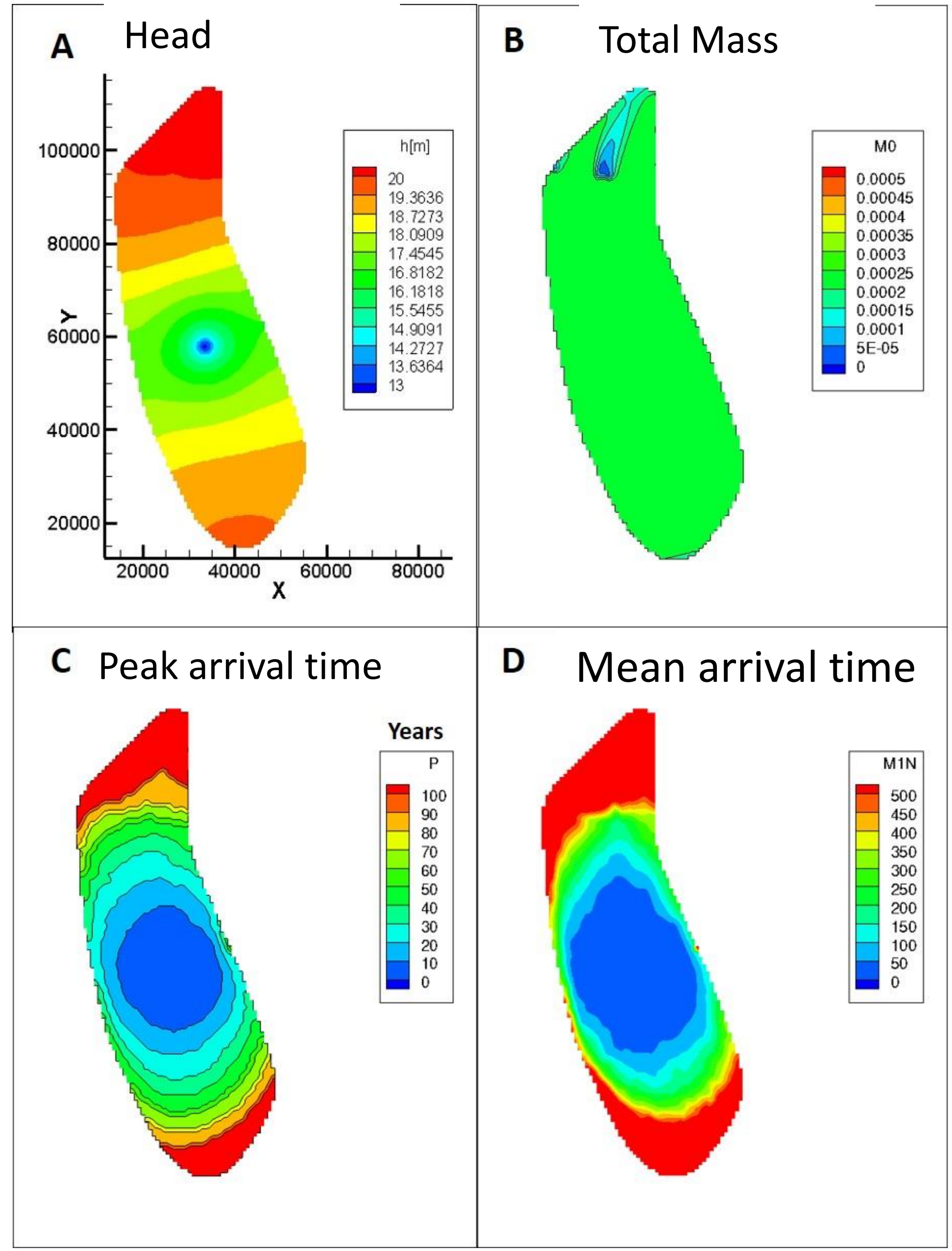
Example Behavioral network: Case 79



Backward Pulse Monte Carlo



Backward Pulse EPM



Conclusions

Conduits tended to develop in topographic lows that drained nearby high regions. Steady springflow occurred when the conduit network reached a stable configuration and the springshed contributing area stabilized.

MM-GSA indicated that parameters that increased paleokarst connectivity and decreased porous matrix conductivity were the most influential in producing first magnitude springs.

Limited combinations of porous media and paleokarst template parameters resulted in the evolution of conduit networks that generated springflows and head distributions that resembled Silver Springs

In addition to the sensitive parameters identified by the Morris Method, the actual random VPF and HPF placements and their resulting connectivity exerted large influence on whether conduit networks evolved that produce first magnitude springs.

Conclusions

Monte Carlo simulation for parameters representative of Silver Springs showed generation of spring flow was “all or nothing” indicating that for high hydraulic conductivity systems specific paleokarst connectivity is very important.

Behavioral replicates showed very low variability in flow and transport predictions indicating that incorporating preferential flow processes into the hydrologic model is important, but that once incorporated flow and transport behavior at springs can be predicted with relatively low uncertainty.

Backwards tracer pulse experiments showed a large vulnerable region stretching north and south of the spring where peak travel times of less than 30 years are predicted for the behavioral replicates with low uncertainty.

Conducting a similar Monte Carlo analysis of behavioral networks and backwards tracer pulse experiments on a calibrated Silver Springs model could enhance current efforts to identify vulnerable areas of the Silver Springshed that could be targeted for management interventions.


Questions? Comments??

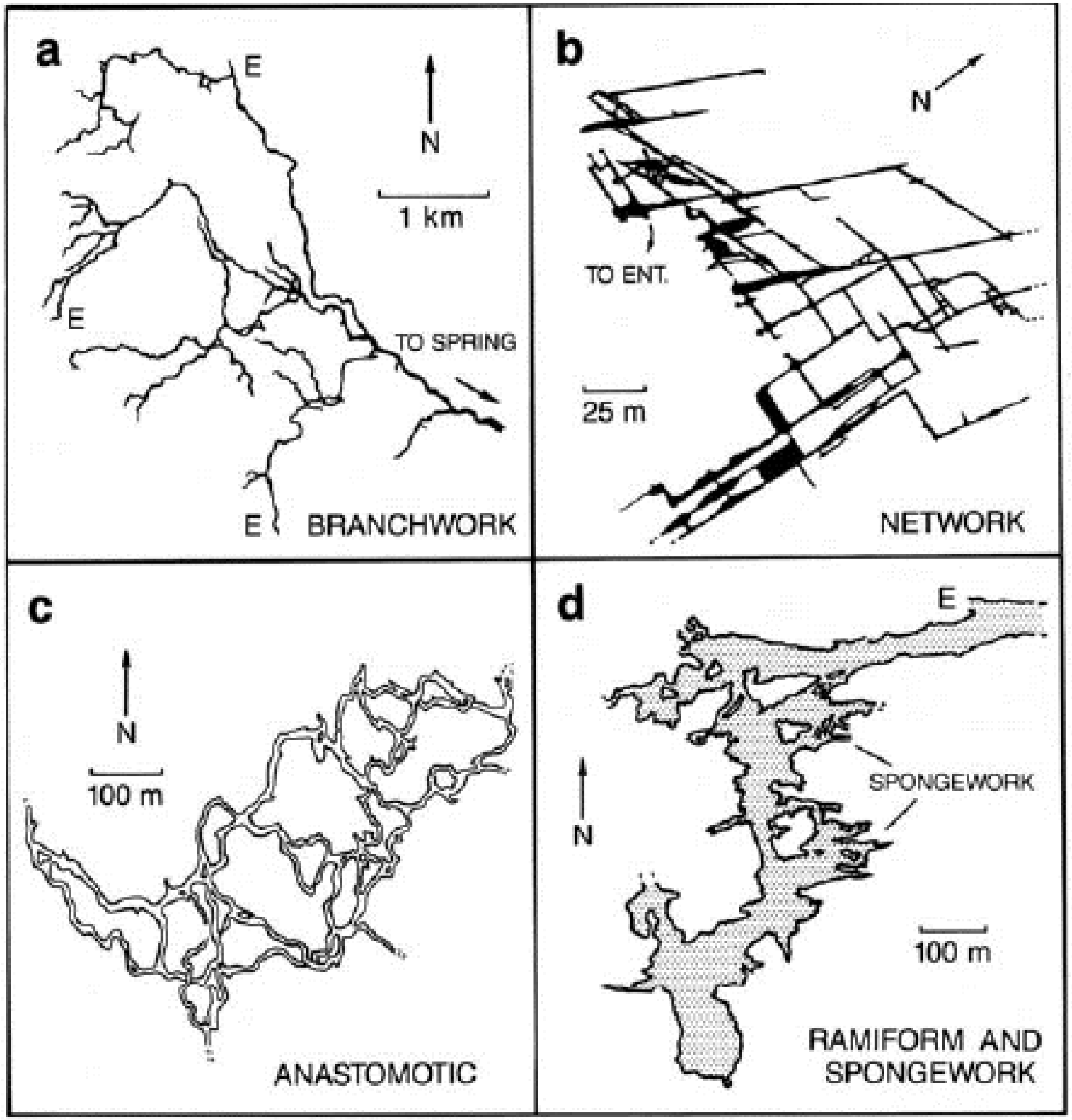
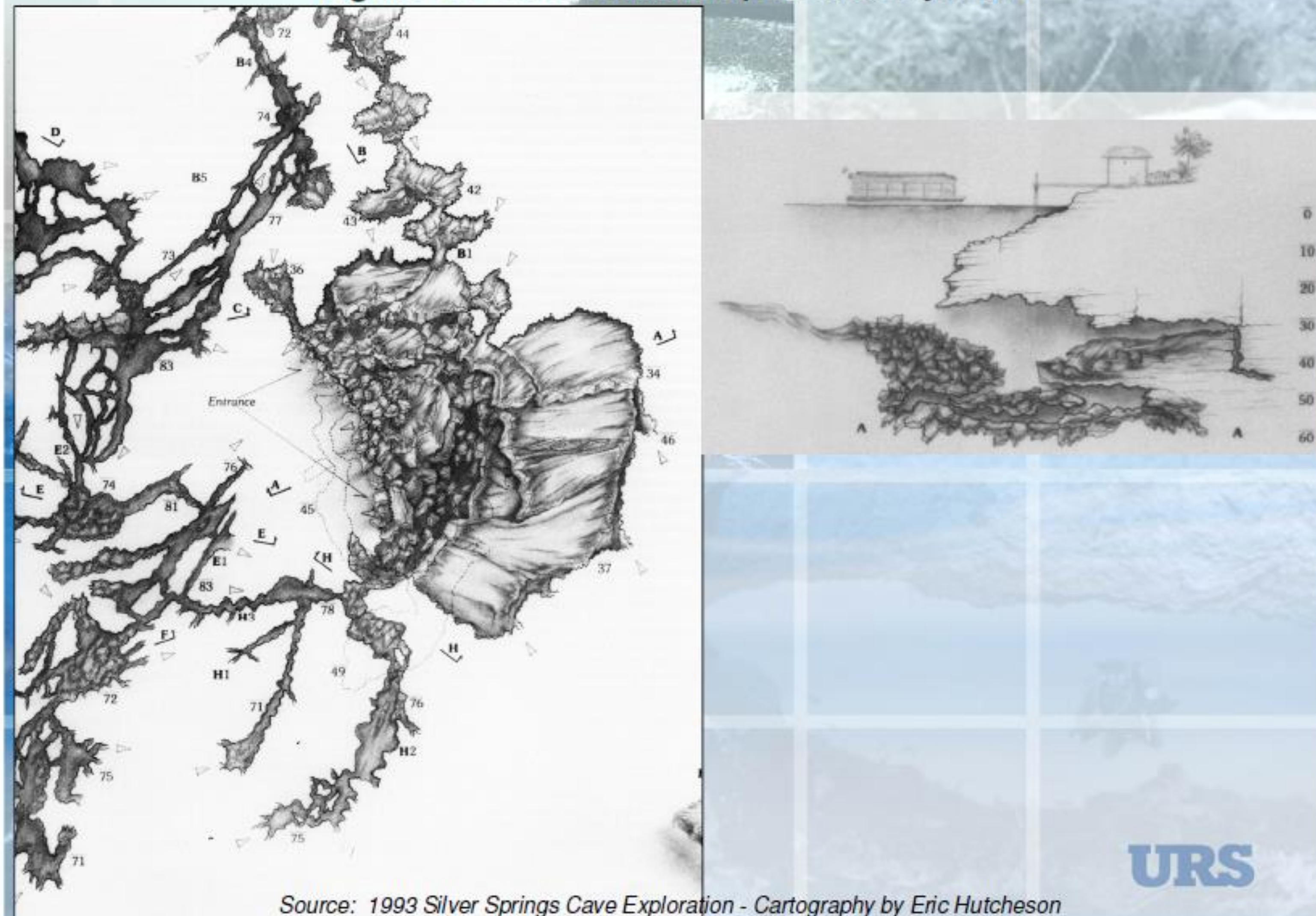


Figure 1. Common patterns of solutional caves: (a) branchwork: Crevice Cave, Missouri (Joachim Fm.); (b) network: part of Crossroads Cave, Virginia (New Scotland Fm.), (c) anastomotic: part of Hölloch, Switzerland (Cretaceous Schrattenkalk), (d) ramiform and spongework: Carlsbad Cavern, New Mexico (Capitan Fm.). E = entrance. Because of their small width-to-length ratio, passages in a and b are shown as solid lines. Maps reproduced with permission of (a) Paul Hauck, (b) H. H. Douglas, (c) Alfred Bögli, (d) Cave Research Foundation.

Figure 23 - SSG Partial Map of Cave System



Source: 1993 Silver Springs Cave Exploration - Cartography by Eric Hutcheson

Conceptual Model Underlying Karst Evolution

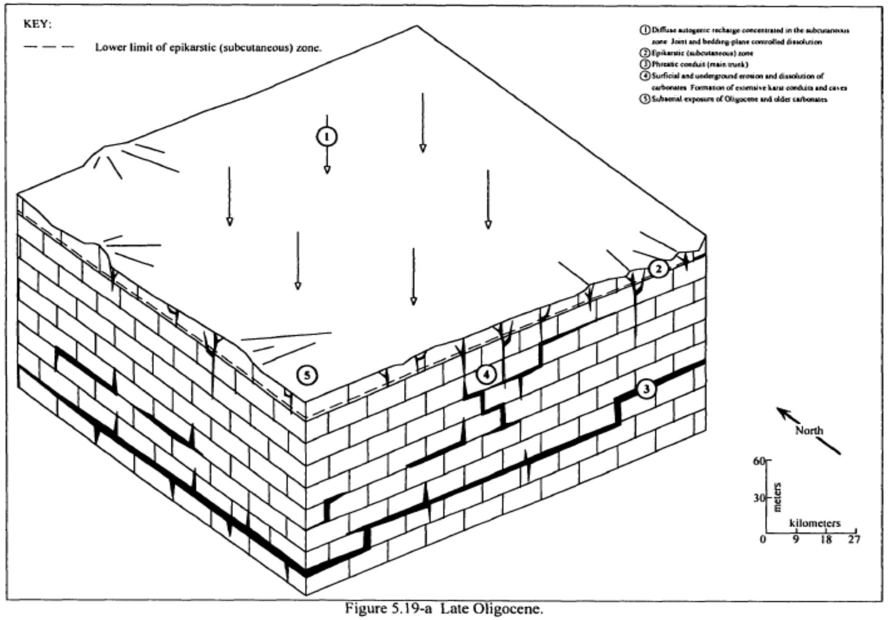


Figure 5.19-a Late Oligocene.

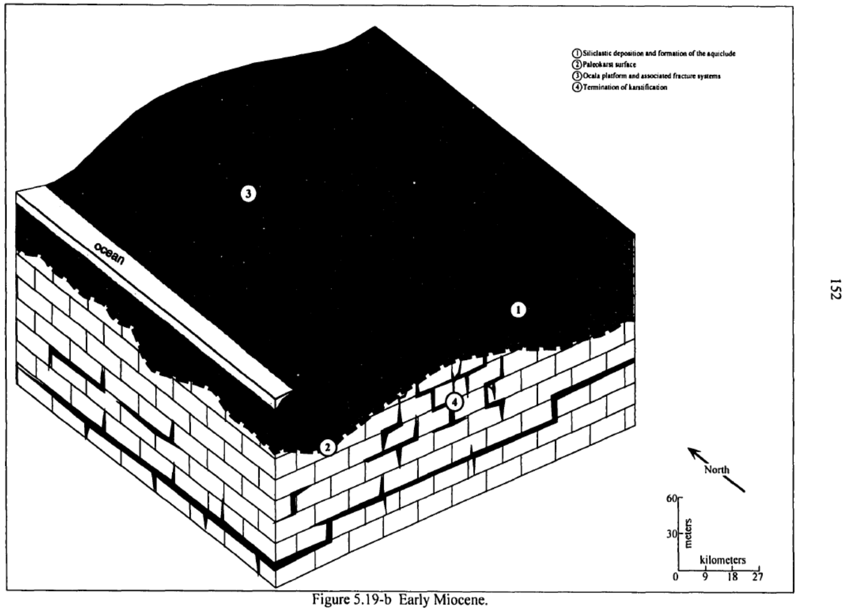


Figure 5.19-b Early Miocene.

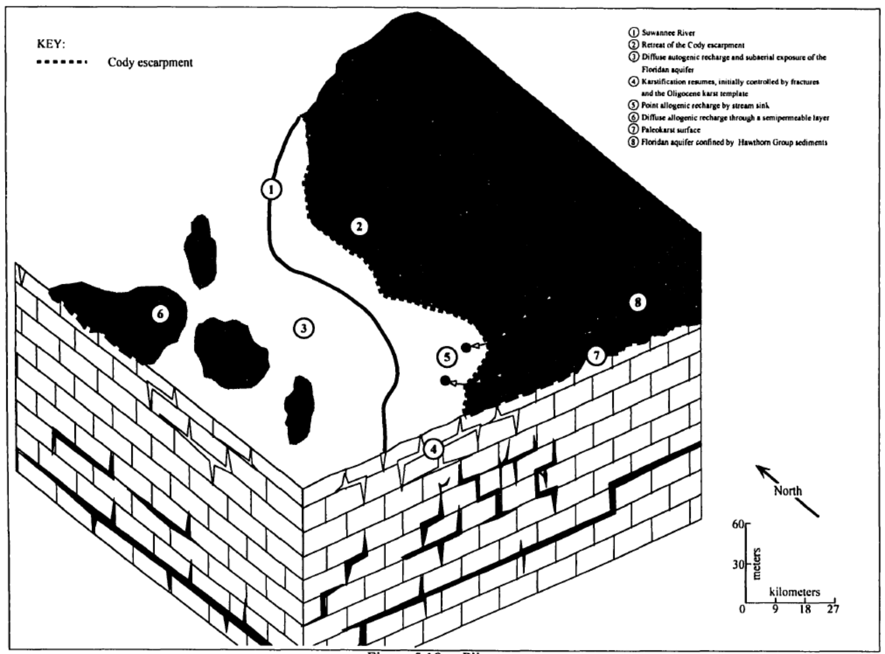
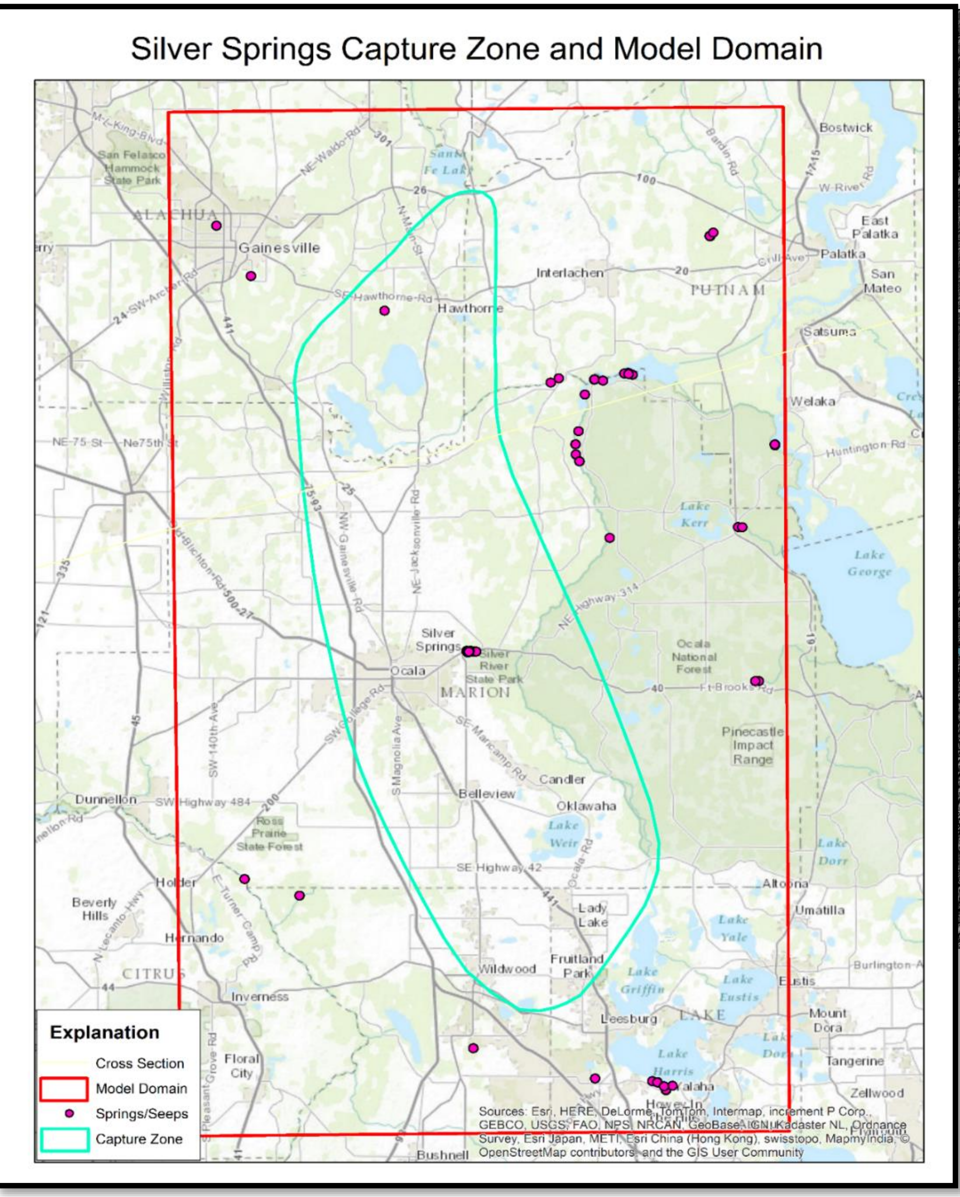
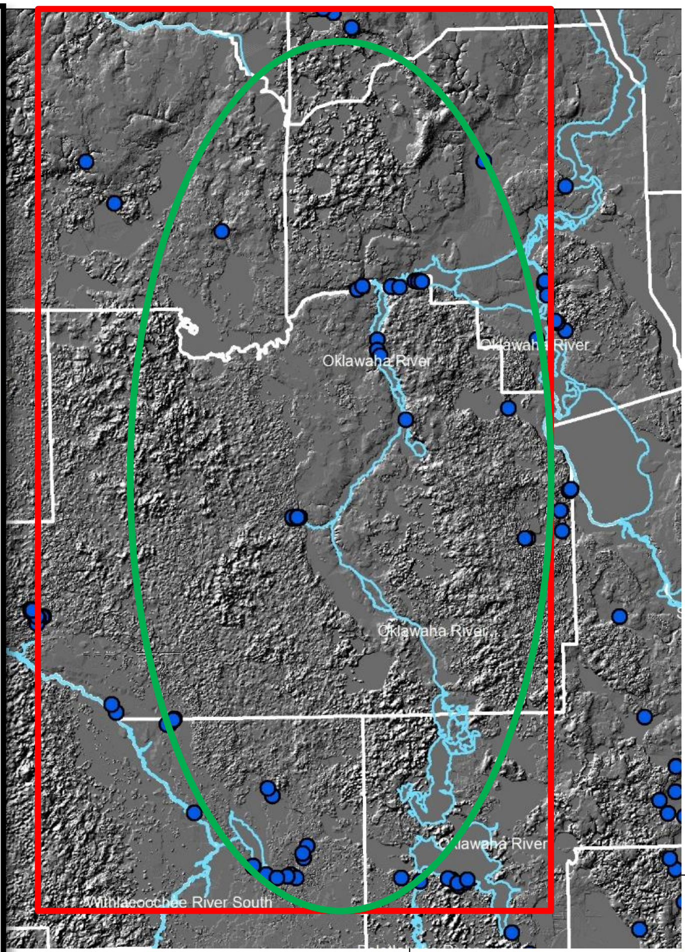
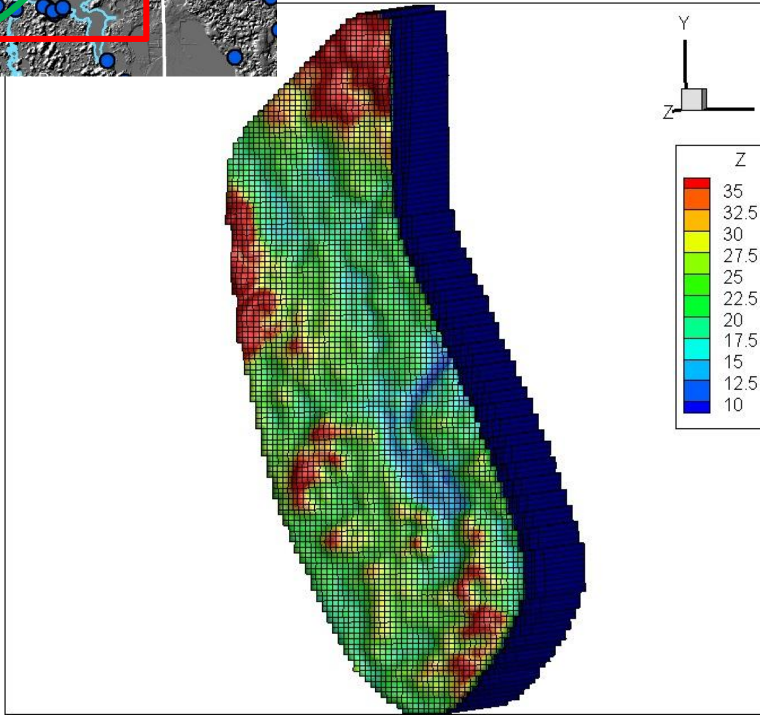


Figure 5.19-c Pliocene.

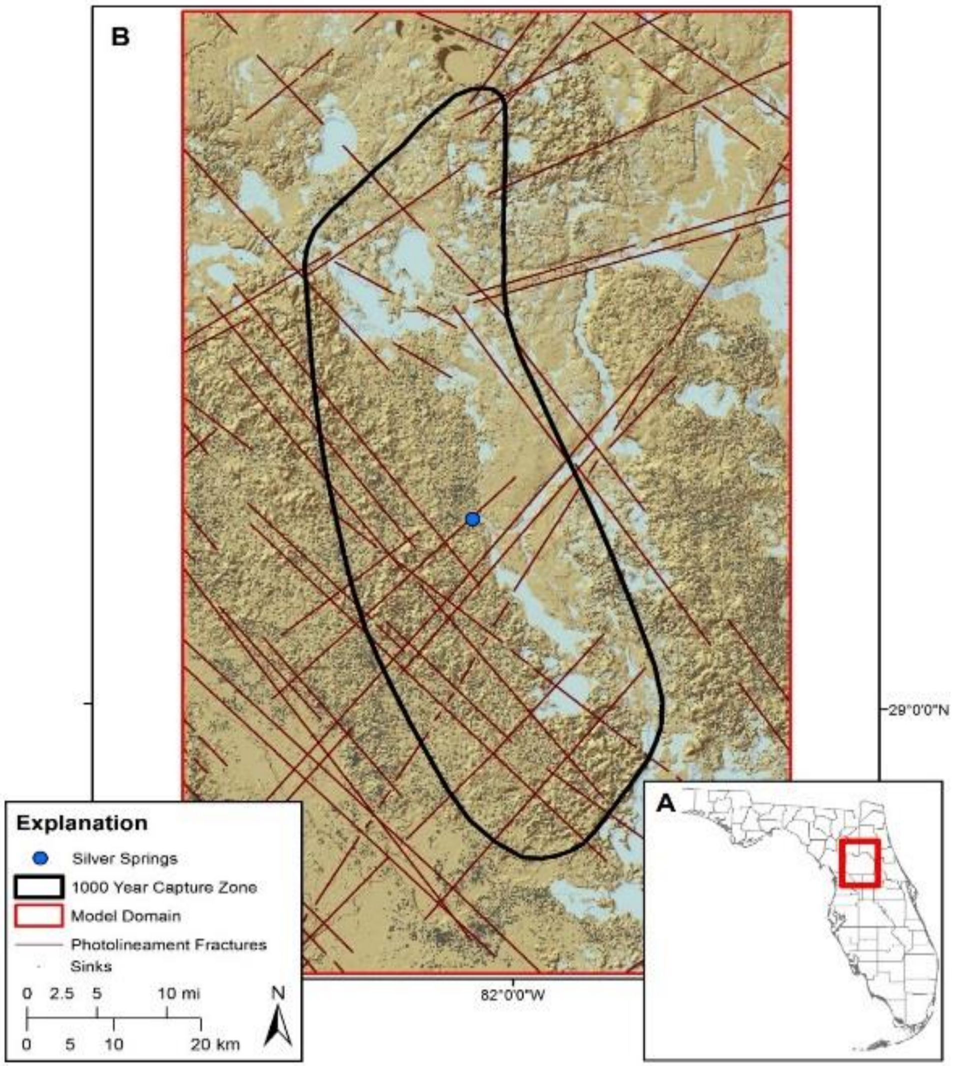
From "Evolution of Karst in the Lower Suwannee River Basin Florida", Denizman, 1998

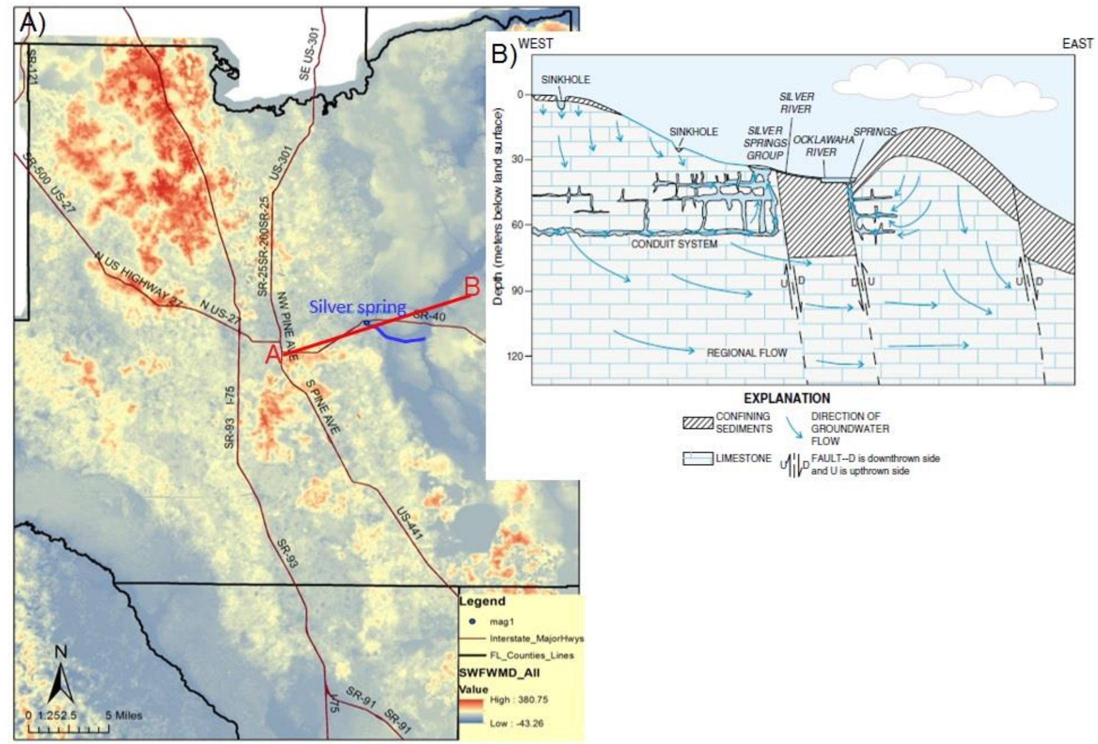

Silver Springs Capture Zone and Model Domain
Gainesville
Hawthorne
Interlachen
PUTNAM
Palatka
East Palatka
San Mateo
Satsuma
Welaka
Bostwick
Lake Kerr
Lake George
Silver Springs
Silver River State Park
Ocala
MARION
Ocala National Forest
Pinecastle Impact Range
Candler
Belleview
Oklawaha
Lake Weir
Dunnellon
Ross Prairie State Forest
Holder
Beverly Hills
Hernando
CITRUS
Inverness
Floral City
Wildwood
Lady Lake
Fruitland Park
Leesburg
LAKE
Lake Griffin
Lake Yale
Lake Eustis
Eustis
Mount Dora
Tangerine
Zellwood
Altoona
Umatilla
Lake Harris
Yalaha
Bushnell
Explanation
Cross Section
Model Domain
Springs/Seeps
Capture Zone
Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community


Oklawaha River
Oklawaha River
Oklawaha River
Oklawaha River
Withlacoochee River South

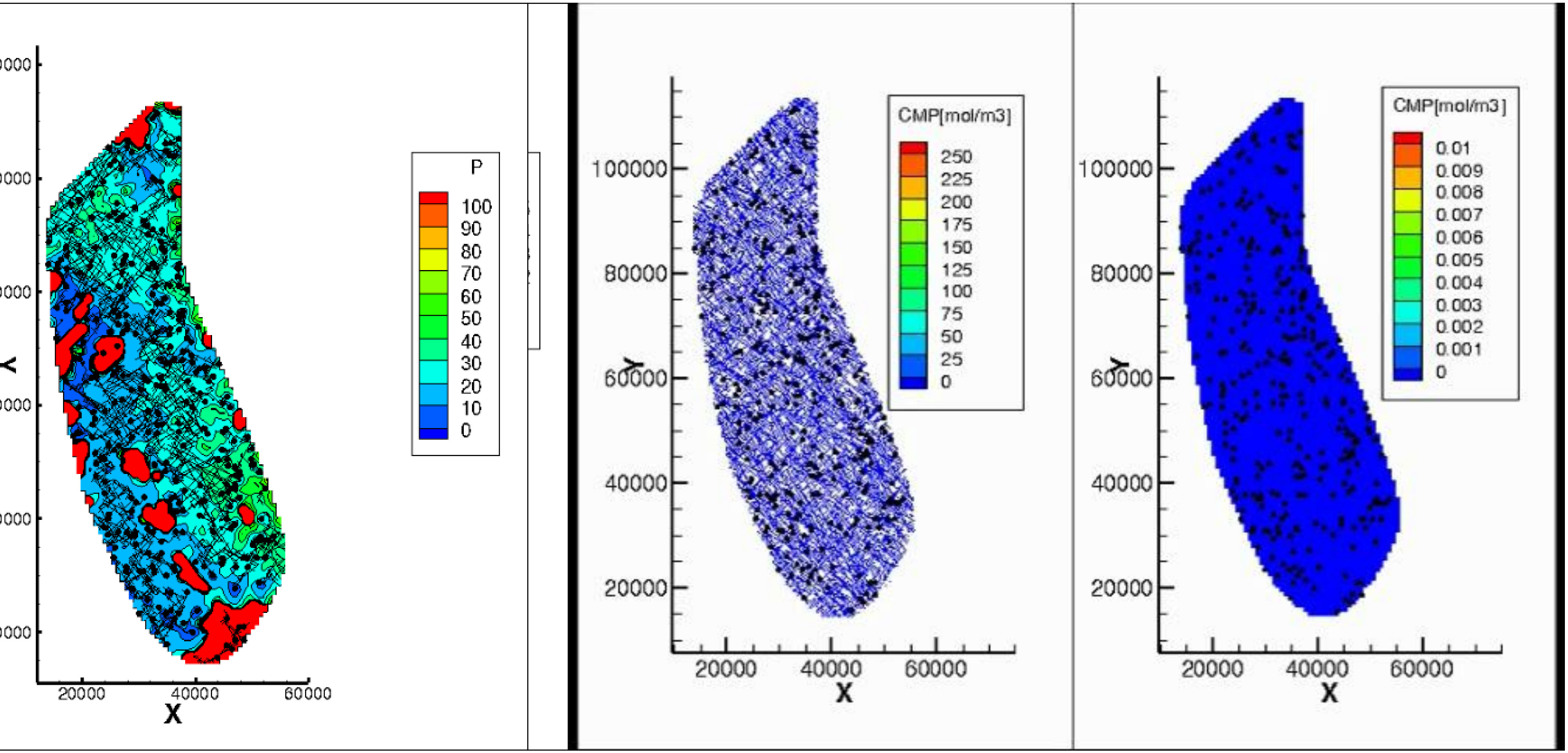

Y
Z
Z
35
32.5
30
27.5
25
22.5
20
17.5
15
12.5
10

Silver Spring Site Map and 1000 Year Capture Zone

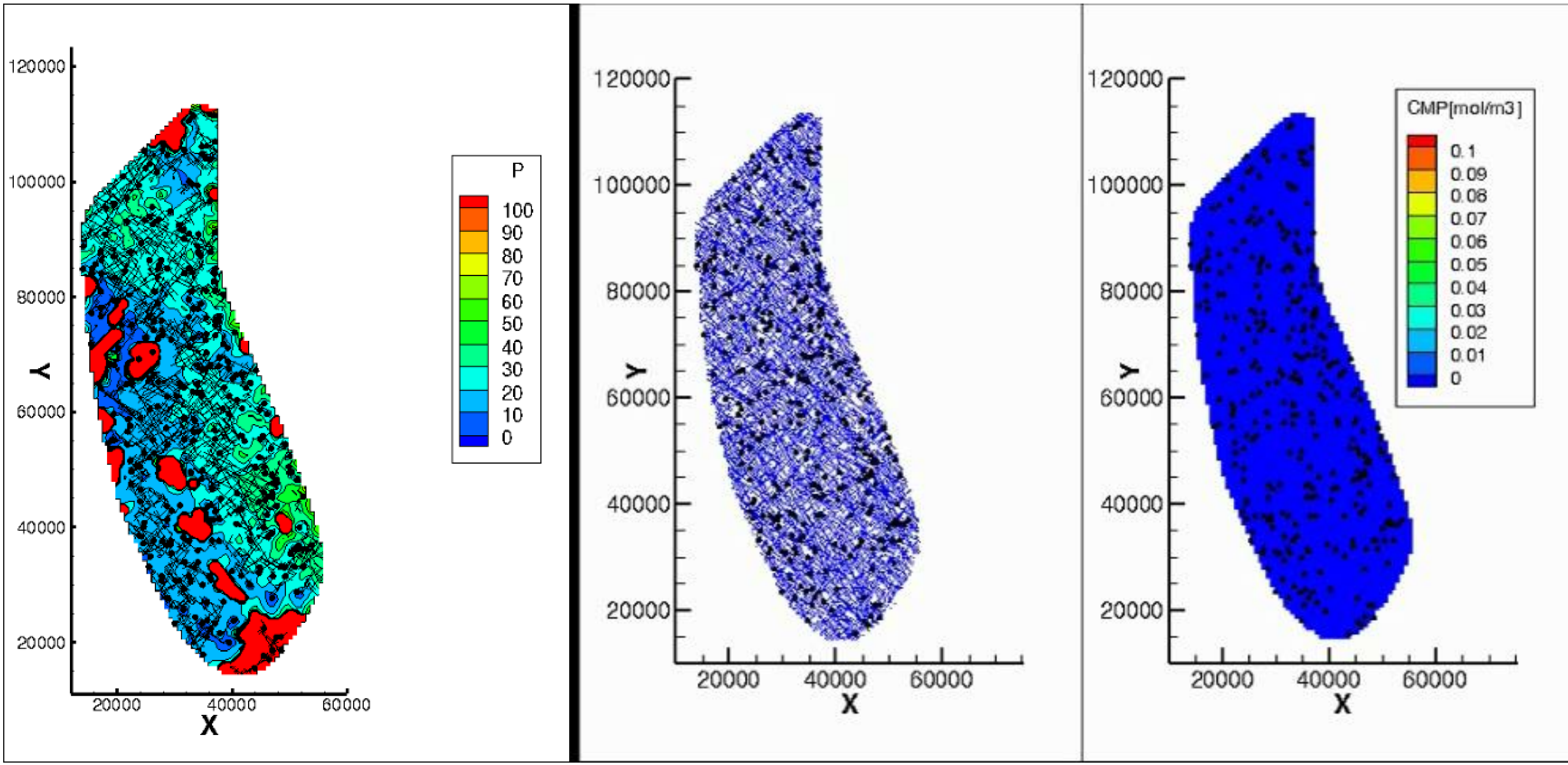




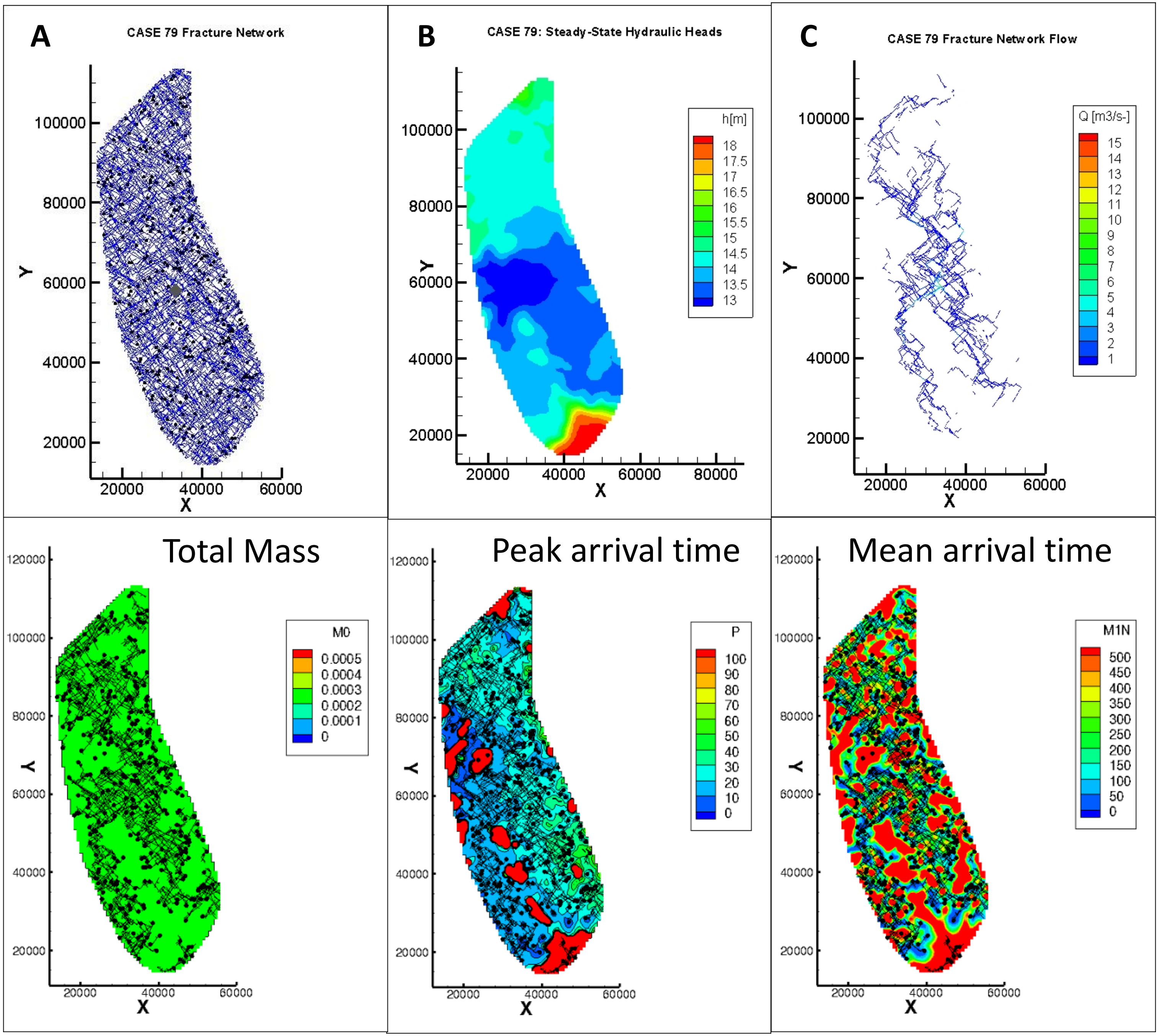
Example behavioral network (case 79) reverse unit solute pulse from spring (1 month animation)

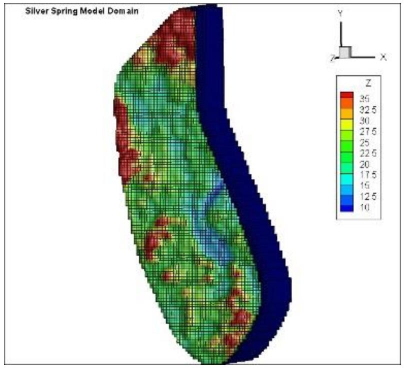


Example behavioral network (case 79) reverse unit solute pulse from spring (10 year animation)



Example Behavioral network: Case 79





Example Behavioral network: Case 83