Regional Simulation Model (RSM)

Next generation regional tool

Workshop
GEER 2008: Greater Everglades Ecosystem Restoration
July 29, 2008

RSM Design considerations

- Regional in nature – simplifications may be needed
- Reproduce the functionality of the legacy code SFWMM (daily, continuous simulation for planning applications)
- Reasonable run times
- Improved process and solution algorithms, use of advances in computer technology including programming languages, GIS and databases
- Better resolution than SFWMM in areas where it is needed
- Eliminate or minimize “hard coding” of simulation alternatives

Regional Simulation Model

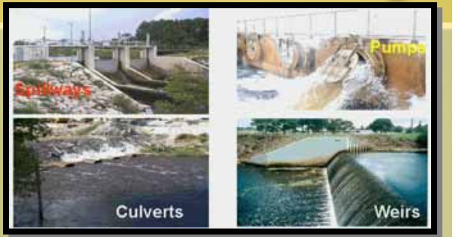
- Integrated 2D overland – groundwater flow, 1D canal flow
  - Irregular triangular mesh
- Finite volume solution to diffusion wave equation
- Object-oriented C++ code, Linux-based open-source
- Spatially variable soil water storage
- Variable overland flow conveyance & groundwater transmissivity
- Abstraction: water-bodies and water-movers
- GUI: input and output processing
- Local water management within cells
- Simulate regional-scale hydrology and complex water management
- Long-term simulations (30+ years)

RSM Engines

HSE

RSM

MSE



South Florida Regional Simulation Model
SFRSM

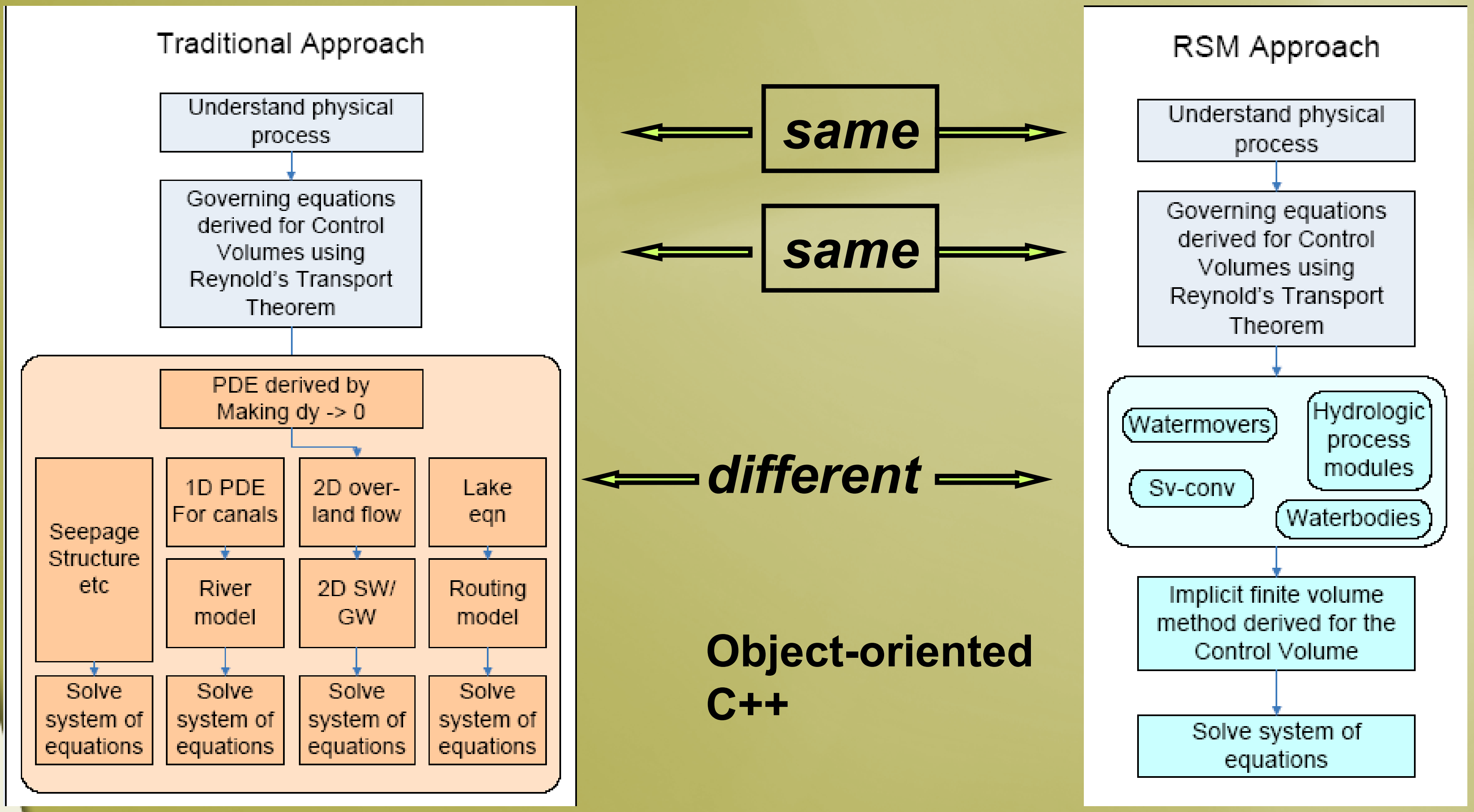
Hydrologic Simulation Engine (HSE)

- Model physical setup
- Simulate hydrologic processes
- Overland flow
- Groundwater flow
- Canal network
- Calibration/validation of model parameters
- Use observed structure flows

Management Simulation Engine (MSE)

- Simulate structure operations
- Implementation of operational rules
- Flood control rules
- Water supply policies
- Maintain minimum flows & levels
- Regional operational coordination

Paradigm Shift in RSM



Traditional Approach

Understand physical process

Governing equations derived for Control Volumes using Reynold's Transport Theorem

PDE derived by Making dy -> 0

Seepage Structure etc

1D PDE For canals

2D over-land flow

Lake eqn

River model

2D SW/ GW

Routing model

Solve system of equations

Solve system of equations

Solve system of equations

Solve system of equations

same

same

different

Object-oriented C++

RSM Approach

Understand physical process

Governing equations derived for Control Volumes using Reynold's Transport Theorem

Watermovers

Hydrologic process modules

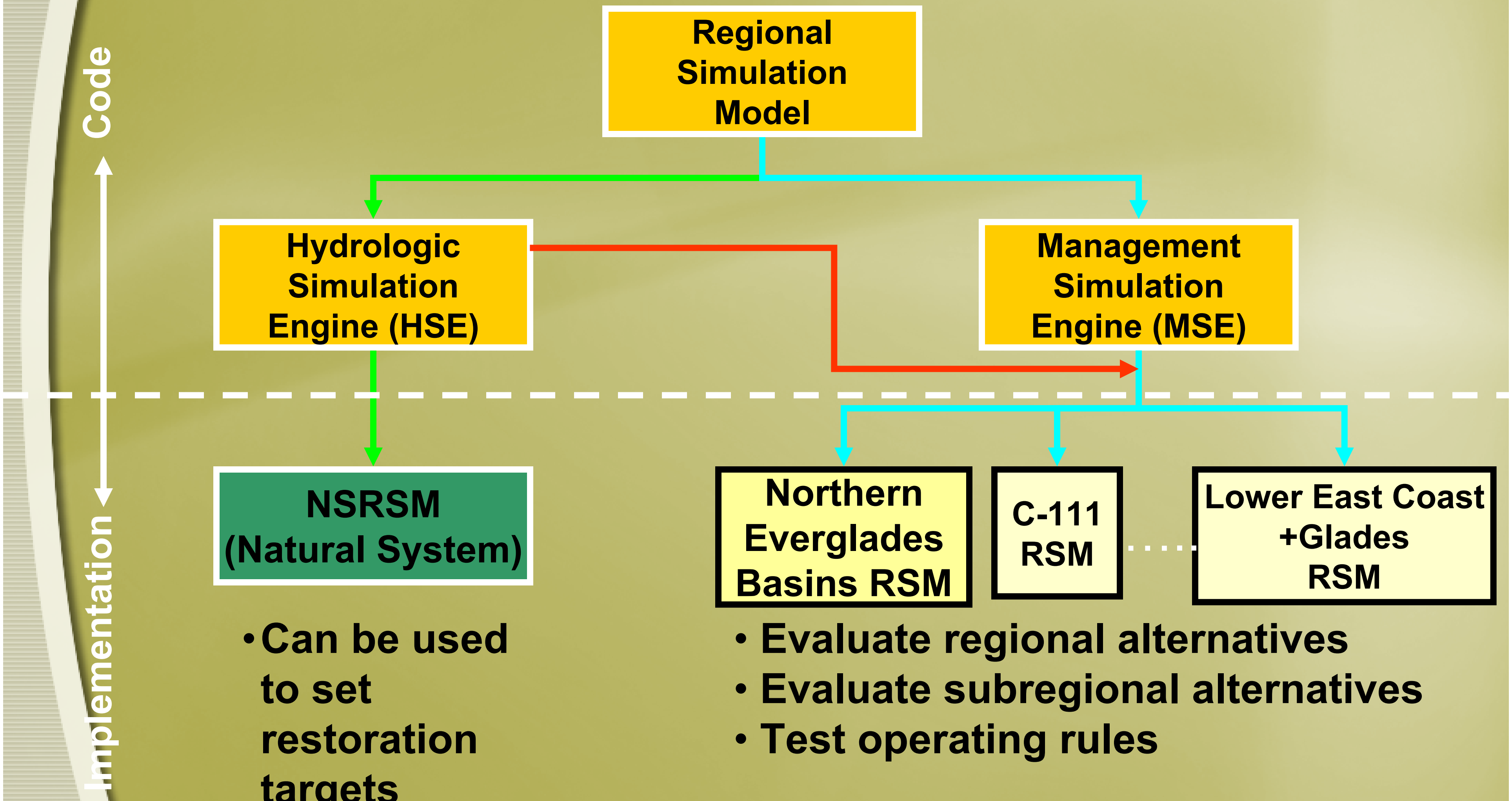
Sv-conv

Waterbodies

Implicit finite volume method derived for the Control Volume

Solve system of equations

Applications of RSM



Regional Simulation Model

Hydrologic Simulation Engine (HSE)

Management Simulation Engine (MSE)

NSRSM (Natural System)

- Can be used to set restoration targets

Northern Everglades Basins RSM

C-111 RSM

Lower East Coast +Glades RSM

- Evaluate regional alternatives
- Evaluate subregional alternatives
- Test operating rules

Natural System RSM (NSRSM)

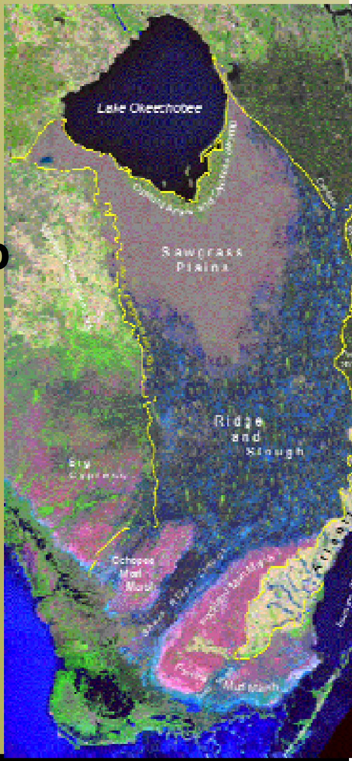
RSM

HSE

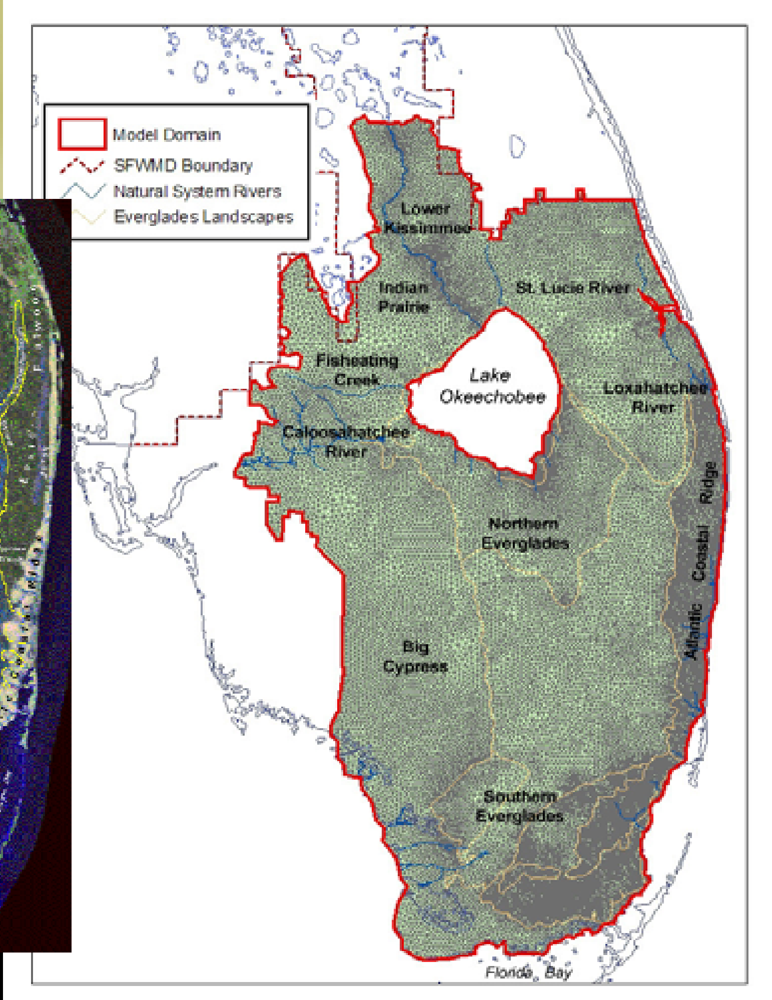
Hydrologic Simulation Engine (HSE)

Natural System RSM

- Pre-drainage physical setup
- Simulate hydrologic processes
- Overland flow
- Groundwater flow
- River network
- Validation against pre-drainage historical records & anecdotal information

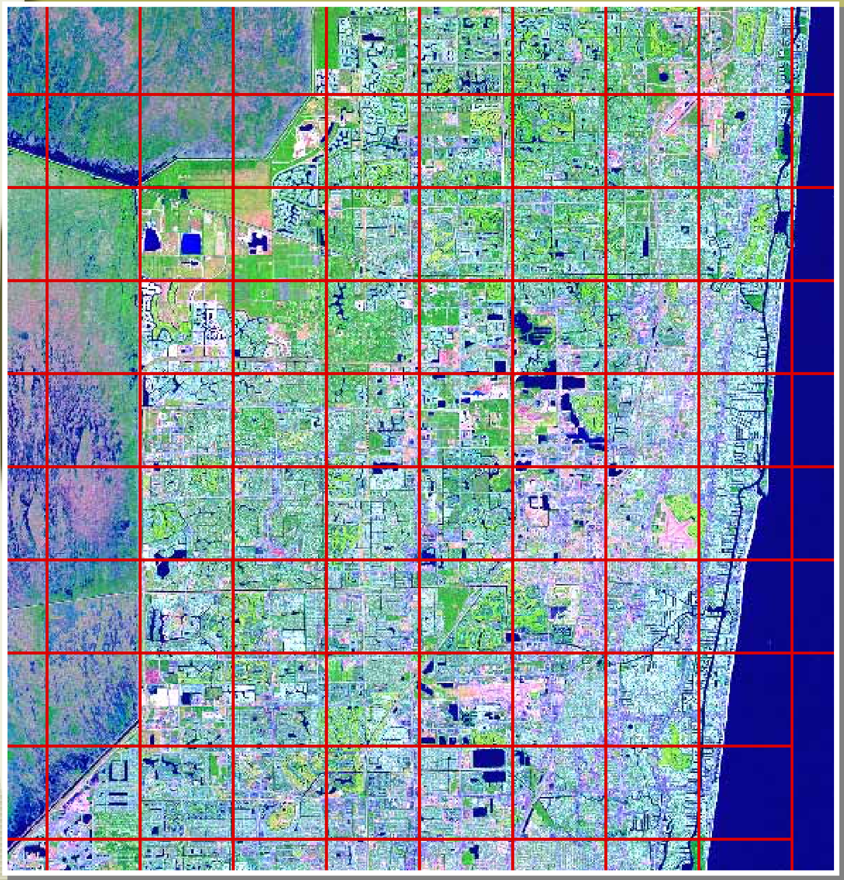


NSRSM Mesh



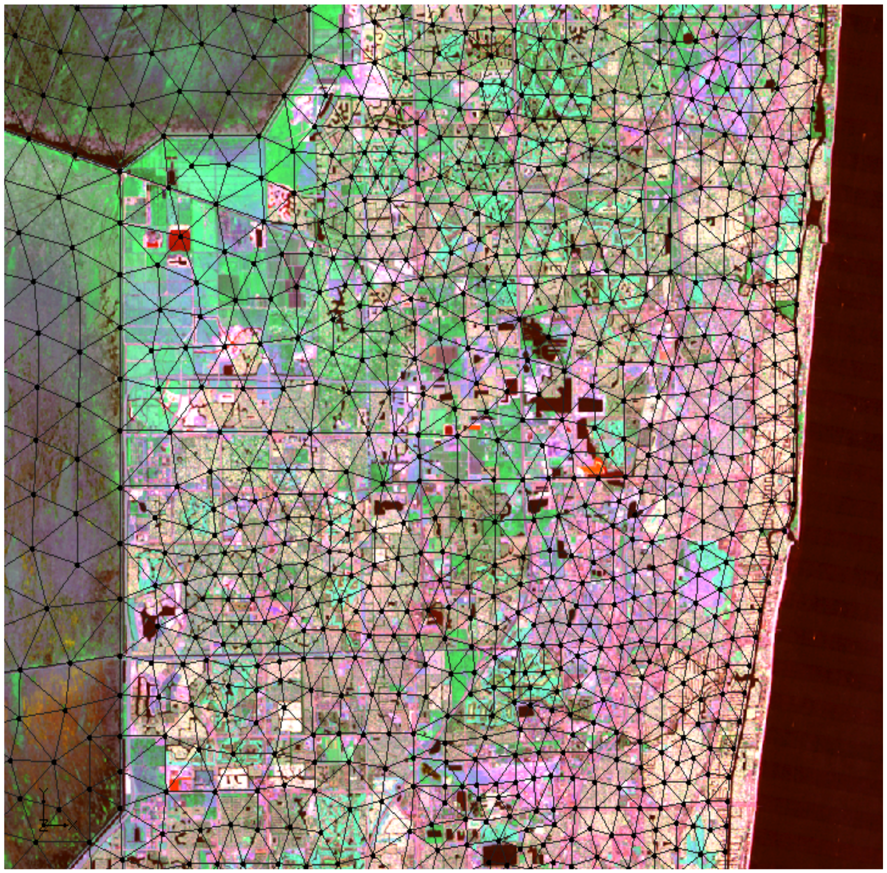
SFWMM (2x2) Versus RSM

SFWMM (2x2)



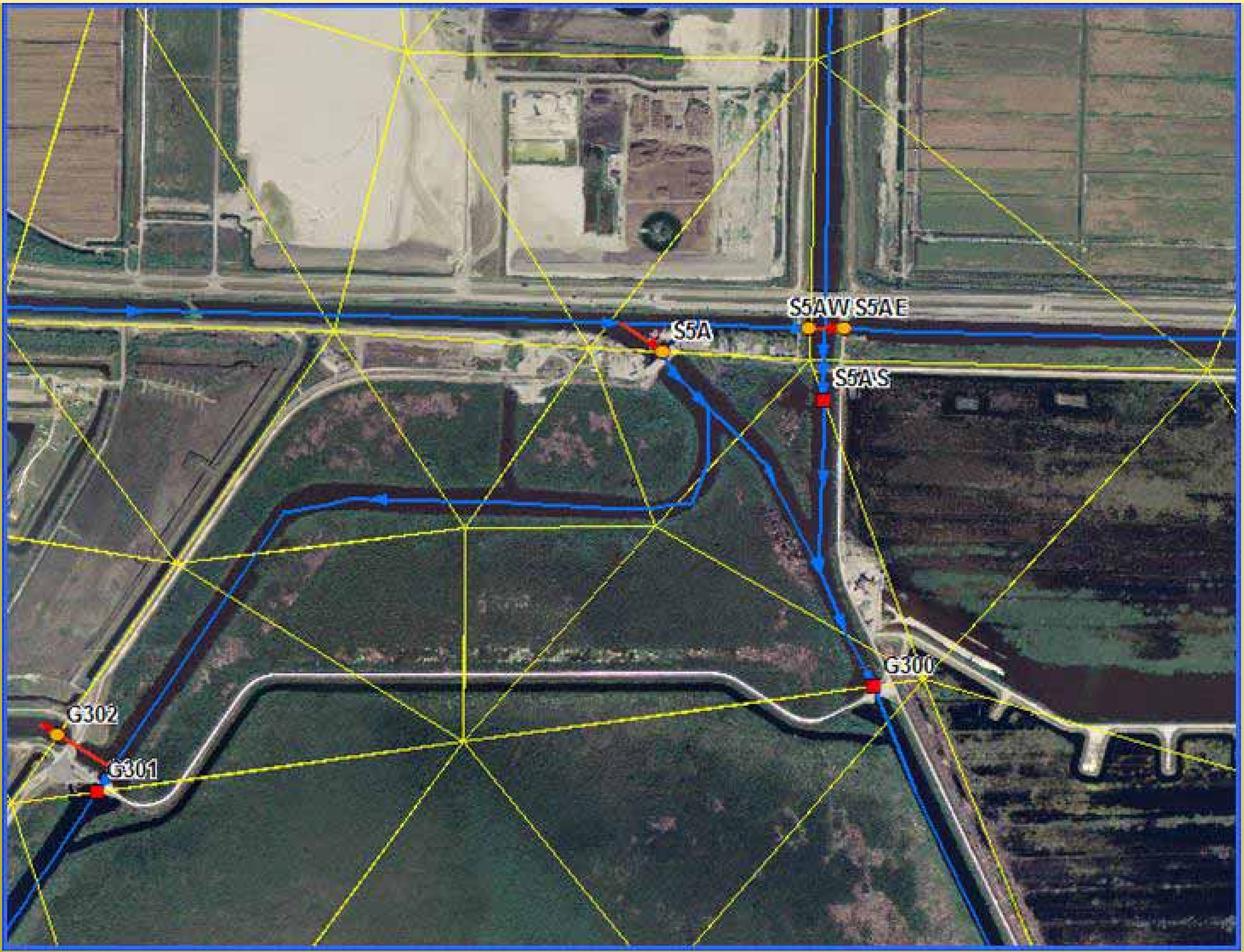
2 mile x 2 mile grid mesh

RSM



Variable triangular mesh

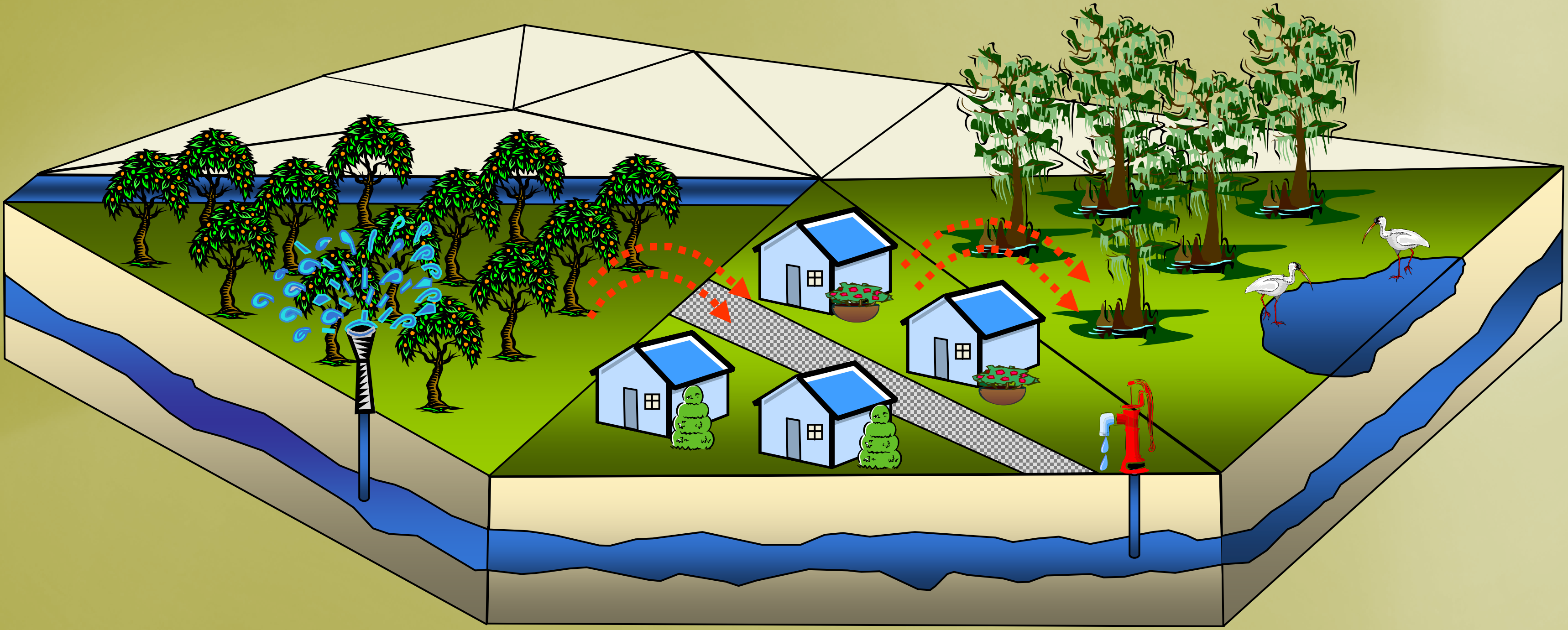
Real Worlds verses Modeled



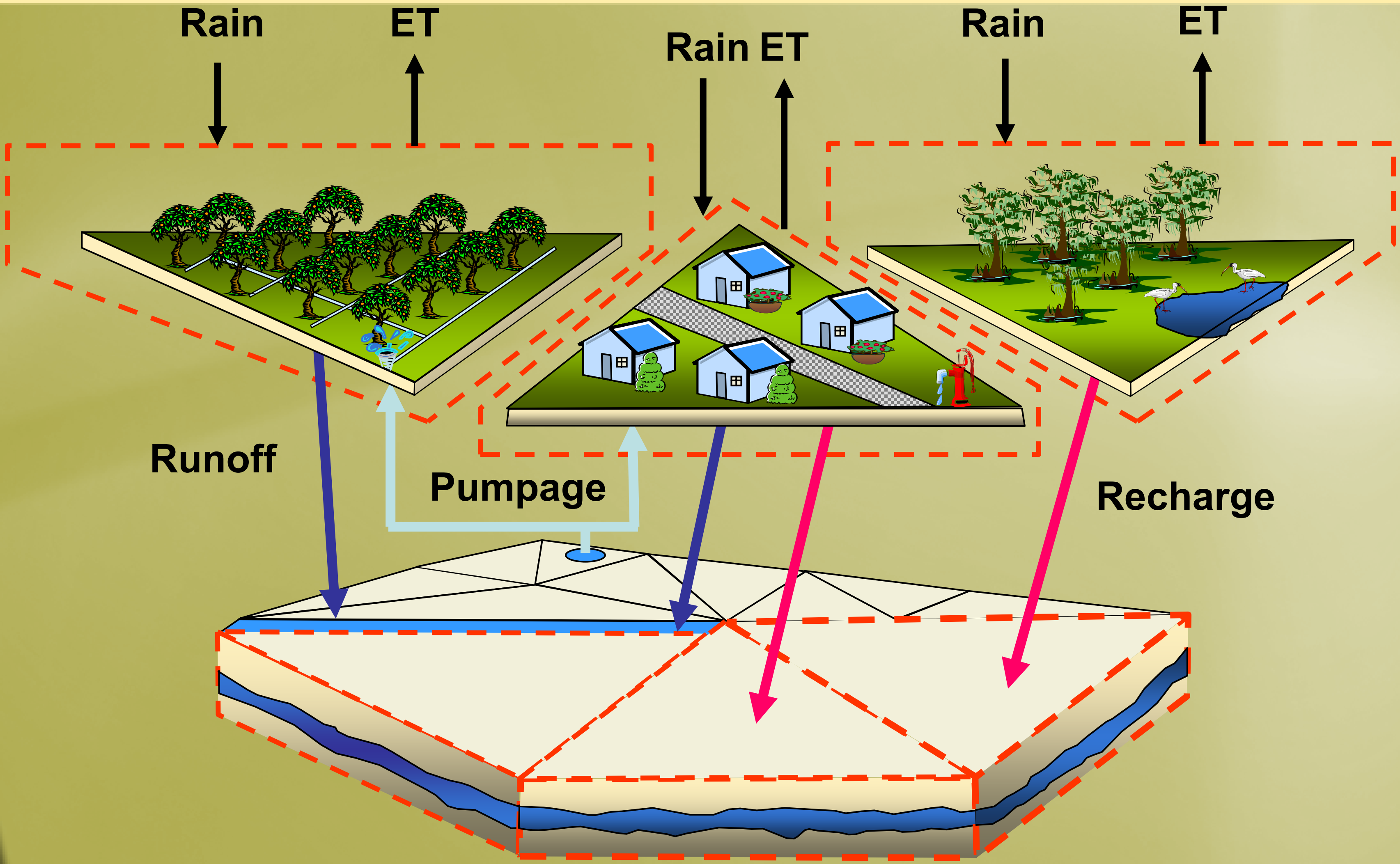
Hydrologic Process Modules (HPM) Concept

- Regional flow simulated with the matrix solution
- Local hydrology simulated by the HPM
  - Detailed local physical processes
  - Local water management systems
  - keeps regional model simple
  - provides flexibility in modelling local hydrology

South Florida Landscape



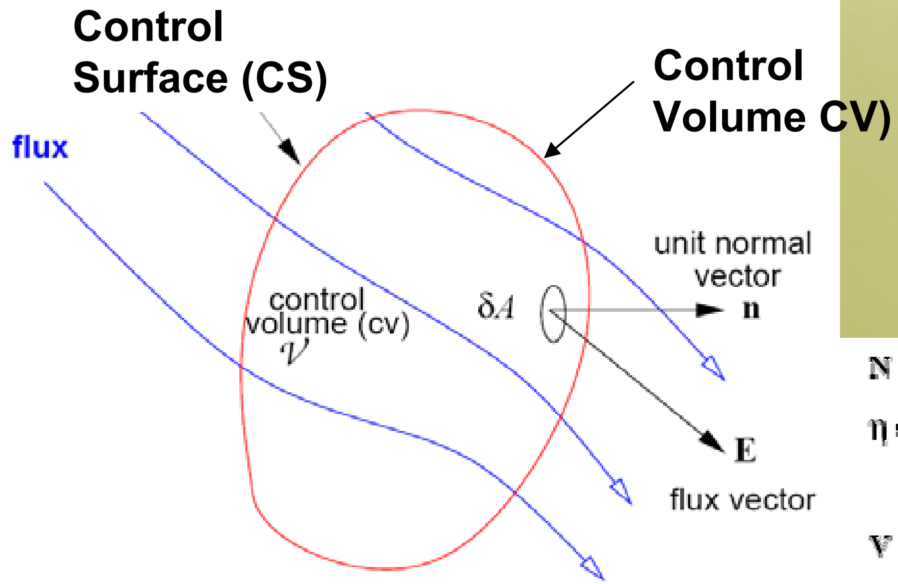
Hydrologic Spatial Modules



Basis of Mesh Solution

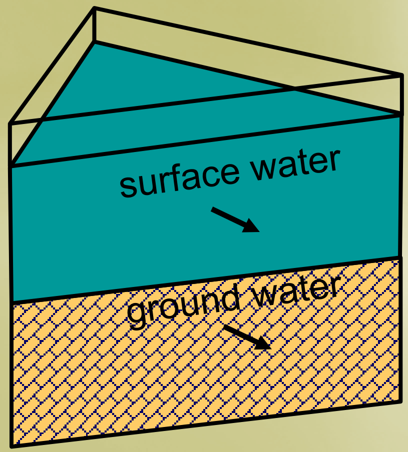
Reynolds Transport Theorem

$$\frac{DN}{Dt} = \frac{\partial}{\partial t}\int_{cv} \eta\rho \, d\mathcal{V} + \int_{cs} \eta\rho(\mathbf{E}\cdot\mathbf{n})\, dA$$



flow out = $\int_{cs}(\mathbf{E}\cdot\mathbf{n})\,d\mathbf{A}$

waterbody



watermover

$N =$ arbitrary extensive property, vector or scalar (eg. mass)

$\eta =$ arbitrary intensive property, or property per unit mass, vector or scalar (eg.concentration)

$\mathbf{V} =$ velocity field

$dv =$ volume element

$\eta = 1$ for mass balance equations

Chow et al. (1988)

Diffusive Wave Formulation

Mass Balance

$$0 = \frac{\partial}{\partial t}\underbrace{\int_{cv} d\mathcal{V}}_{\text{Waterbody}} + \underbrace{\int_{cs} (\mathbf{E}\cdot\mathbf{n})\, dA}_{\text{Watermover}}$$

Momentum Equation

$$\mathbf{F} = \frac{\partial}{\partial t}\int_{cv} \mathbf{E}\rho\, d\mathcal{V} + \int_{cs} \mathbf{E}\rho(\mathbf{V}\cdot\mathbf{n})\, dA$$

$$F = \begin{pmatrix} \rho g h S_x - \tau_{bx} \\ \rho g h S_y - \tau_{by} \end{pmatrix}$$

***For diffusive formulation, neglect all the inertia terms in RHS**

Implications of Diffusive Wave

- Number of equations is reduced
- Equations are stable without nonlinear inertia terms
- Suitable for shallow rough sloping conditions
- Shown to be applicable for most 2-D overland flow problems in Florida
- Conditions of applicability are known (Ponce, 1978)

Numerical Solution

$$\frac{\partial}{\partial t}\int_V dV = -\int_{cs}(\mathbf{E}\cdot\mathbf{n})\,dA$$ Mass balance (1)

$$\mathbf{A}(\mathbf{H})\cdot\frac{d\mathbf{H}}{dt} = \mathbf{q_s}\cdot(\mathbf{H}) + S_i + \mathbf{S}(\mathbf{H})$$ (2)

$$A_iH_i^{n+1} = A_iH_i^n + \Delta t\left[\alpha q_{si}^{n+1} + (1-\alpha)q_{si}^n\right] + \Delta t\left[\alpha S_i^{n+1} + (1-\alpha)S_i^n\right]$$ (3)

$$\mathbf{q_s}(\mathbf{H}) = \mathbf{M}(\mathbf{H})\cdot\mathbf{H}$$ (4)

Qs(H) – vector of flows entering water bodies

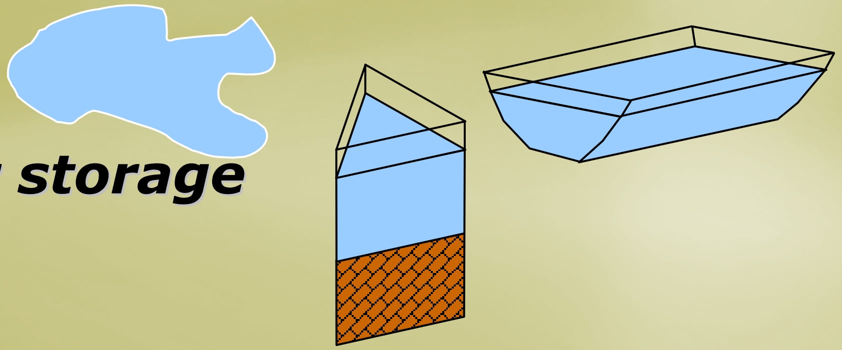
M(H) – global flow resistance matrix

$$\left[\mathbf{A} - \alpha\Delta t\mathbf{M}^{n+1}\right]\cdot\Delta\mathbf{H} = \Delta t\left[\mathbf{M}^n\right]\cdot\mathbf{H}^n + \Delta t(1-\alpha)\left[\mathbf{M}^n - \mathbf{M}^{n+1}\right]\cdot\mathbf{H}^n + \Delta t\left[\alpha\mathbf{S}^{n+1} + (1-\alpha)\mathbf{S}^n\right]$$ (5)

A · x = B ← **As implemented in PETSc** (6)

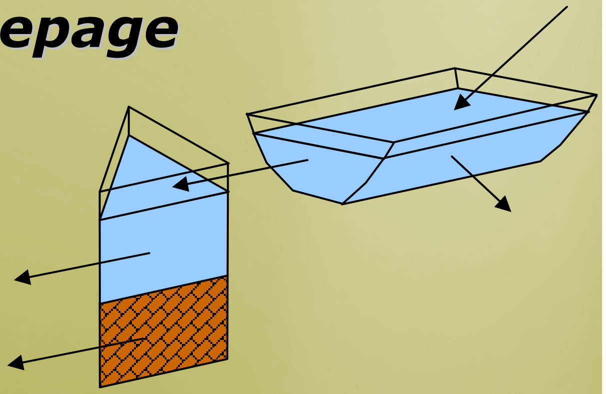
Basic Building Blocks

Water Bodies and Water Movers



Waterbodies include:

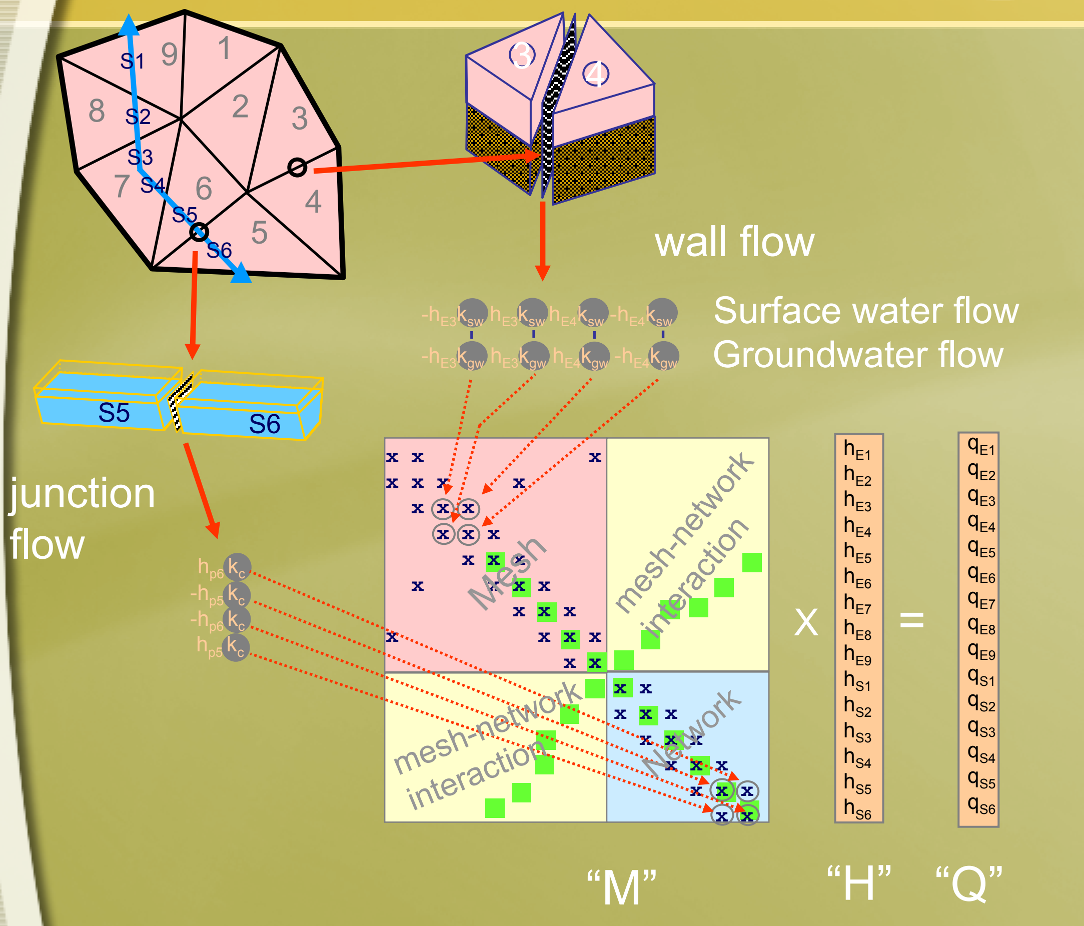
-lakes, reservoirs, canals
-Wetland, land area with water storage
-Represented as cells in RSM



Watermovers include:

-flows through structures, canal bank seepage
-overland flow, surface flow
-canal segment to segment flow
-Can be managed or unmanaged

Watermover to Sparse Matrix Interaction



- Simultaneous solution
  - surface / groundwater
  - canal network
  - Interactions
- Watermovers' submatrices fall into place in overall matrix
- All components of the system are coupled

Legend

S_n - segment
E_n - cell
h_n - head in cell & segment
k_c - segment hydraulic conductivity
k_{sw} - surface water conductivity
markers

M - stiffness matrix
H - head vector
Q - flow vector
x - 2D & 1D network matrix markers
🟩 - mesh-network interaction matrix
k_{gw} - groundwater conductivity

Sparse Matrix Solver

- Portable, Extensible Toolkit for Scientific Computation (PETSc)
- Close to unconditional problems can be solved
- Adjustable error (~10^{-5})
- Preconditioned, Conjugate gradient method
- PetSc is freeware
  - Supported by a government agency
  - Free annual updates and tech support

Model Testing & Validation

I. Numerical error analysis (WRR Lal, 2000)

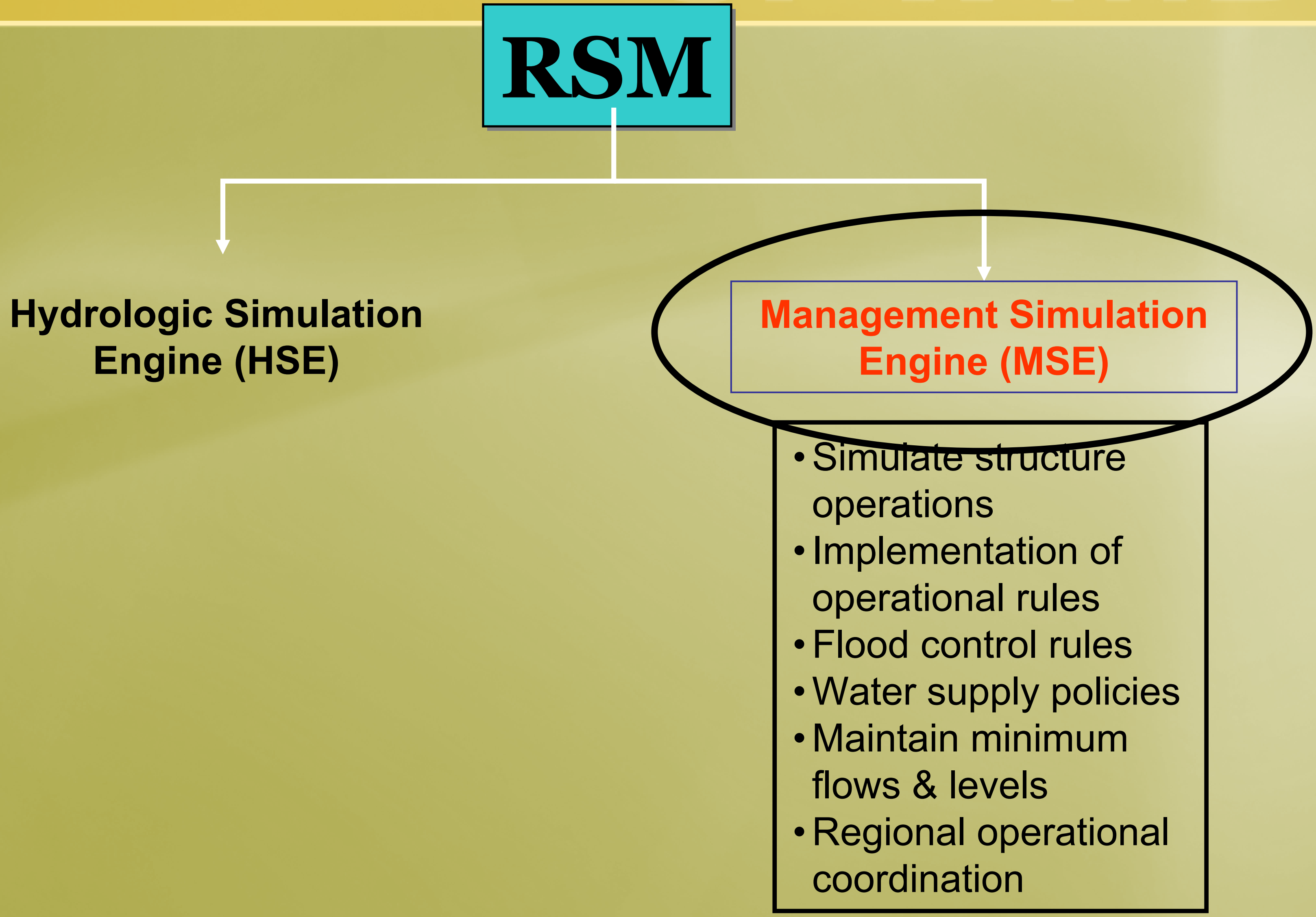
II. Cell size, time step, run time analysis (ASCE HY Lal, 1998)

III. Analytical solutions used for calibration and verification (ASCE HY 127(7) Lal, 2001, 2005)

IV. Development of tools for calibration and parameter analysis (PEST) (PEST manual, Lal, 1998)

V. Early test beds (JHE Lal, 1998c)

Management Simulation Engine



RSM

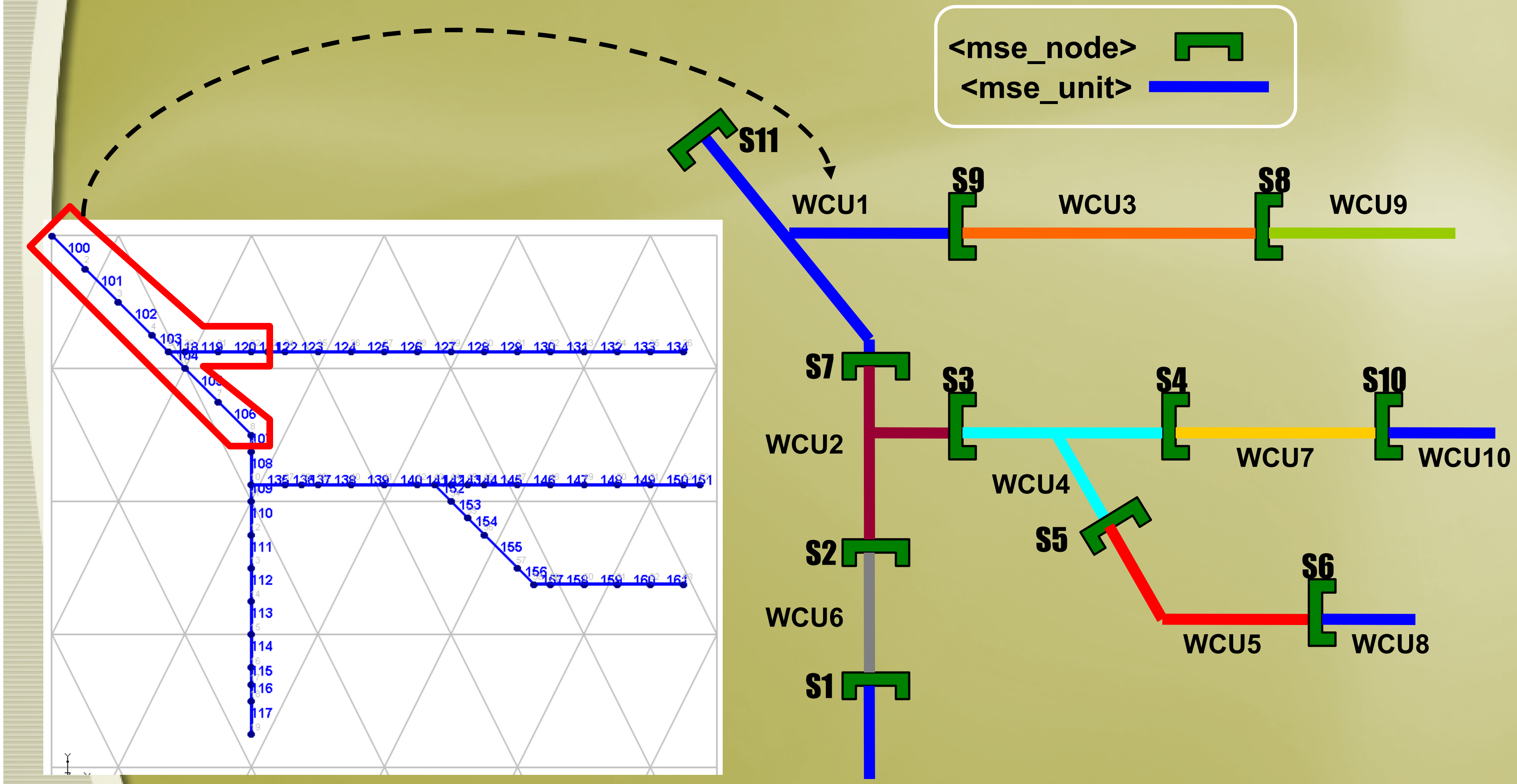
Hydrologic Simulation Engine (HSE)

Management Simulation Engine (MSE)

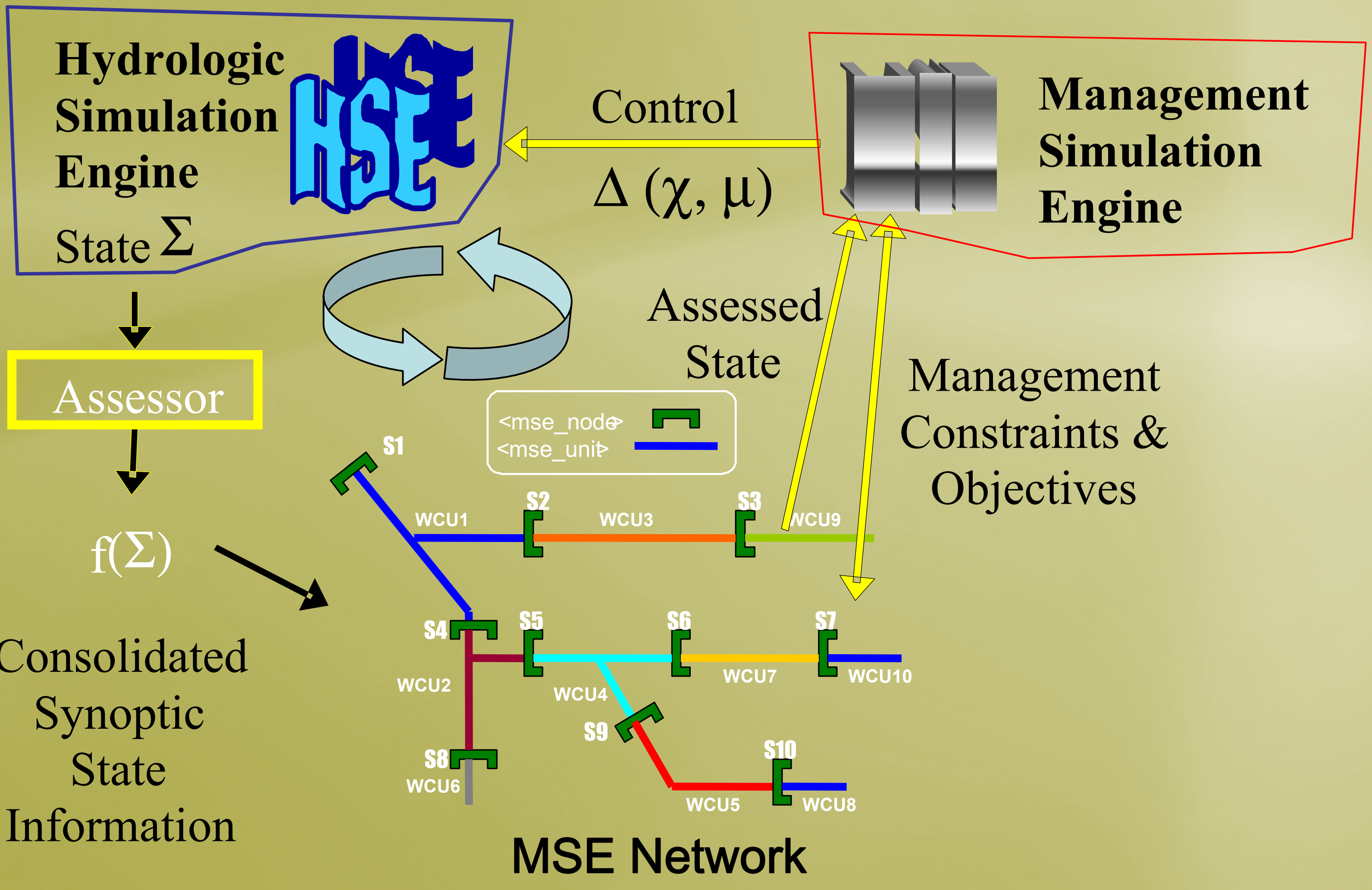
- Simulate structure operations
- Implementation of operational rules
- Flood control rules
- Water supply policies
- Maintain minimum flows & levels
- Regional operational coordination

MSE: Water Control Unit (WCU) Network

Provides one-to-one representation of managerial abstraction



Integration of HSE & MSE



Hydrologic Simulation Engine

State Σ

Control

Δ (χ, μ)

Management Simulation Engine

Assessor

Assessed State

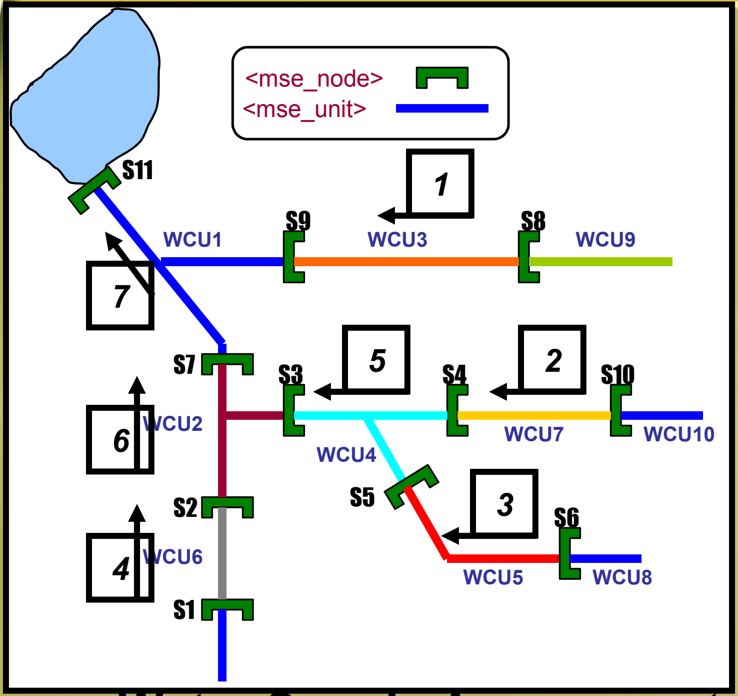
Management Constraints & Objectives

f(Σ)

Consolidated Synoptic State Information

MSE Network

Water Supply & Flood Control



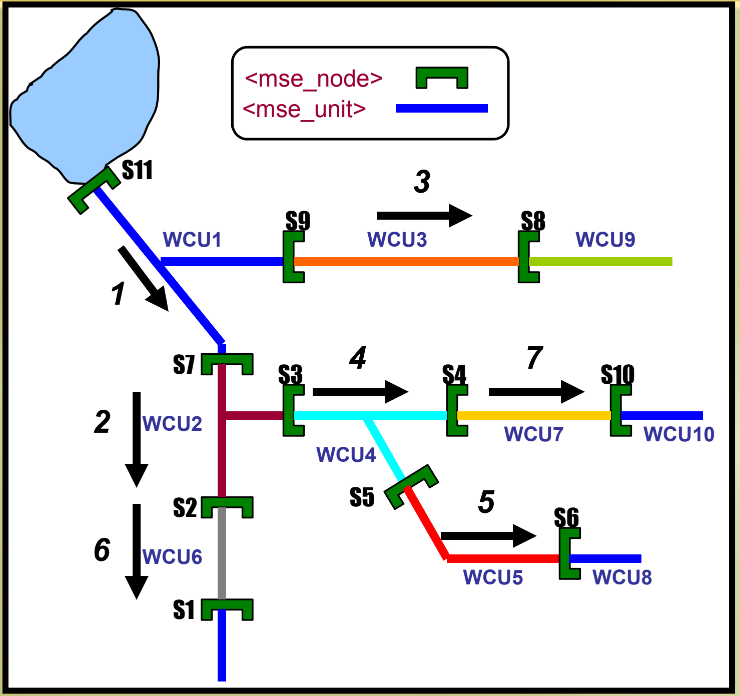
Water Supply Assessment

Pass 1 – set inlet WS releases (upstream)

- WS needs computed for each wcu and combined with downstream needs

Pass 2 – Allocation (downstream)

- Releases subject to water availability and conveyance constraints



Flood Control Assessment

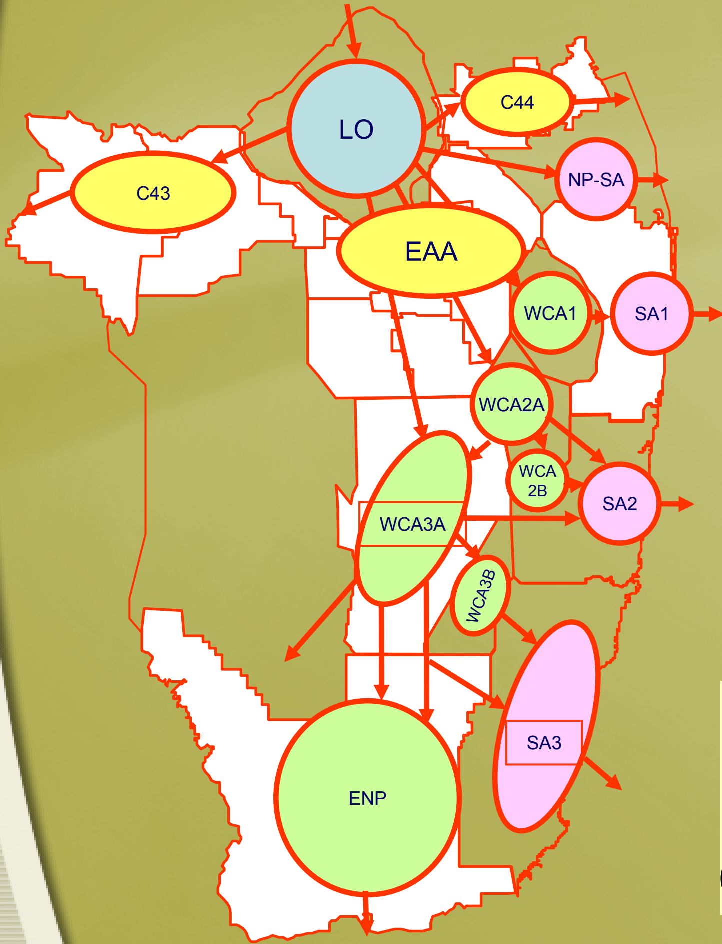
Process downstream

For each wcu,

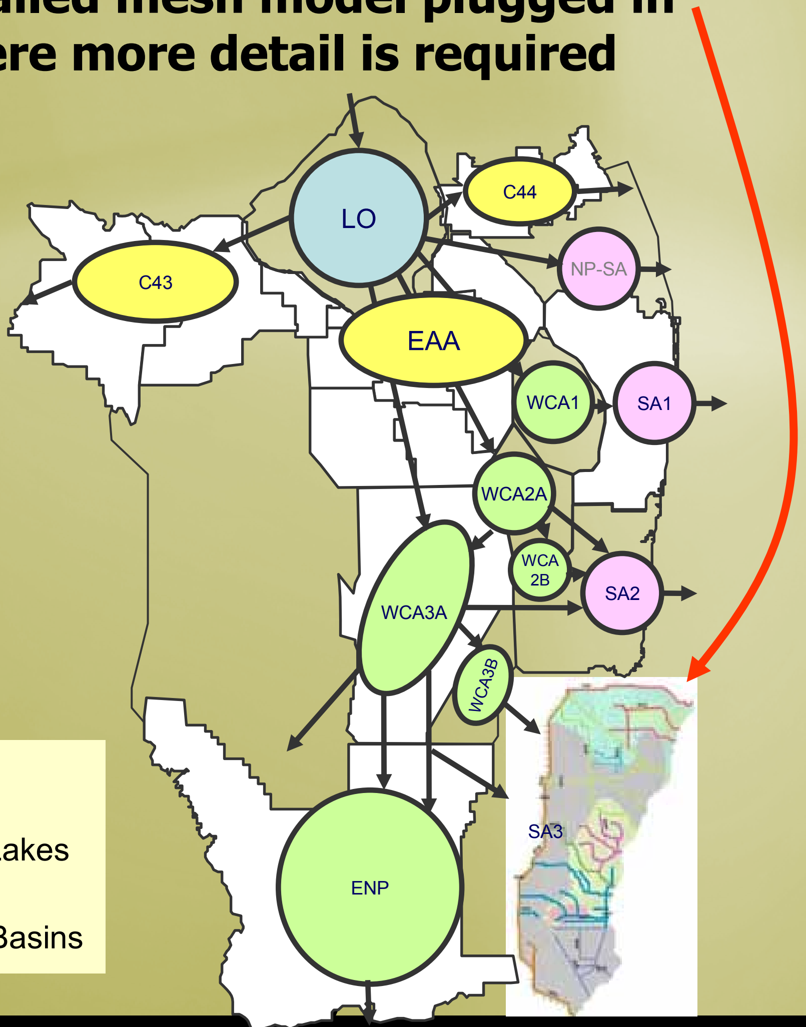
- Set outlet releases (maximum of flood control and water supply)
- Refine outlet release until downstream conveyance test passes

RSM Basins & Plug & Play

RSM: Linked Basin System-Wide Model



Basin is plugged out and detailed mesh model plugged in where more detail is required



Legend

● Lakes

● ● ● Basins

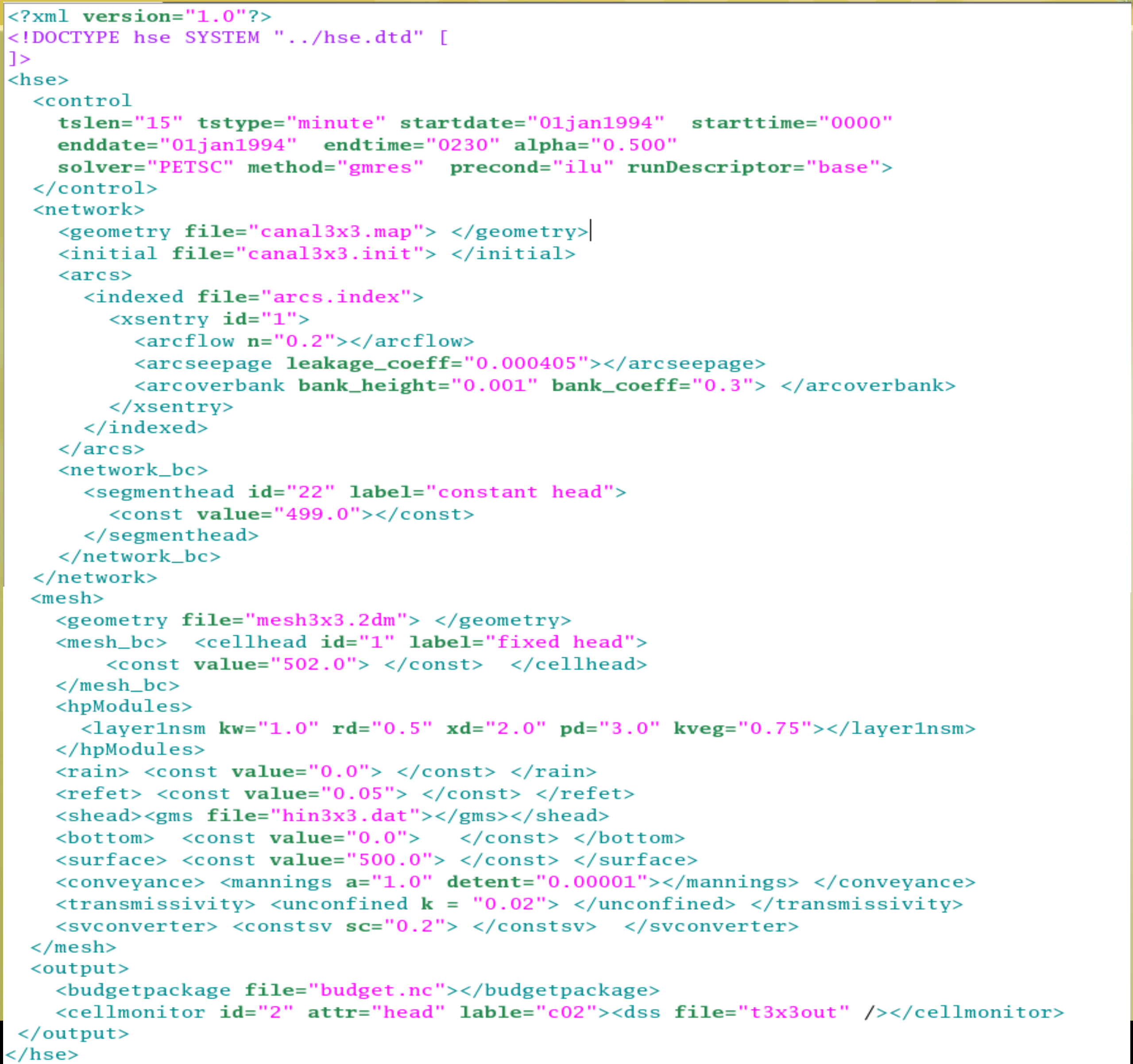
Components of simple RSM

Control

Network

Mesh

Output



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  </control>
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          <arcoverbank bank_height="0.001" bank_coeff="0.3"> </arcoverbank>
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    </arcs>
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    </network_bc>
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 </output>
</hse>
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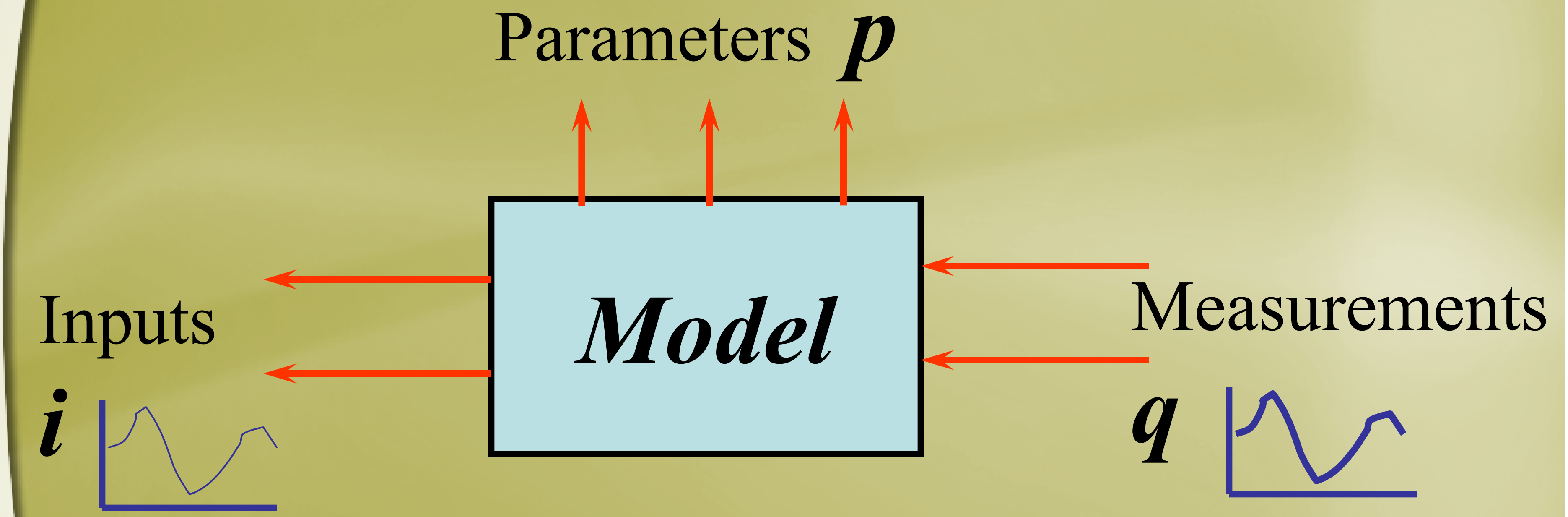
Inverse Modeling Using PEST



Parameters ***p***

Model

Inputs

i

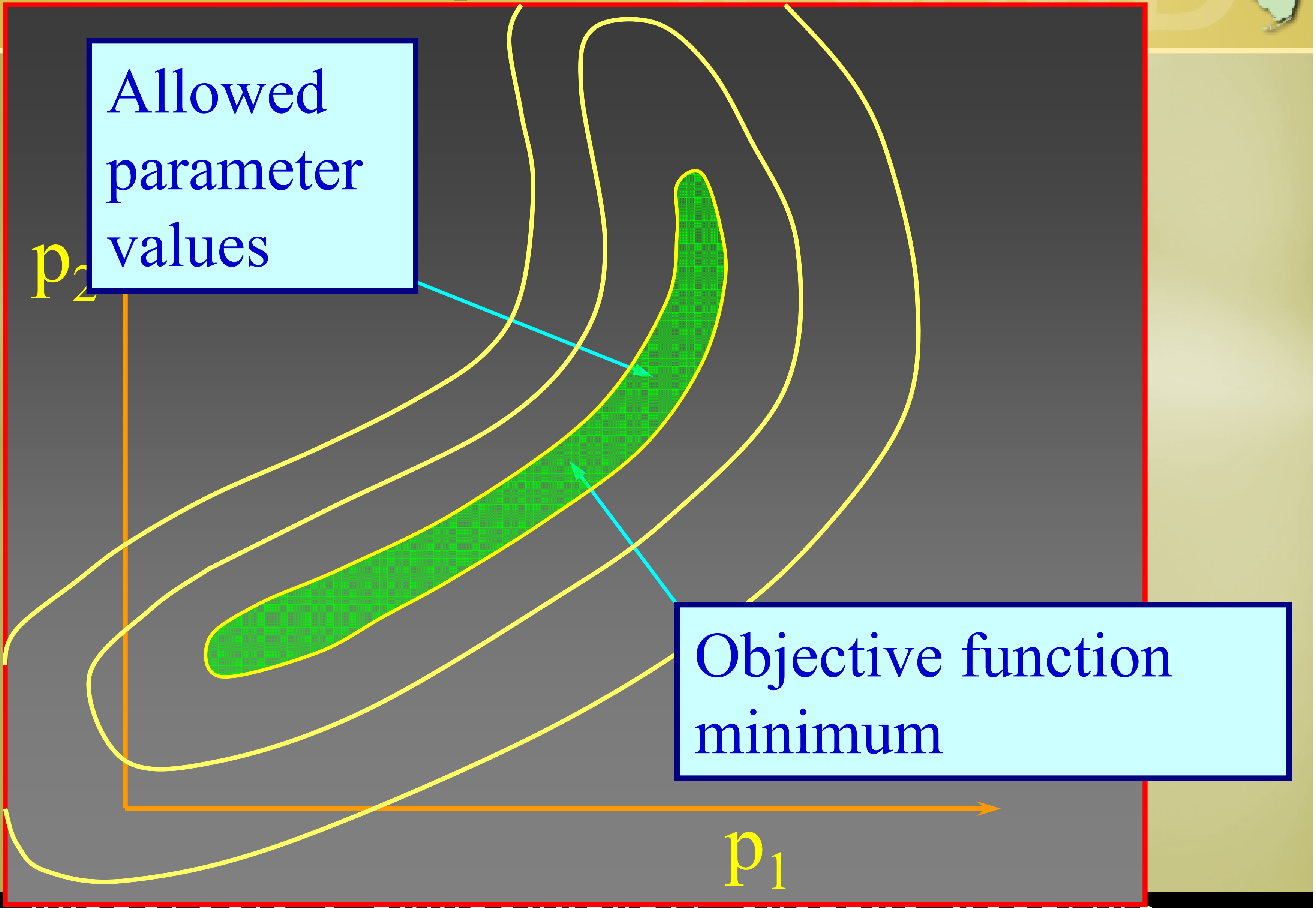
Measurements

q

x describes system configuration

$$p, i = M^{-1}\,(x,q)$$

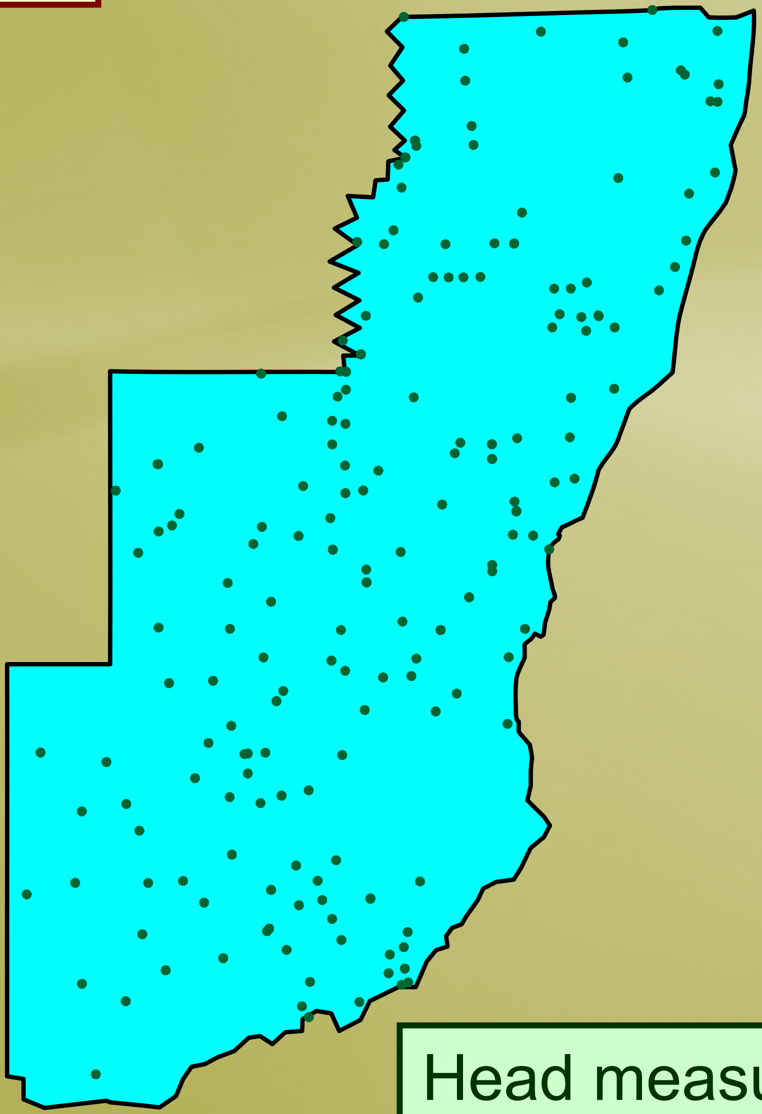
PEST concepts



Allowed parameter values

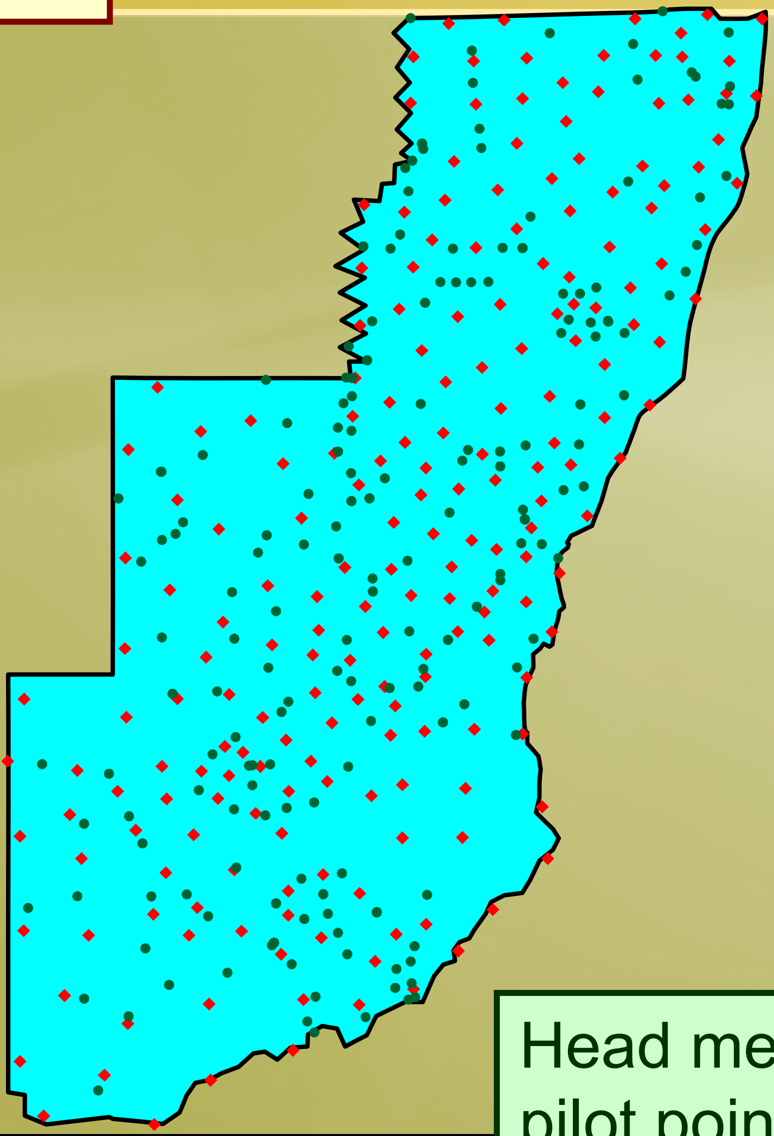
Objective function minimum

SFWMD RSM model



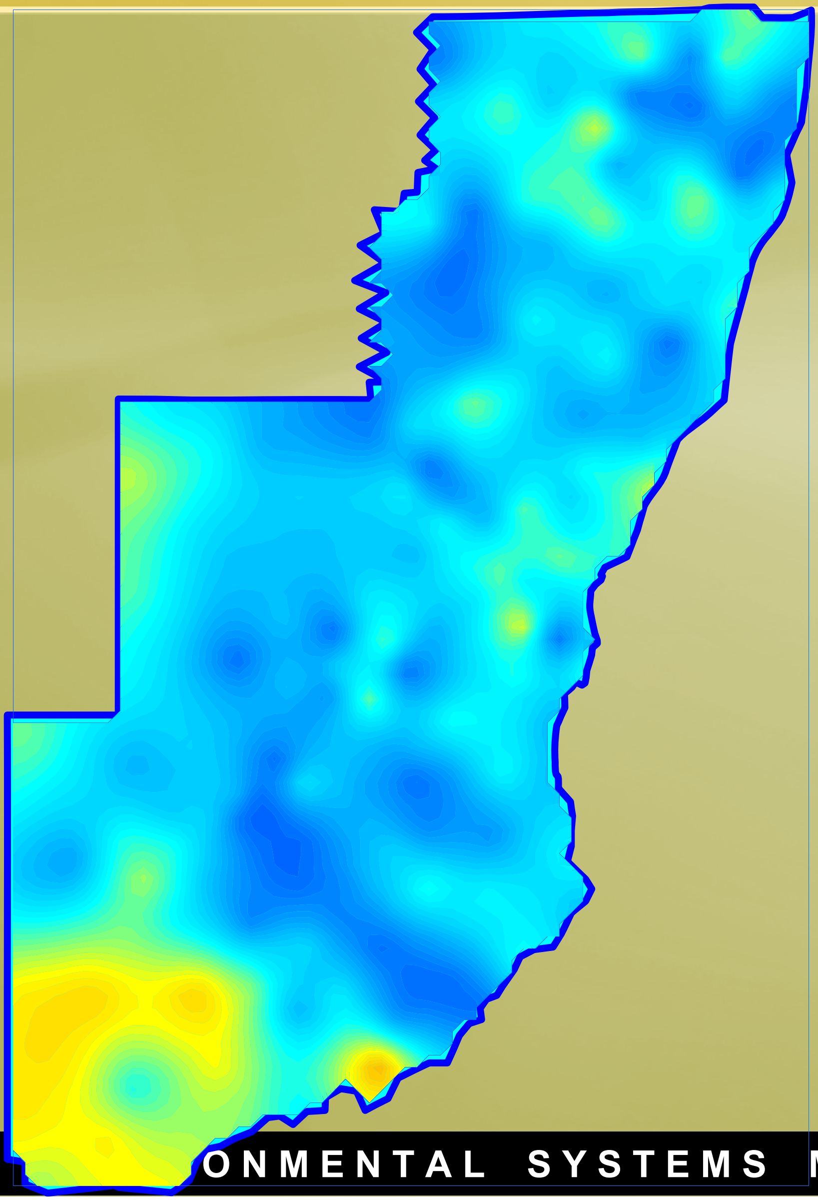
Head measurement locations

SFWMD RSM model

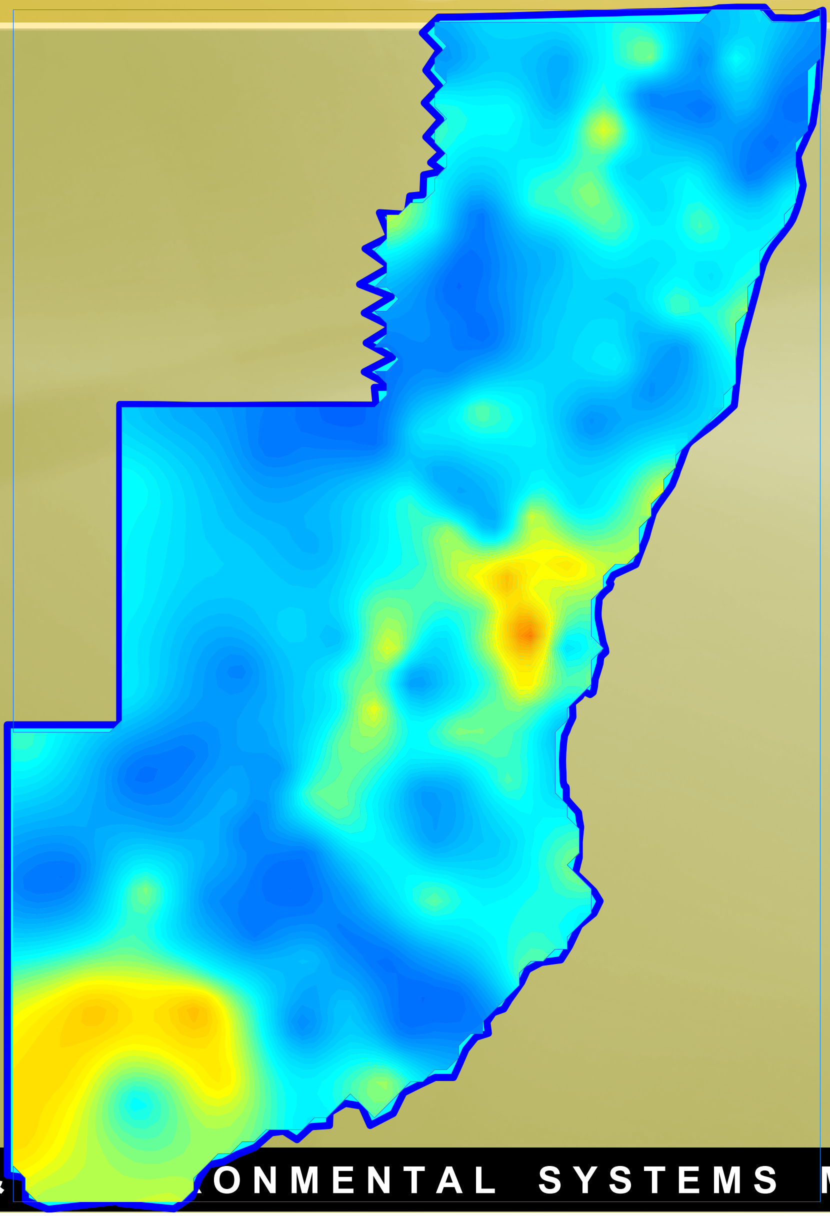


Head measurement and pilot point locations

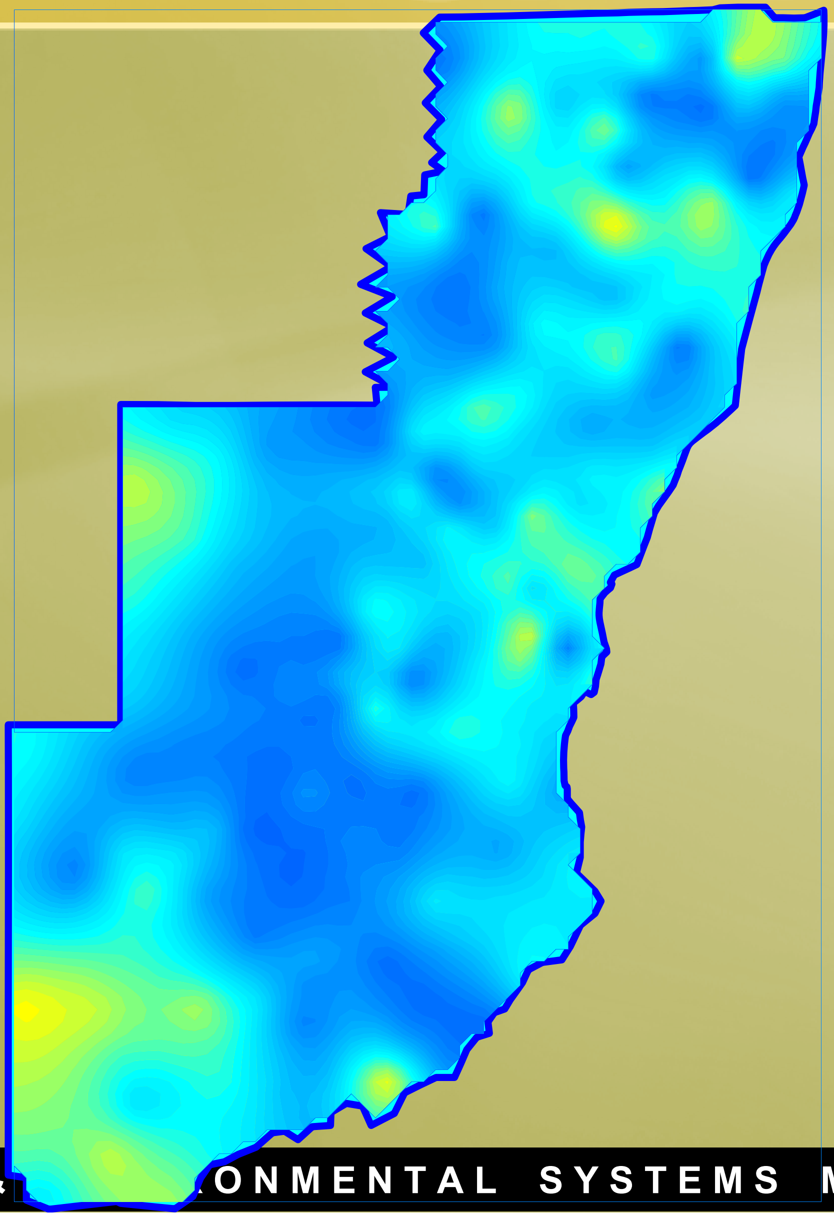
Calibrated K field



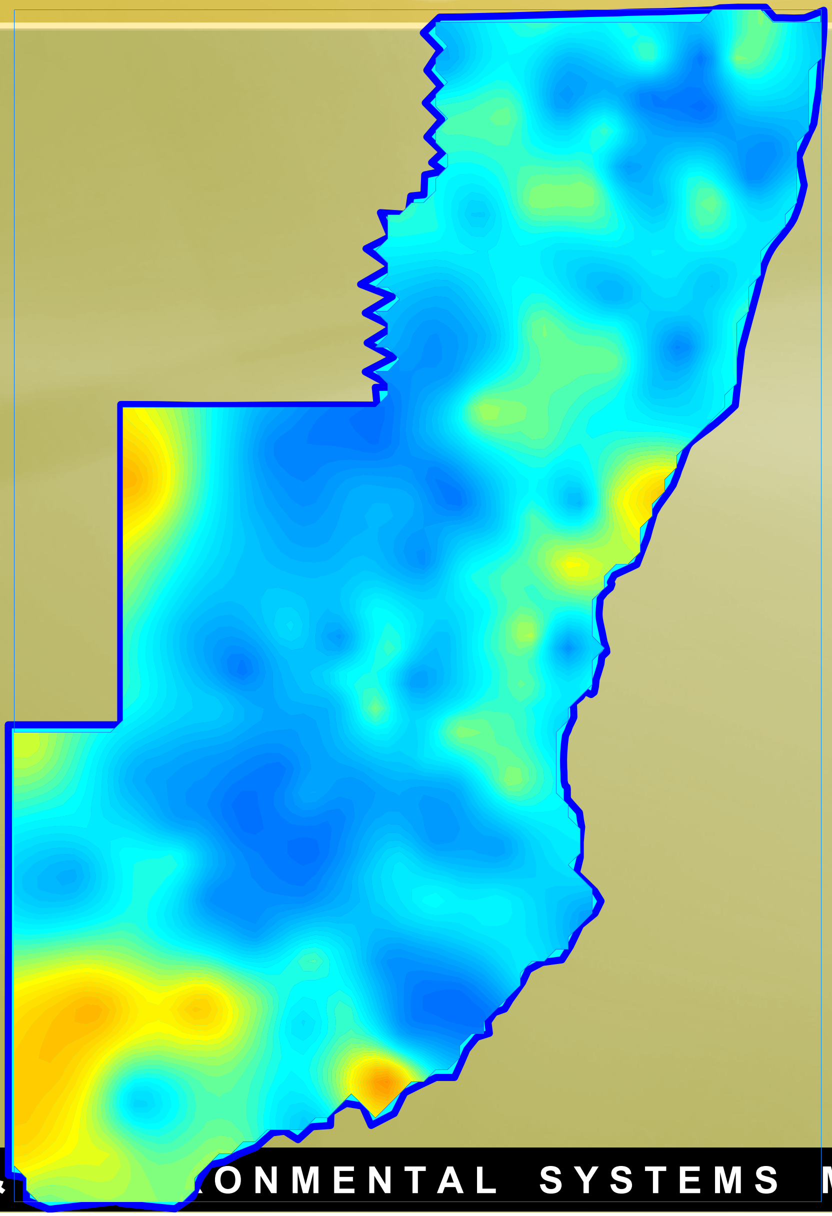
Realisation 1



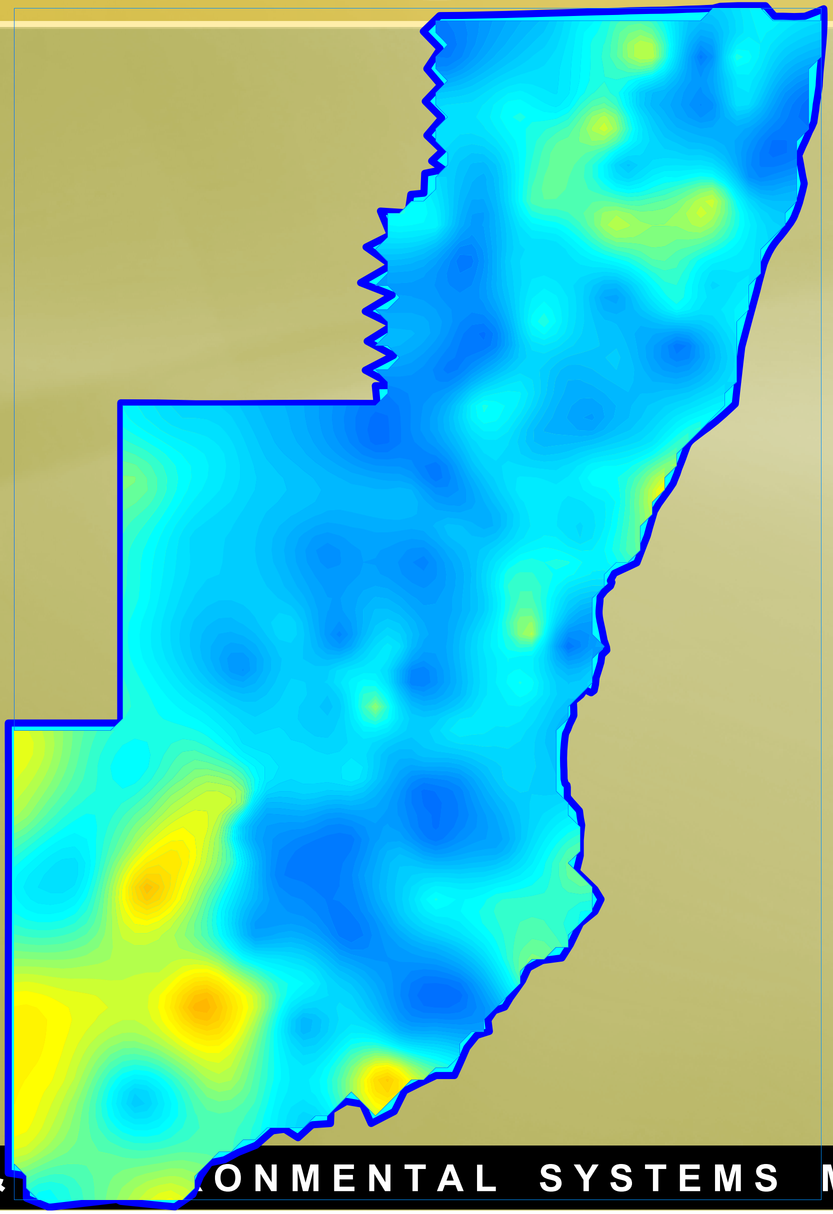
Realisation 2



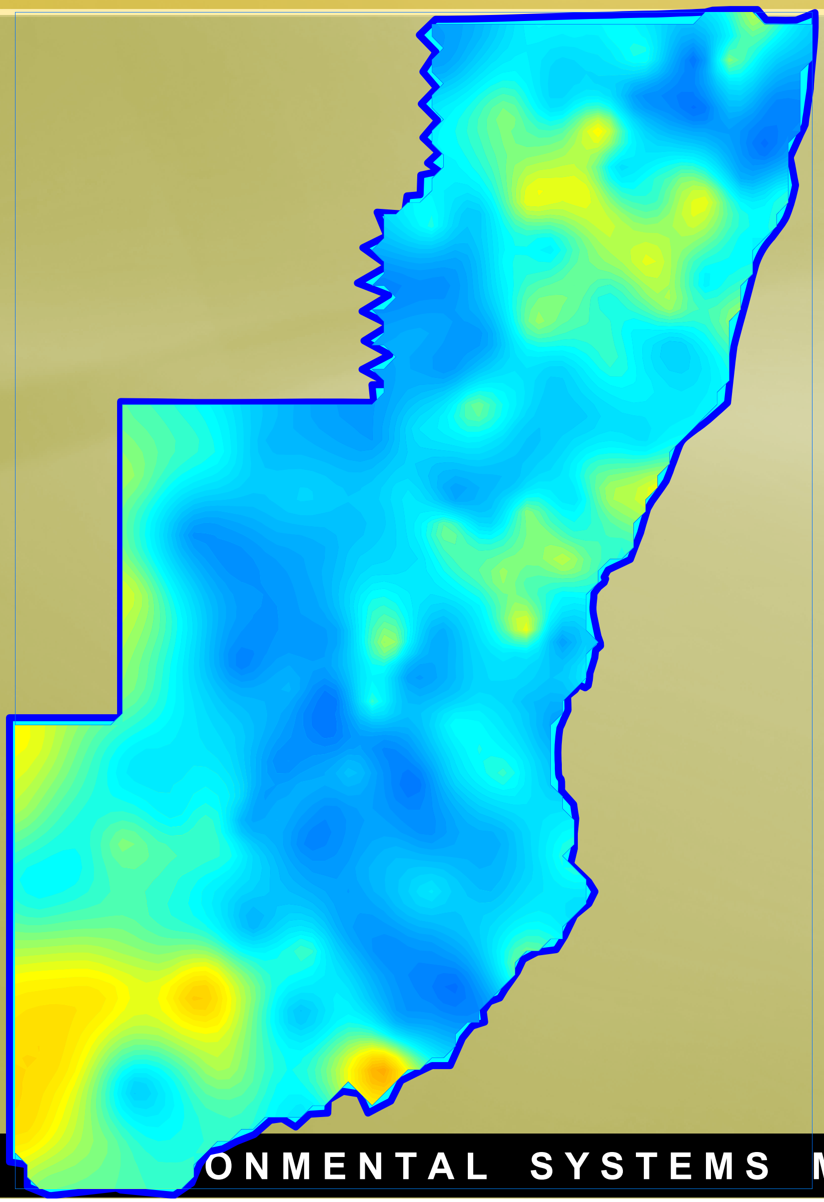
Realisation 3

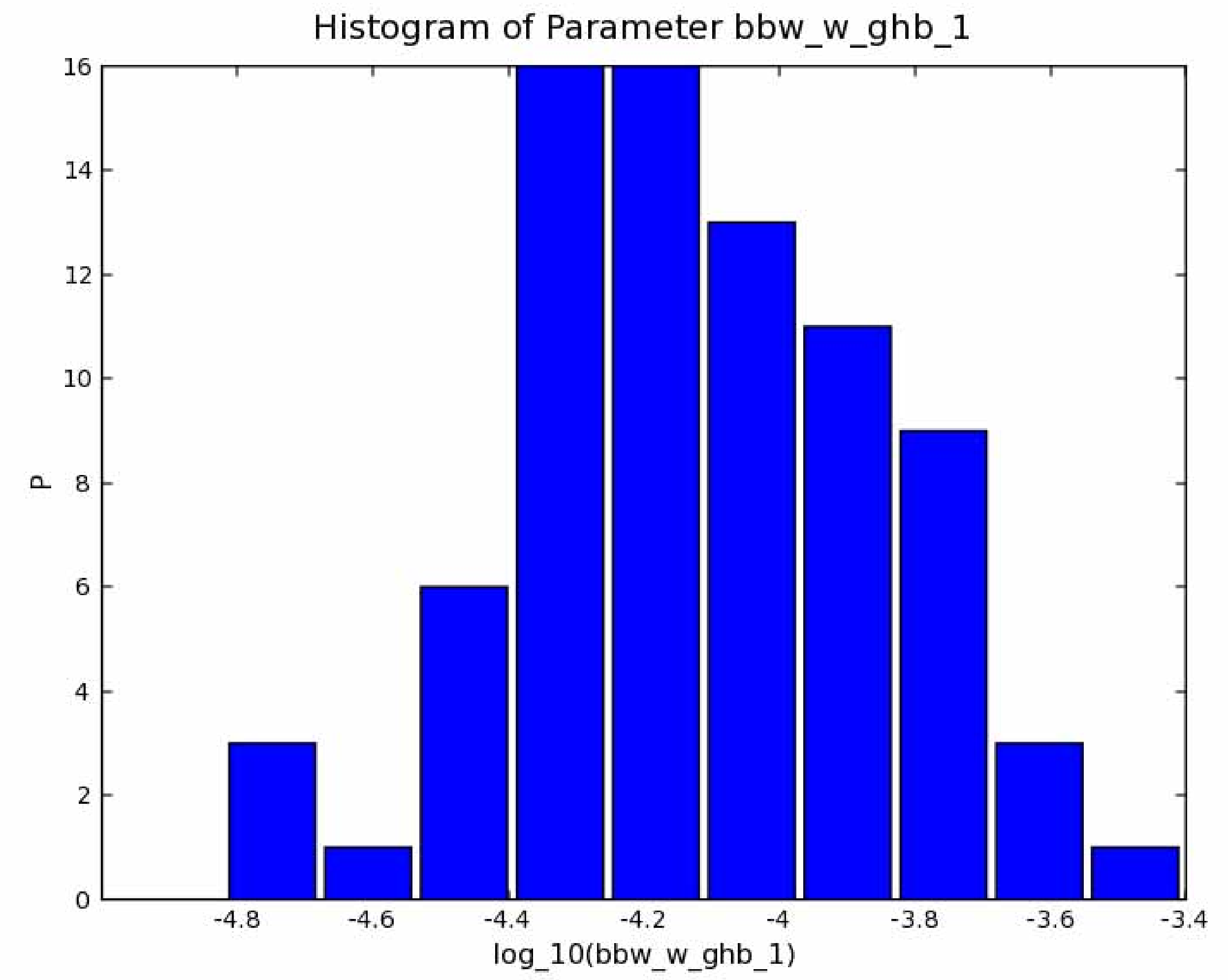


Realisation 4



Realisation 5

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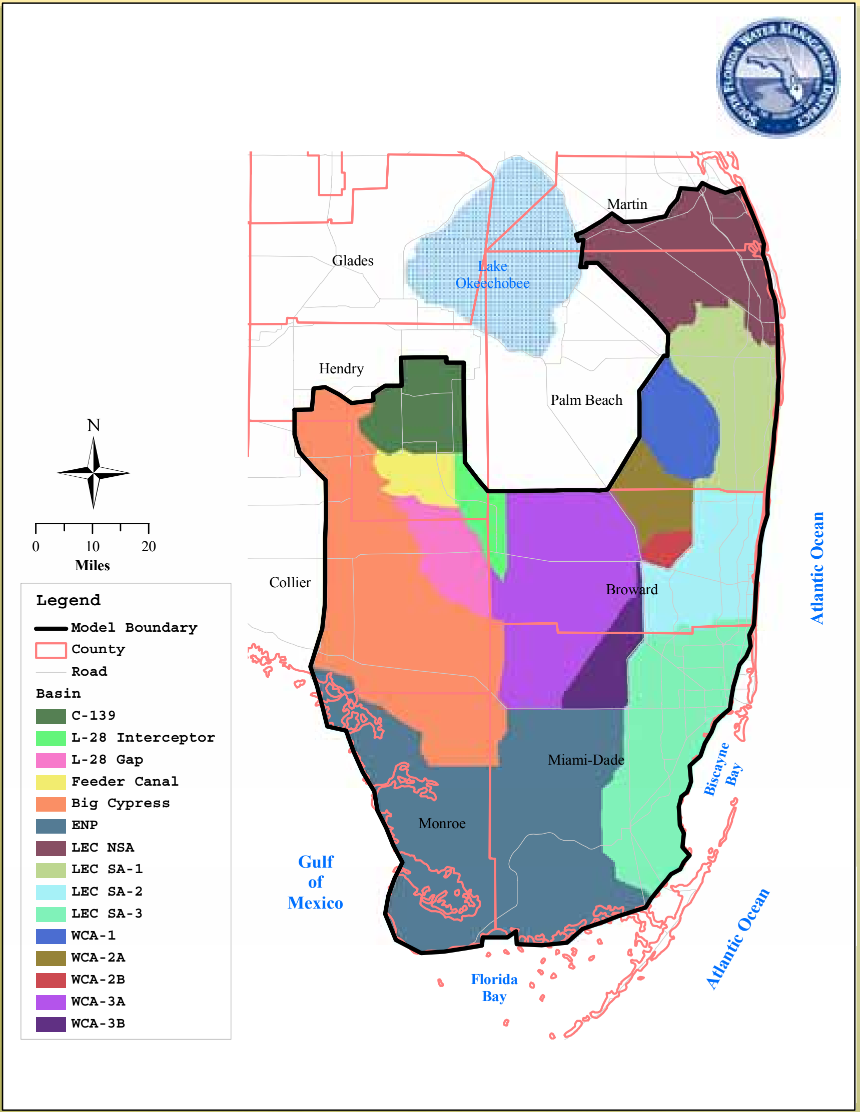
p
0
2
4
6
8
10
12
14
16
-4.8
-4.6
-4.4
-4.2
-4
-3.8
-3.6
-3.4
log_10(bbw_w_ghb_1)

RSM Applications

- C-111 Spreader Canal (Screening Tool)
- Biscayne Bay Coastal Wetlands
- Northern Everglades Technical Plan
- River Watershed Protection Plan

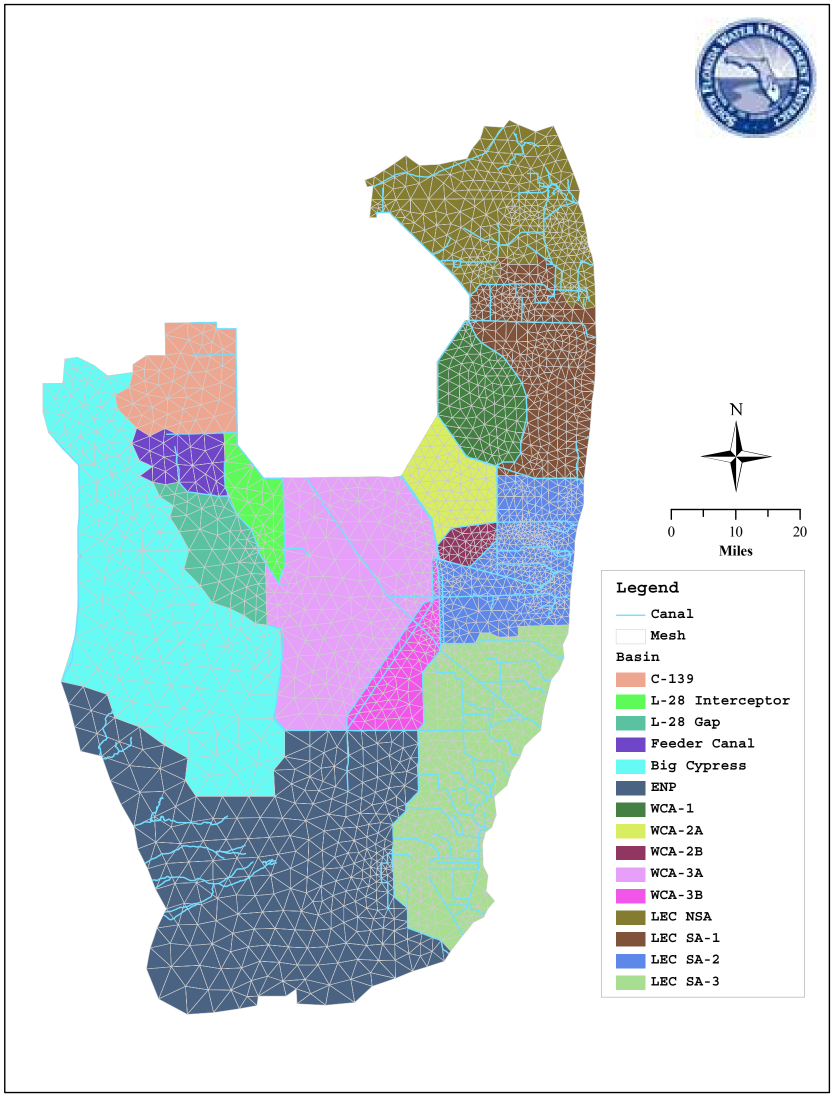
Glades-LECSA Model Domain

- 7,121 square miles
- 7 counties (some are only partially covered)
- 15 hydrologic basins:
    - Urban areas (Lower East Coast Service Areas)
    - Natural areas (all water conservation areas, ENP & BCNP)
    - Agricultural areas (e.g., C-139 basin)

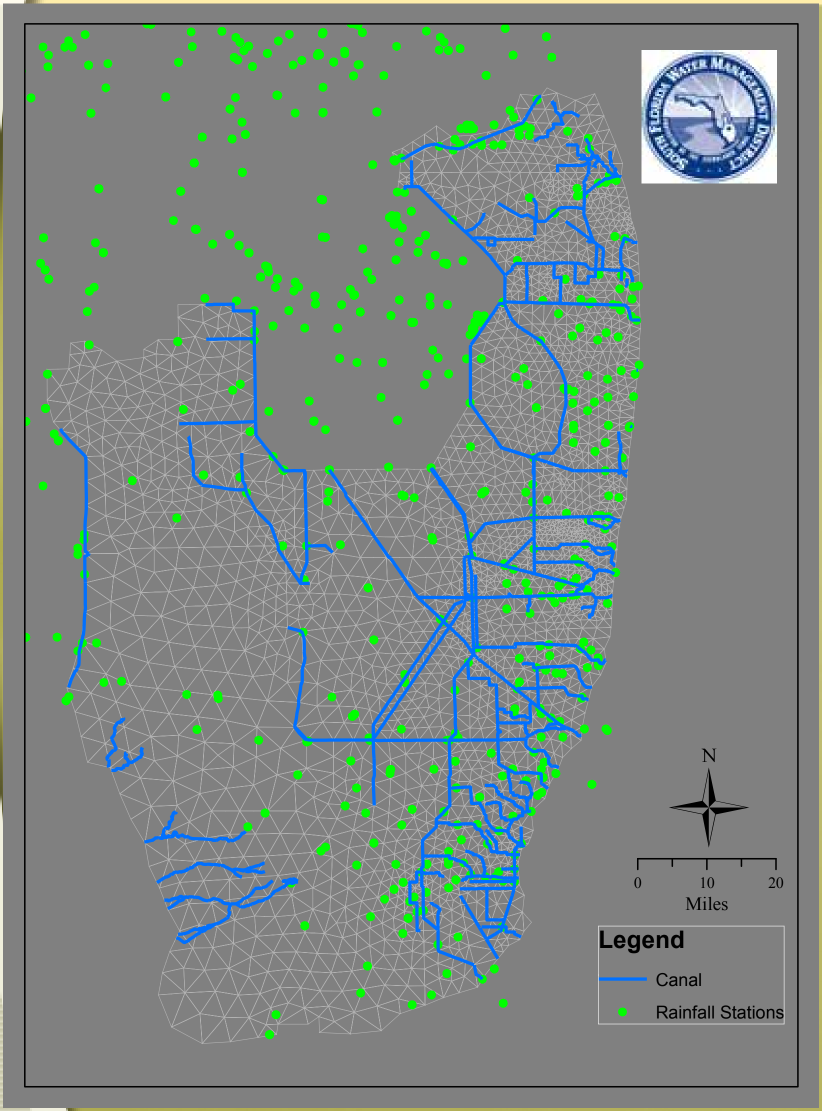


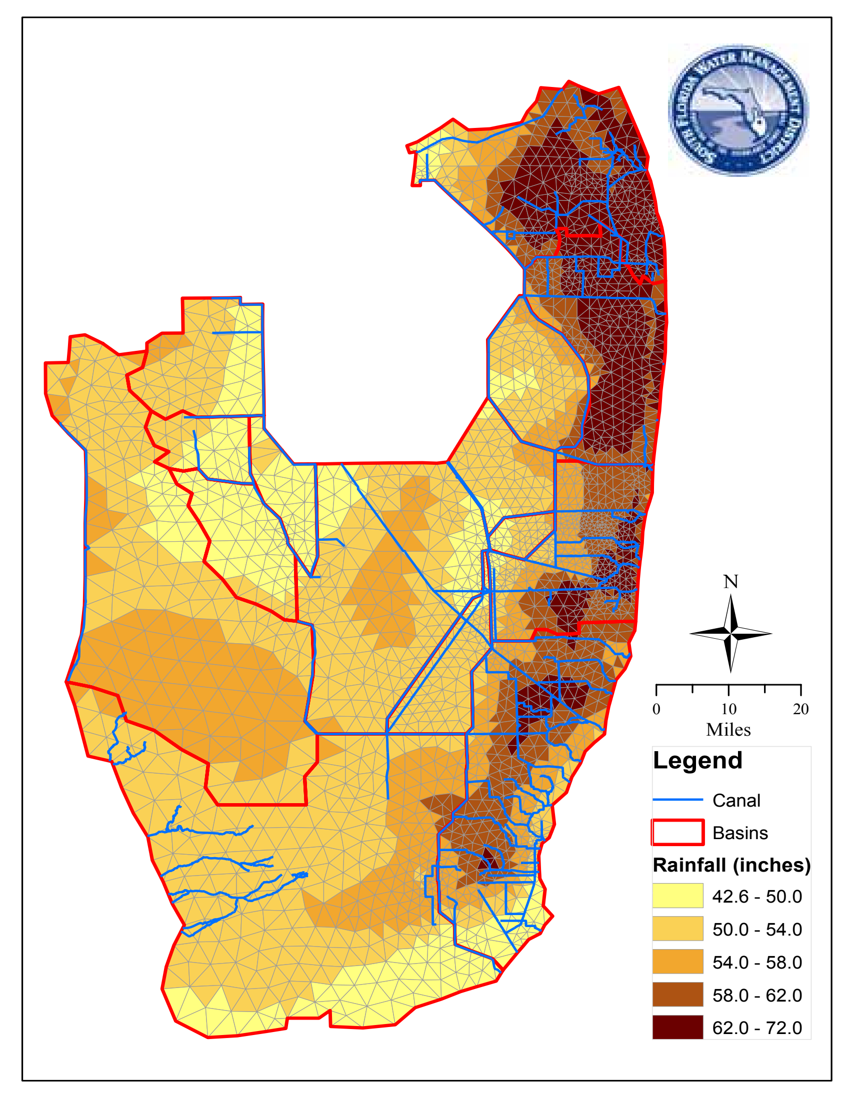
Numerical Mesh

- 4,510 triangular cells
- Mean & standard deviation of mesh cell sizes: 1.58 mi^2 & 1.51 mi^2
- Mesh cell size range: 0.04 mi^2 to 10.48 mi^2
- Service Area 2 has the finest resolution; BCNP has the coarsest resolution
- WCA-3 has a total of 482 cells
- WCA-3 average cell size is 1,228 acres or 1.92 mi^2 (SFWMM: 2,560 acres or 4 mi^2)

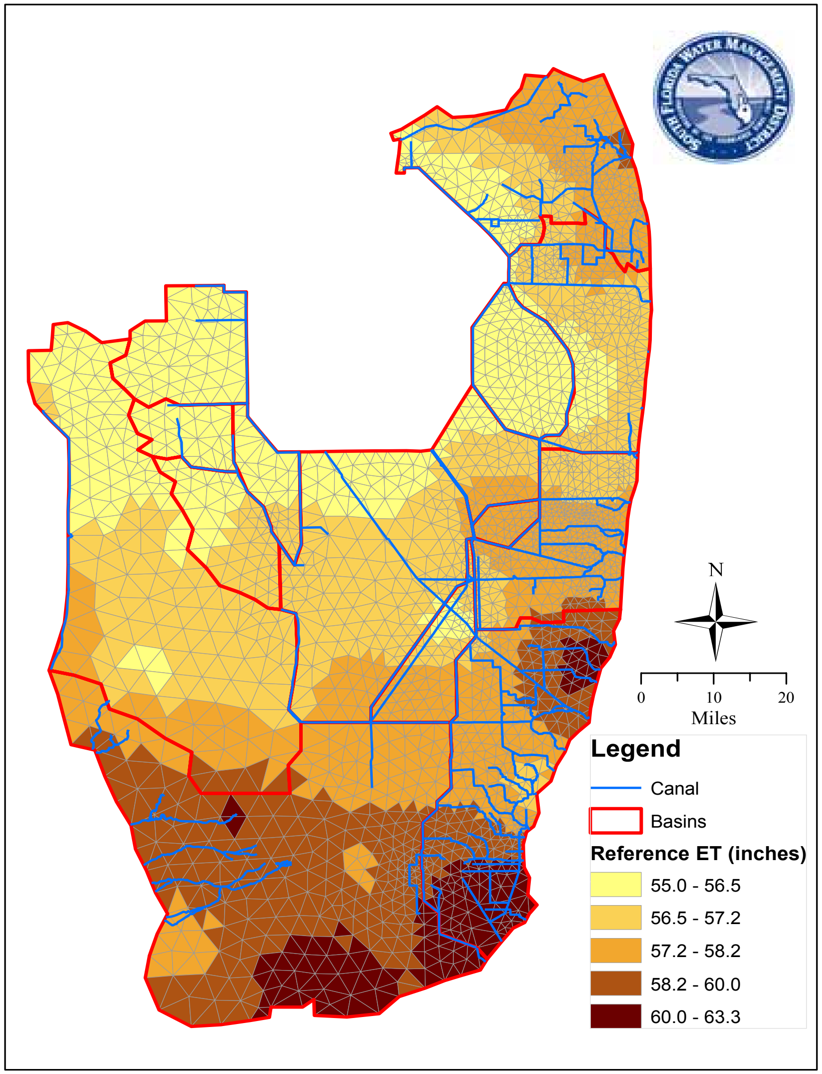


Rainfall


N
0
10
20
Miles
Legend
Canal
Rainfall Stations

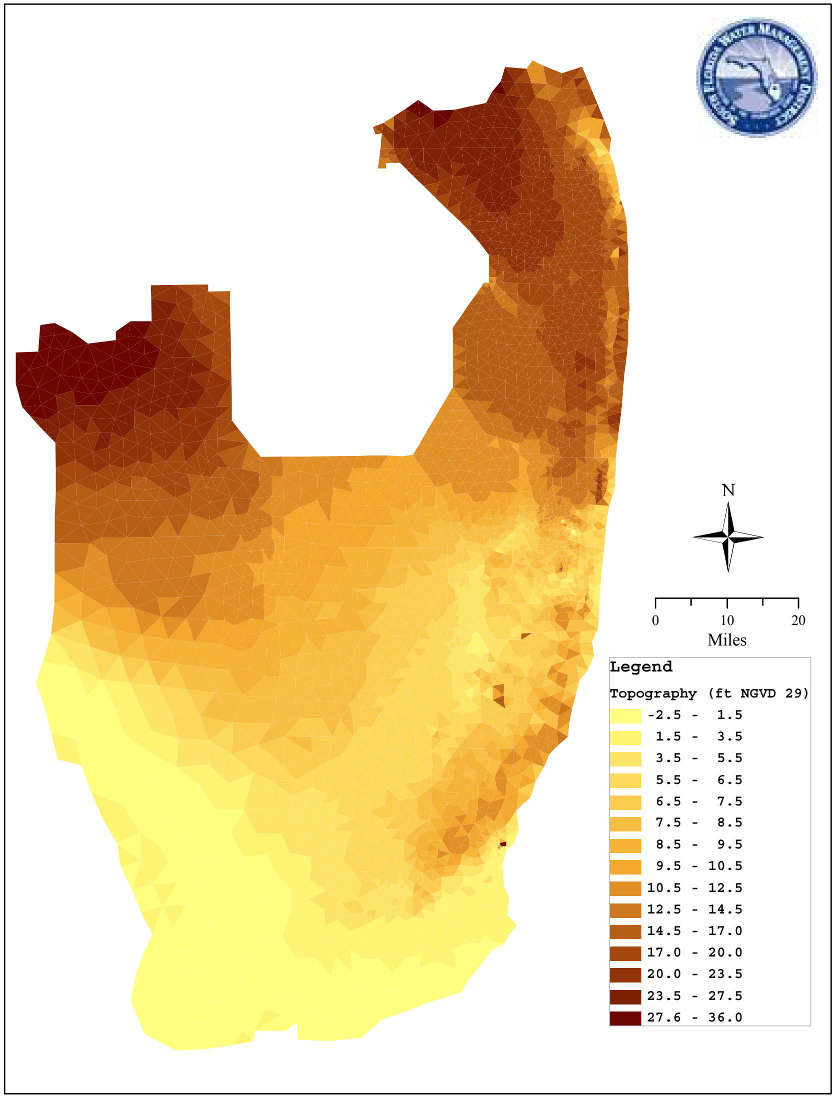

N
0
10
20
Miles
Legend
Canal
Basins
Rainfall (inches)
42.6 - 50.0
50.0 - 54.0
54.0 - 58.0
58.0 - 62.0
62.0 - 72.0

Reference Evapotranspiration (RET)



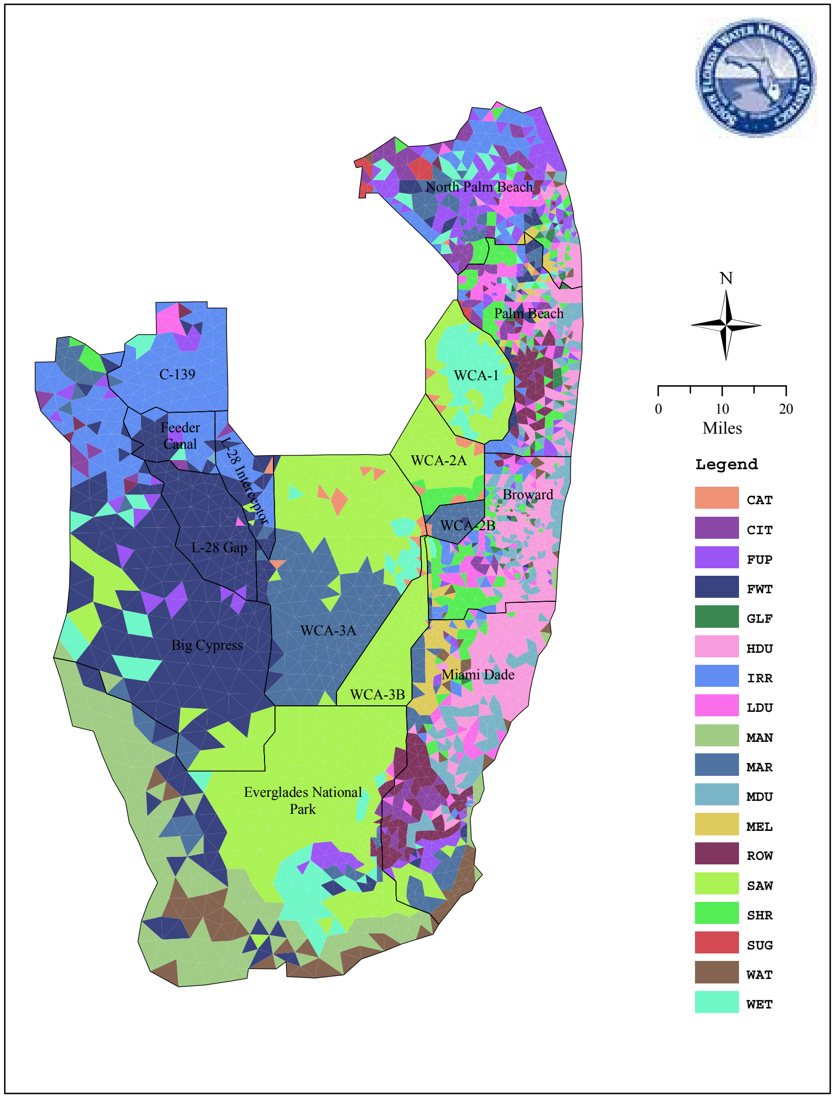
Land Surface Elevation (Topography)

- Mean & standard deviation of land surface elevation data: 11.3’ & 6.8’
- Range: -2.5’ to 35.87’
- Primary data source for WCA-3 & ENP is the USGS High Accuracy Elevation Data (HAED)
- USGS HAED data has an accuracy of ±15 cm (~ ±0.5 ft)

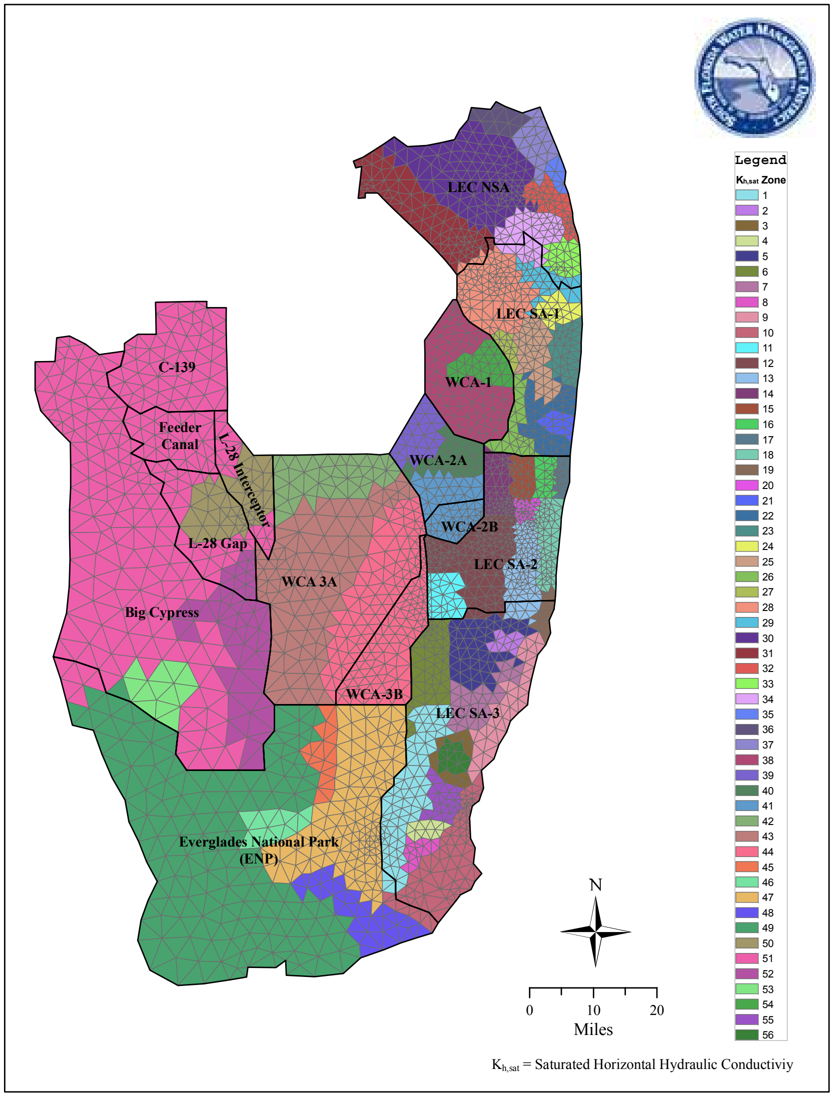


Land-Use & Land-Cover (LULC)

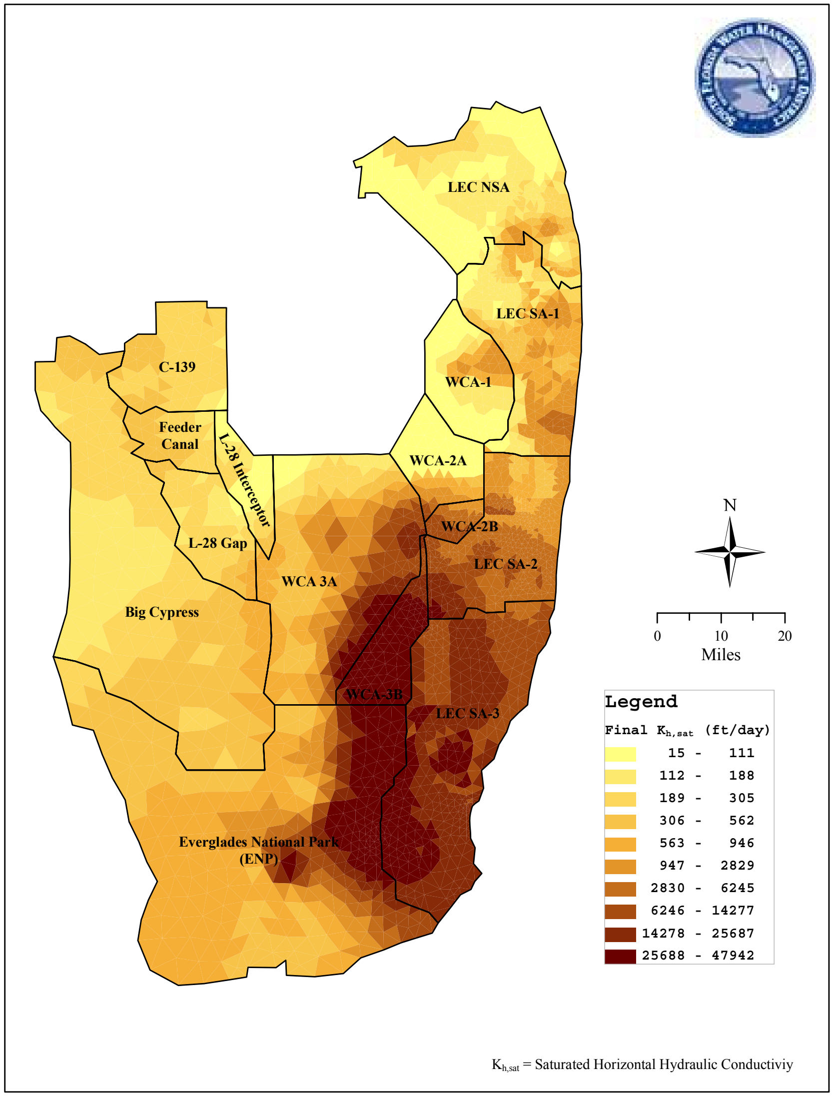
- 18 LULC types
- Top 5 LULC types (65%):
  1. Sawgrass (1524 mi^2)
  2. Forested wetlands (1219 mi^2)
  3. Irrigated pasture (657 mi^2)
  4. Marsh (649 mi^2)
  5. Mangroves (557 mi^2)
- Urban LULC classes (high-, medium- & low-density) cover 12%
- Used for the calibration of surface roughness and ET parameter values



Saturated Hydraulic Conductivity

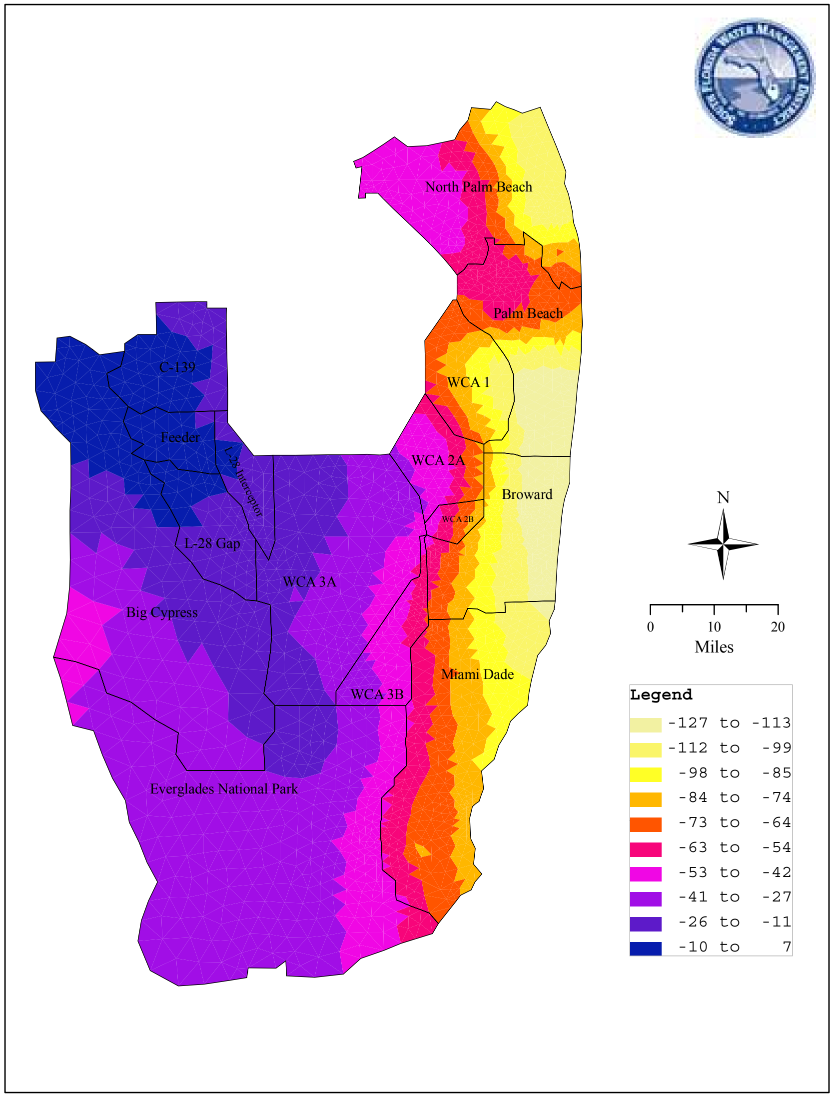


$K_{h,sat}$ = Saturated Horizontal Hydraulic Conductiviy

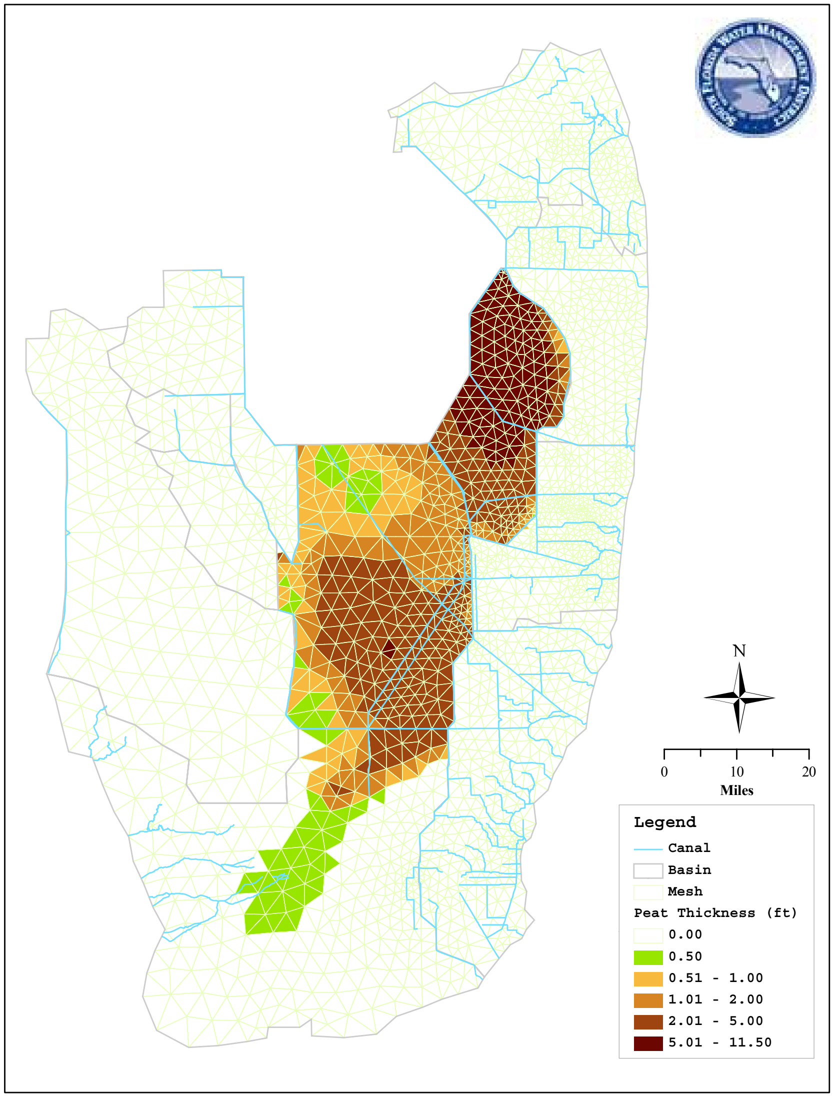


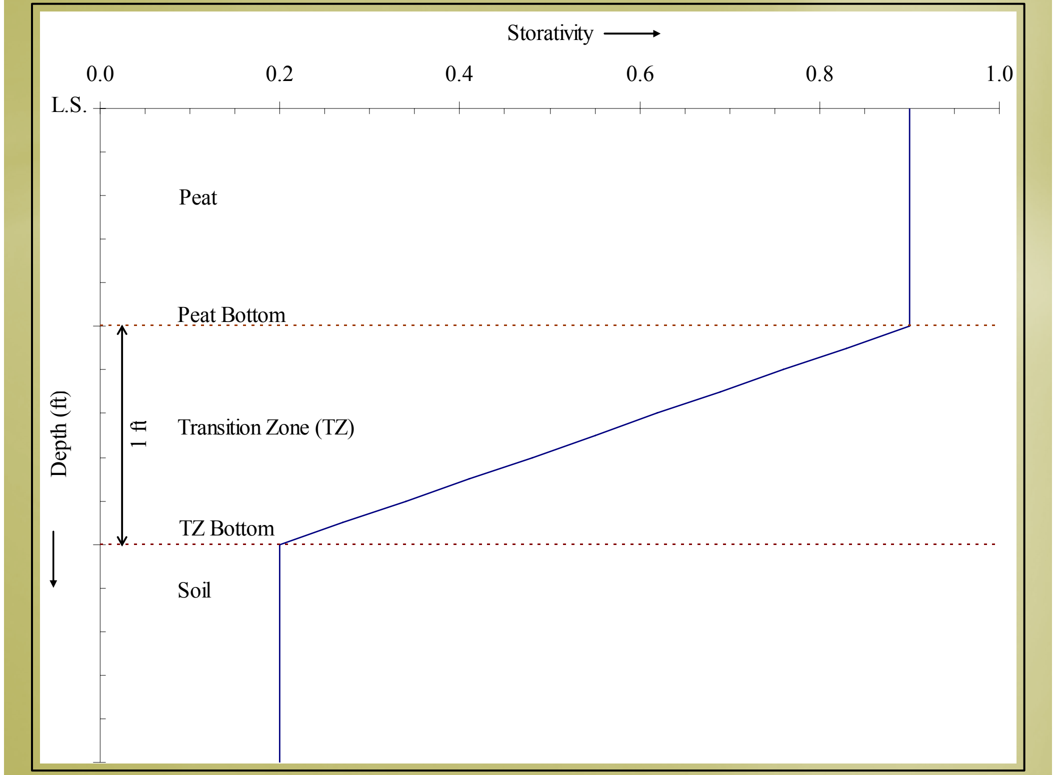
$K_{h,sat}$ = Saturated Horizontal Hydraulic Conductiviy

Surficial Aquifer Bottom Elevation



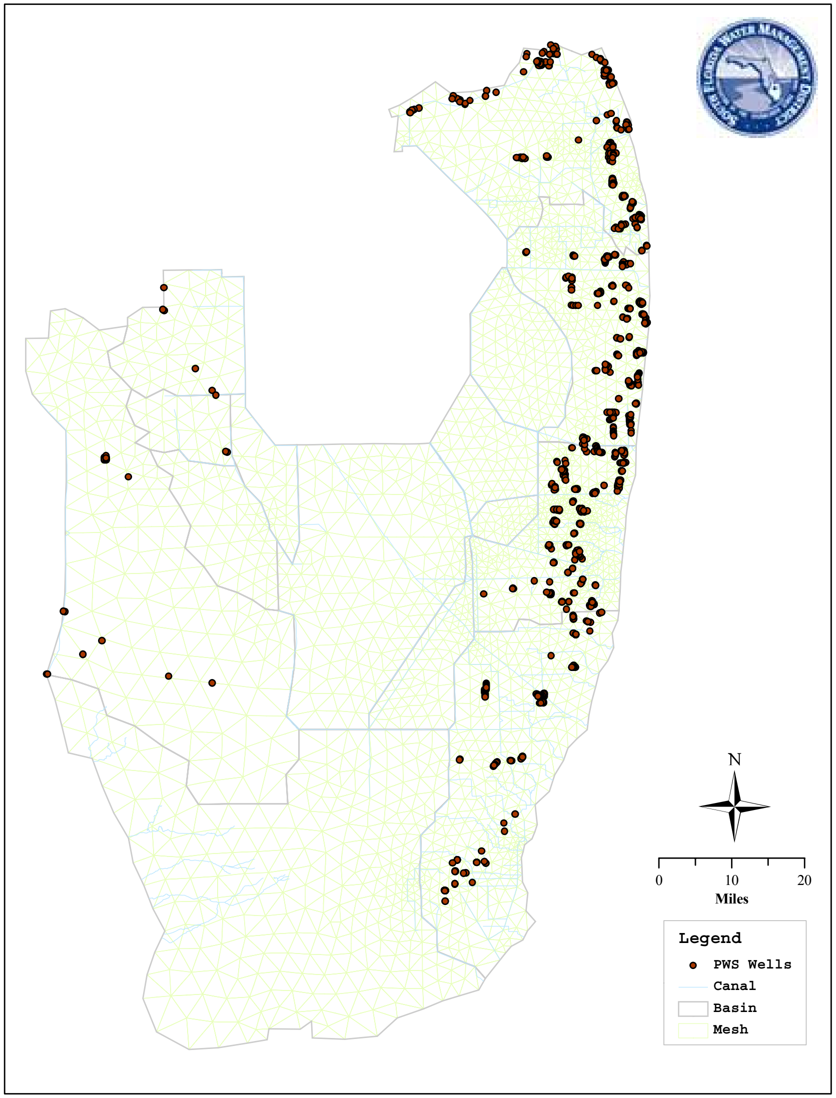
Peat Layer Thickness & Storativity

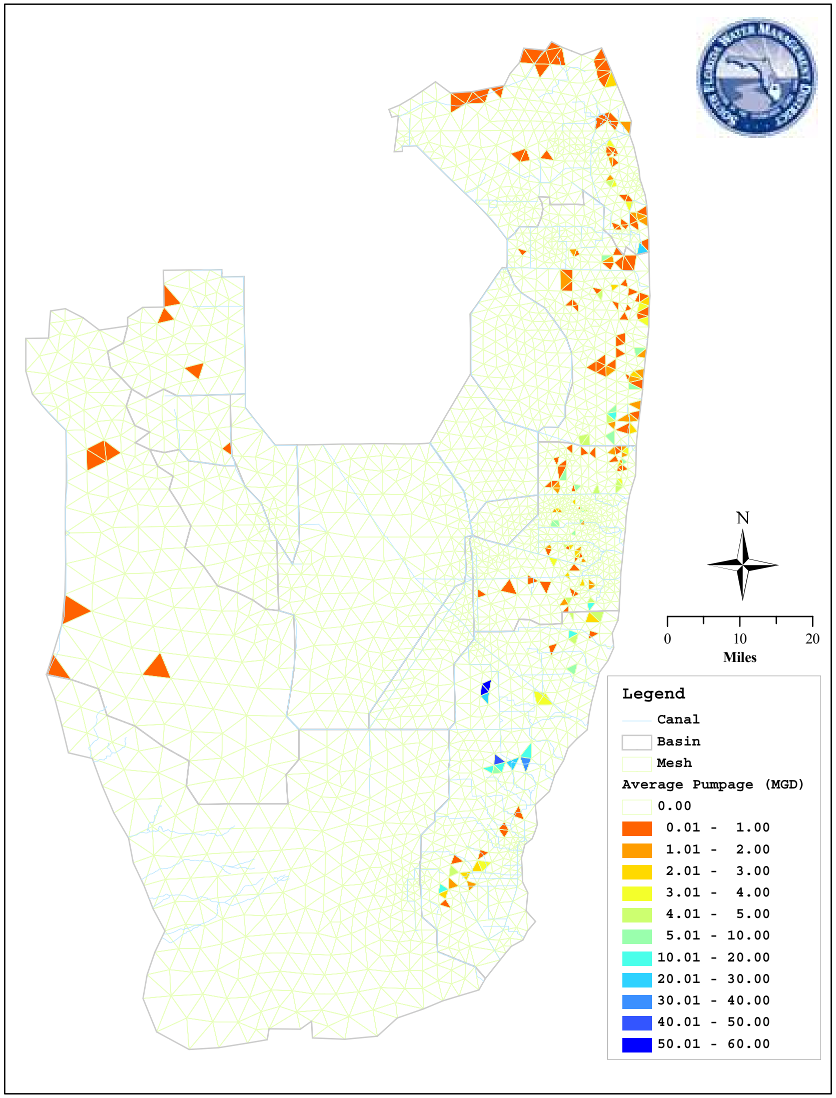




SOUTH FLORIDA WATER MANAGEMENT DISTRICT

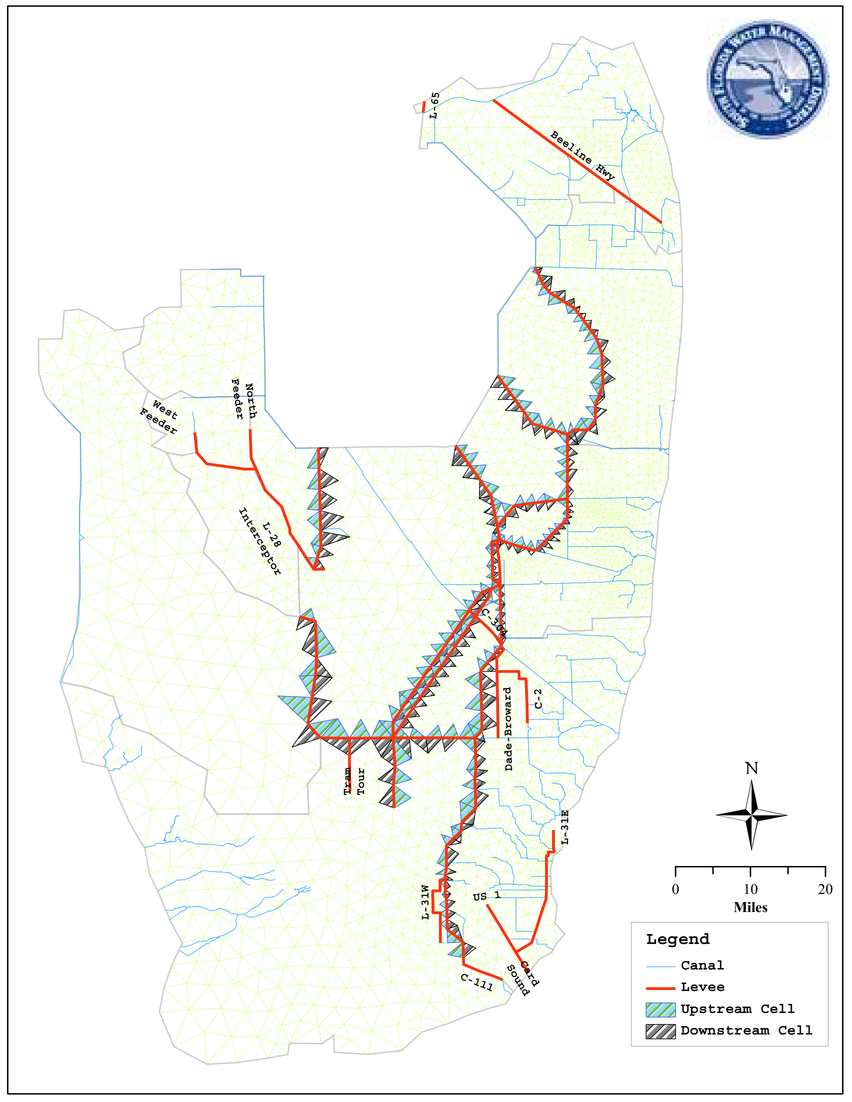
Public Water Supply Wells



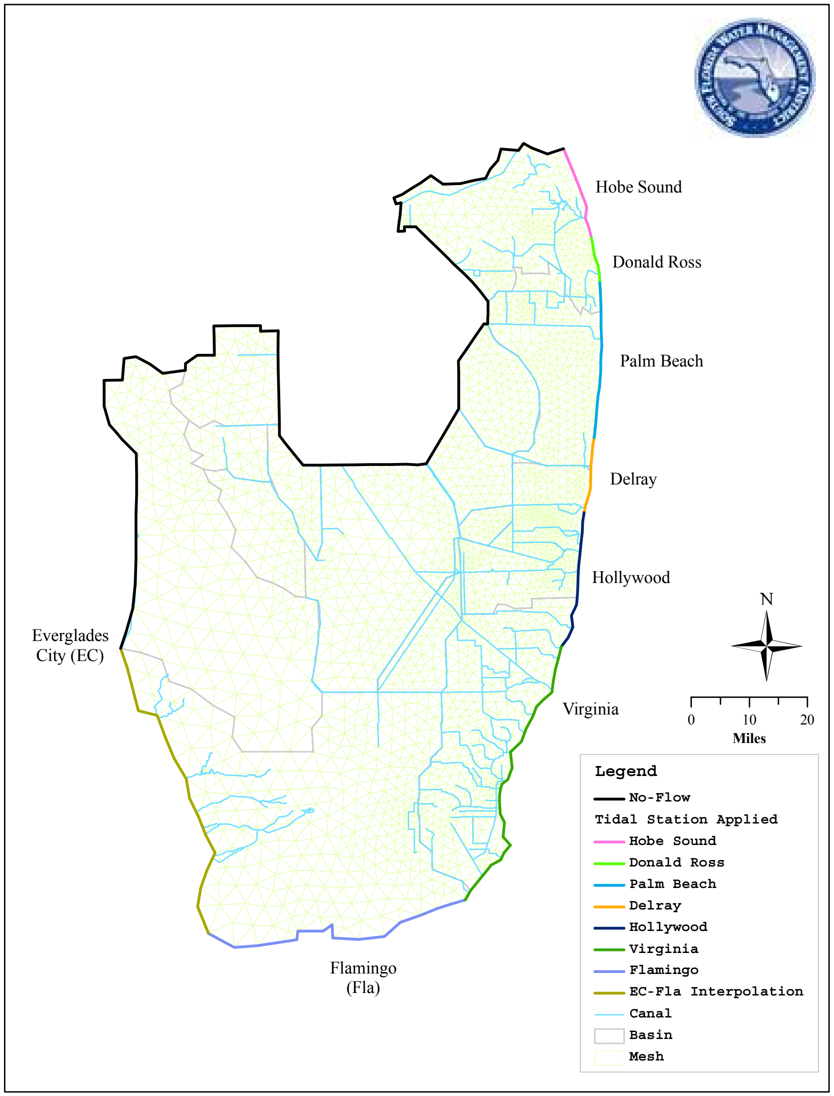


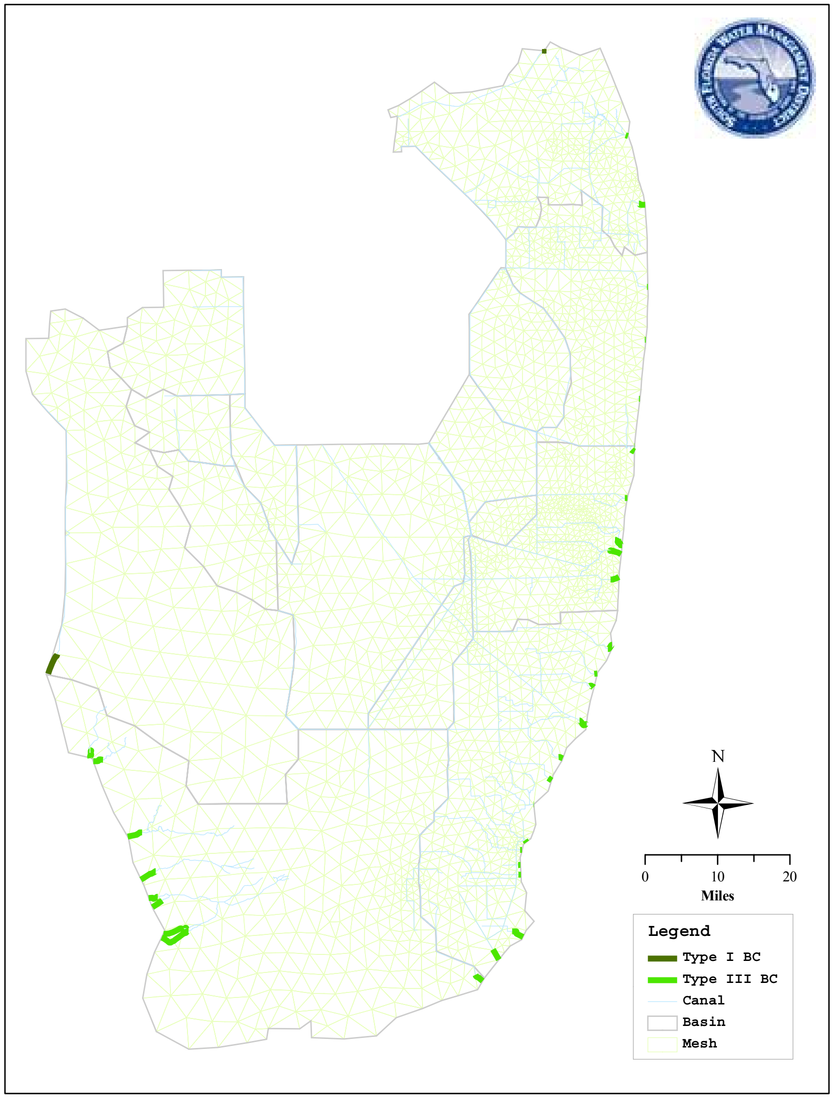
HYDROLOGIC & ENVIRONMENTAL SYSTEMS MODELING

Levee Seepage

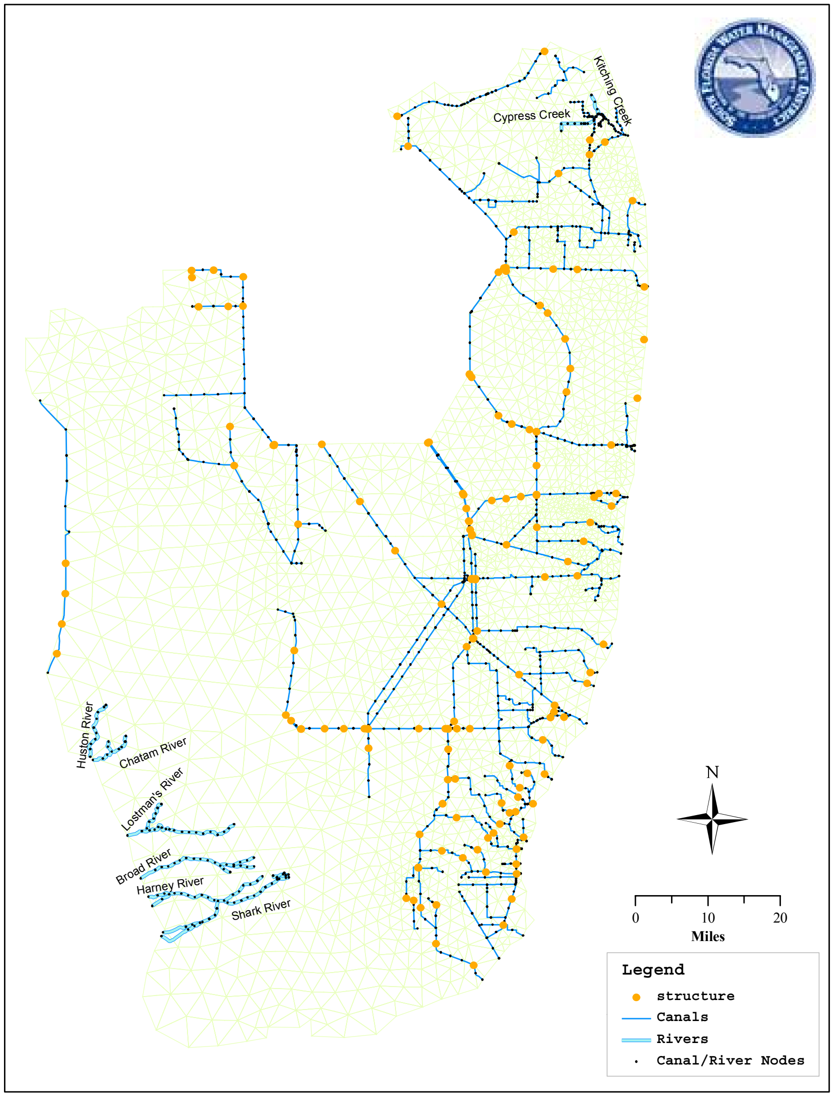


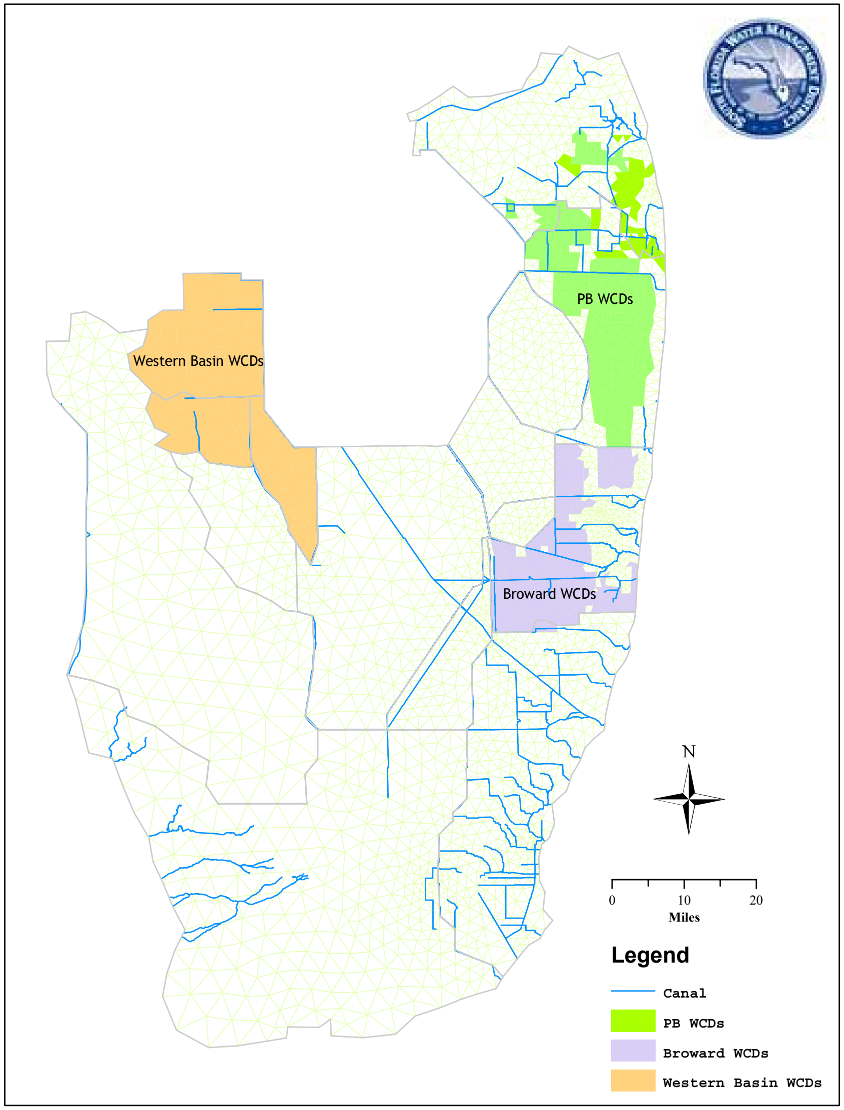
Tidal & No-Flow Boundary Conditions



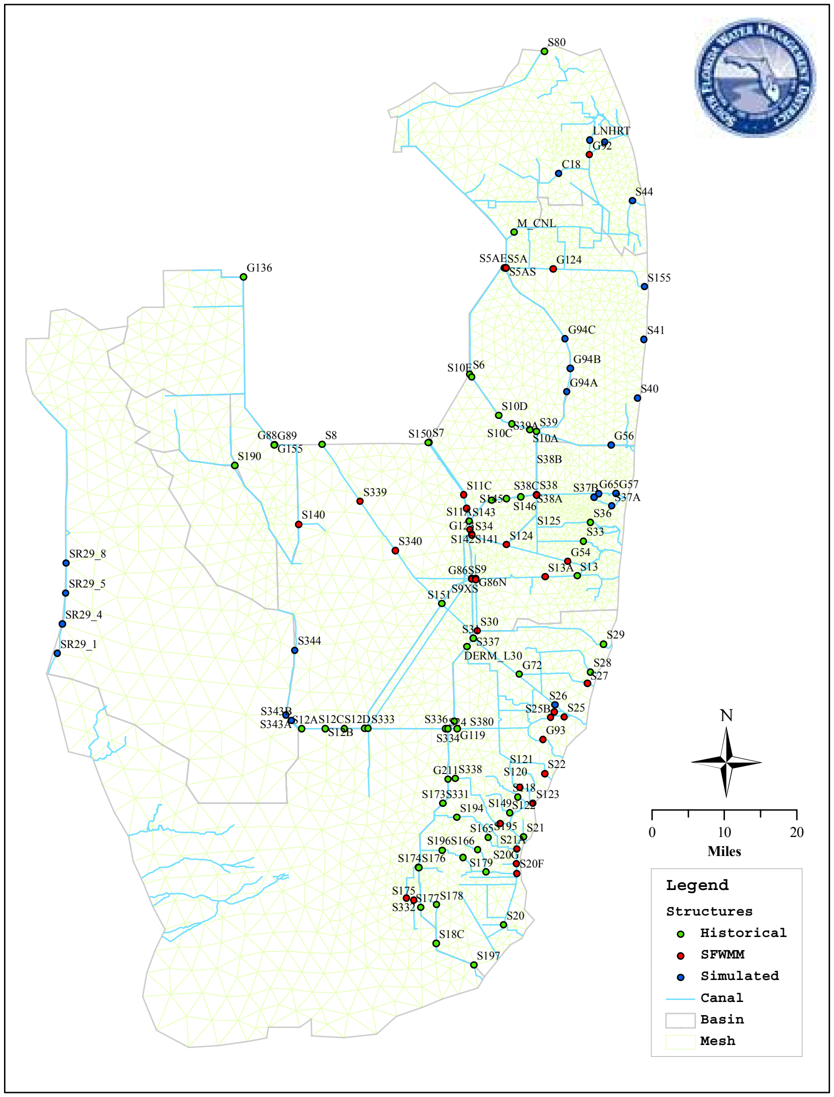


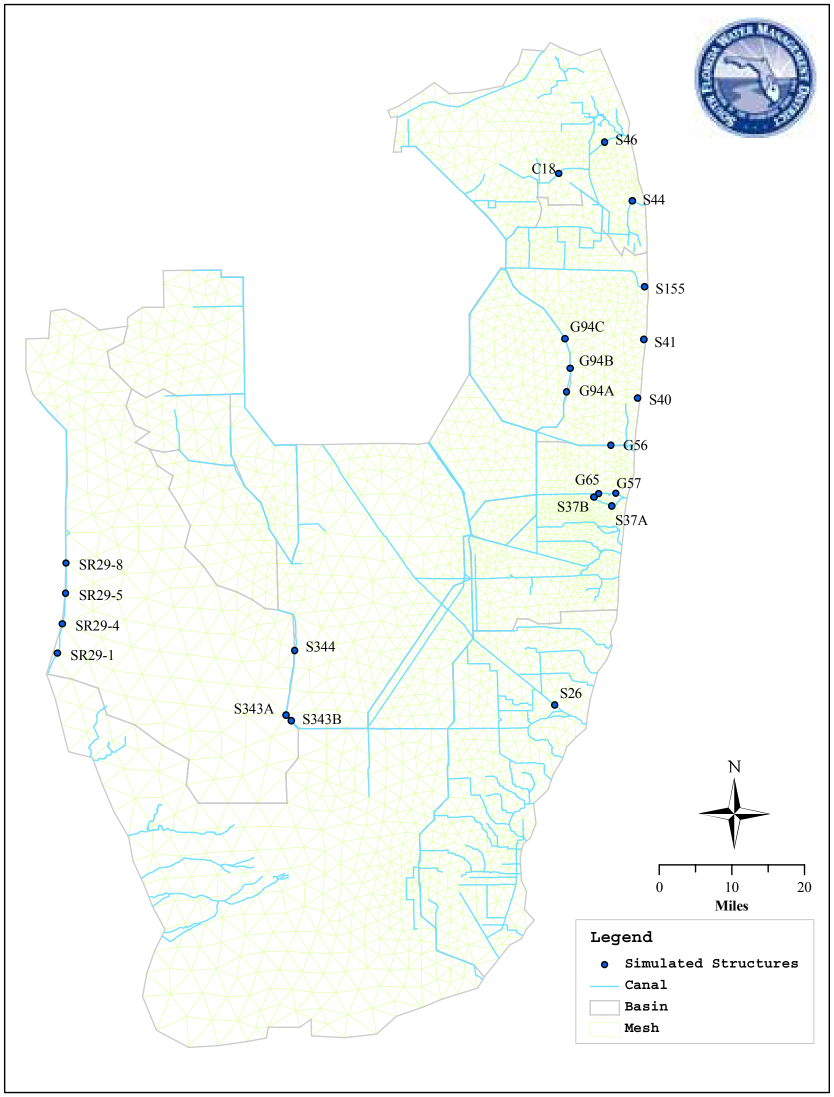
Structures, Canals & Rivers



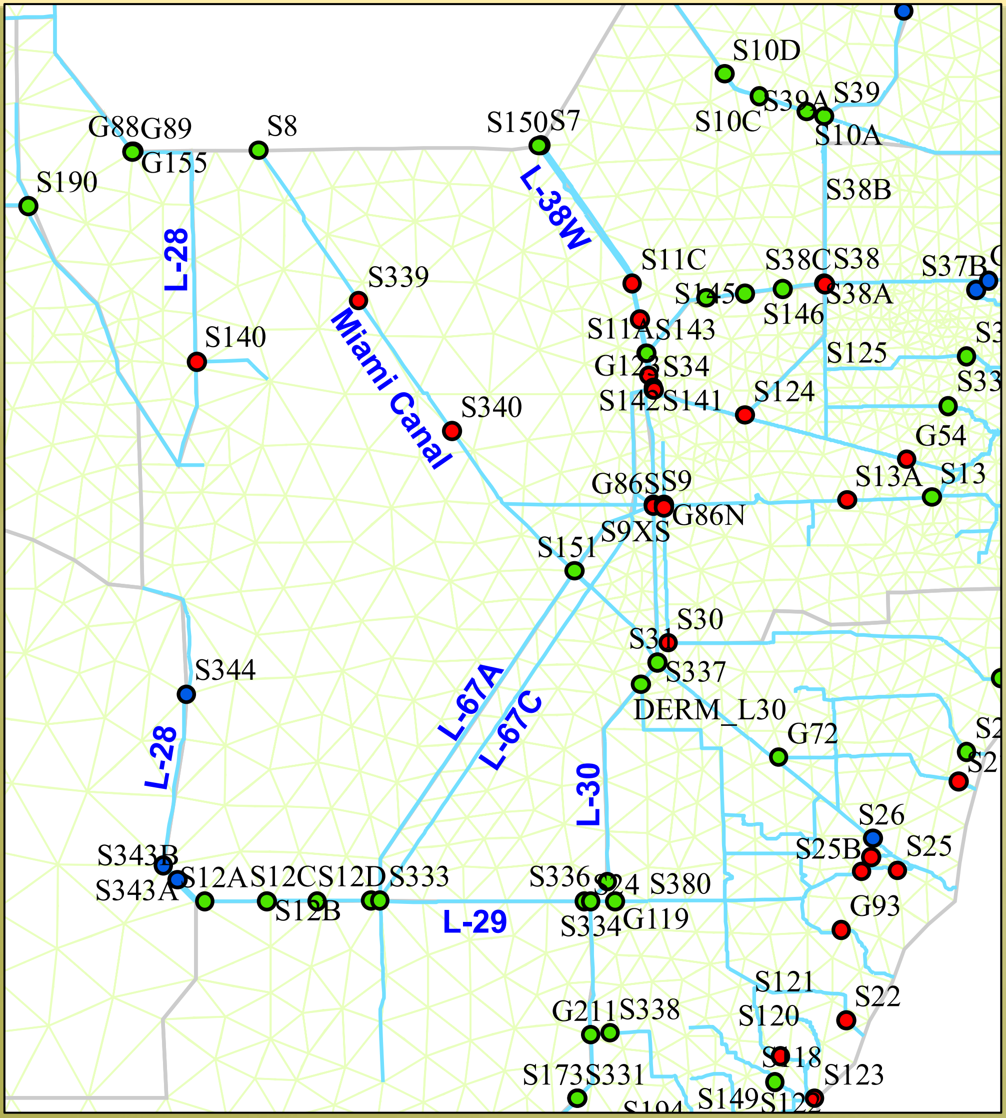


Simulated & Imposed Structures





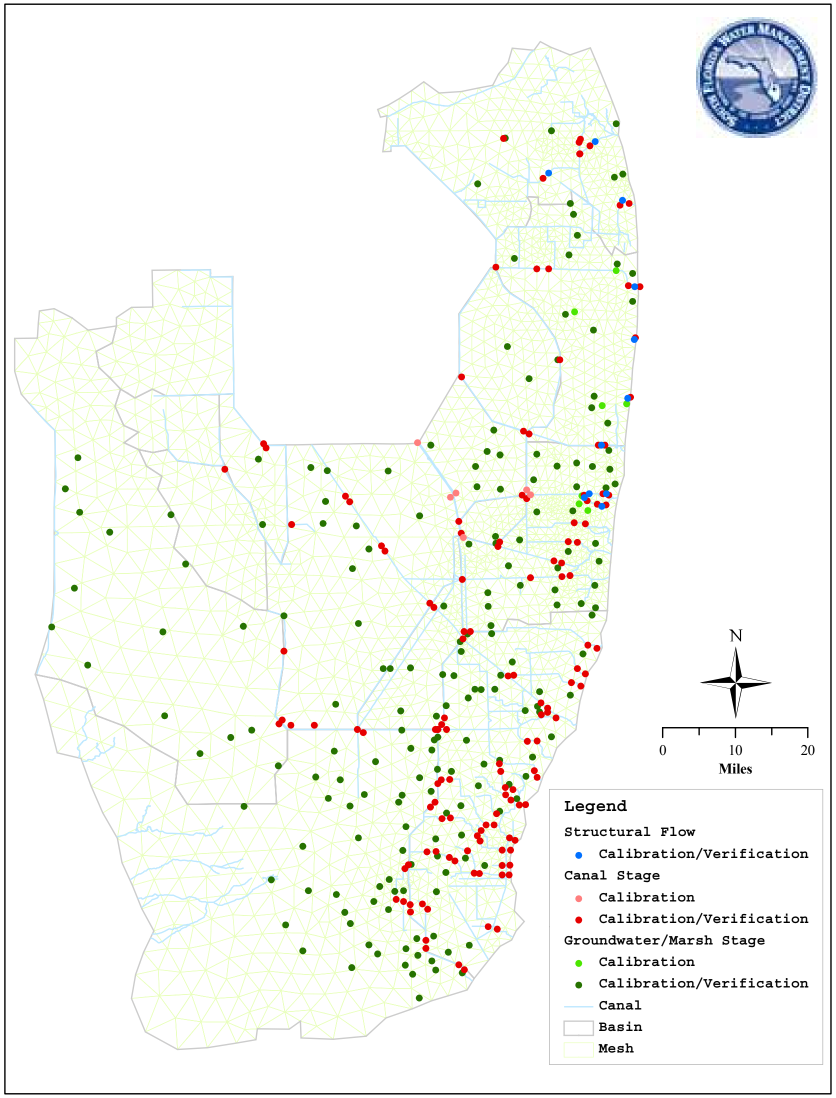
Structures & Canals (in & around WCA-3)

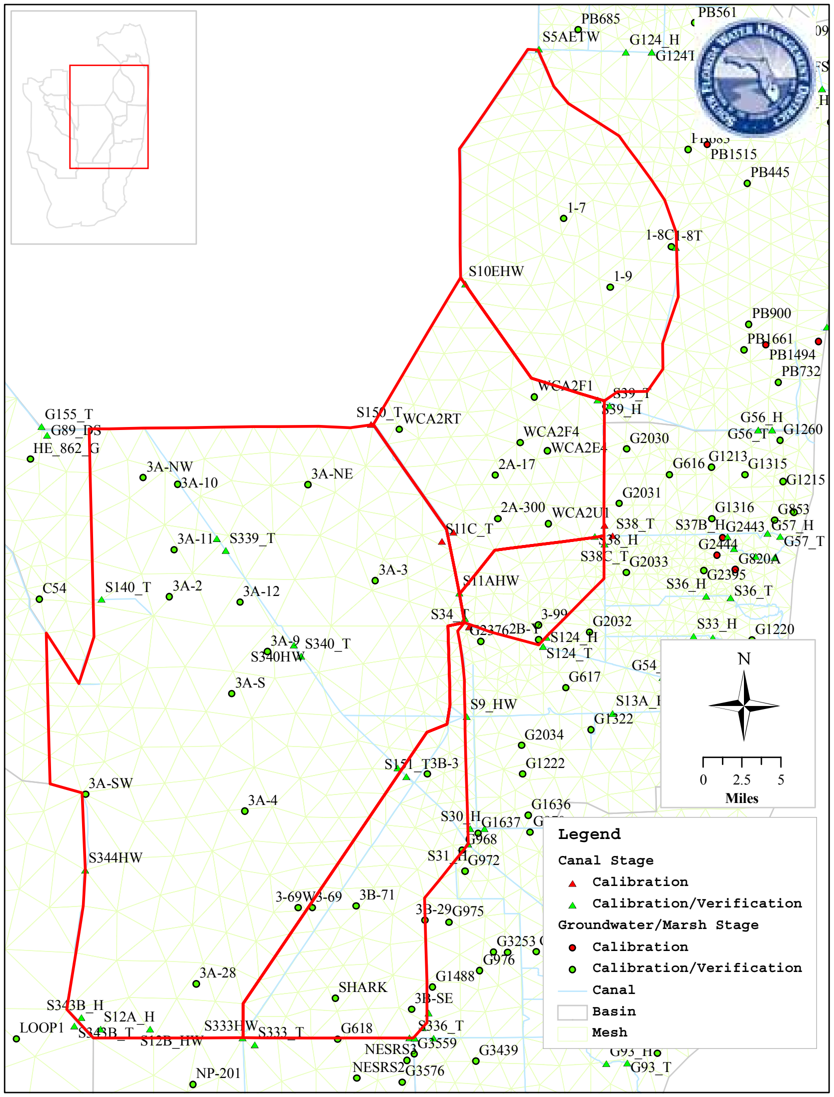


Model Calibration & Verification

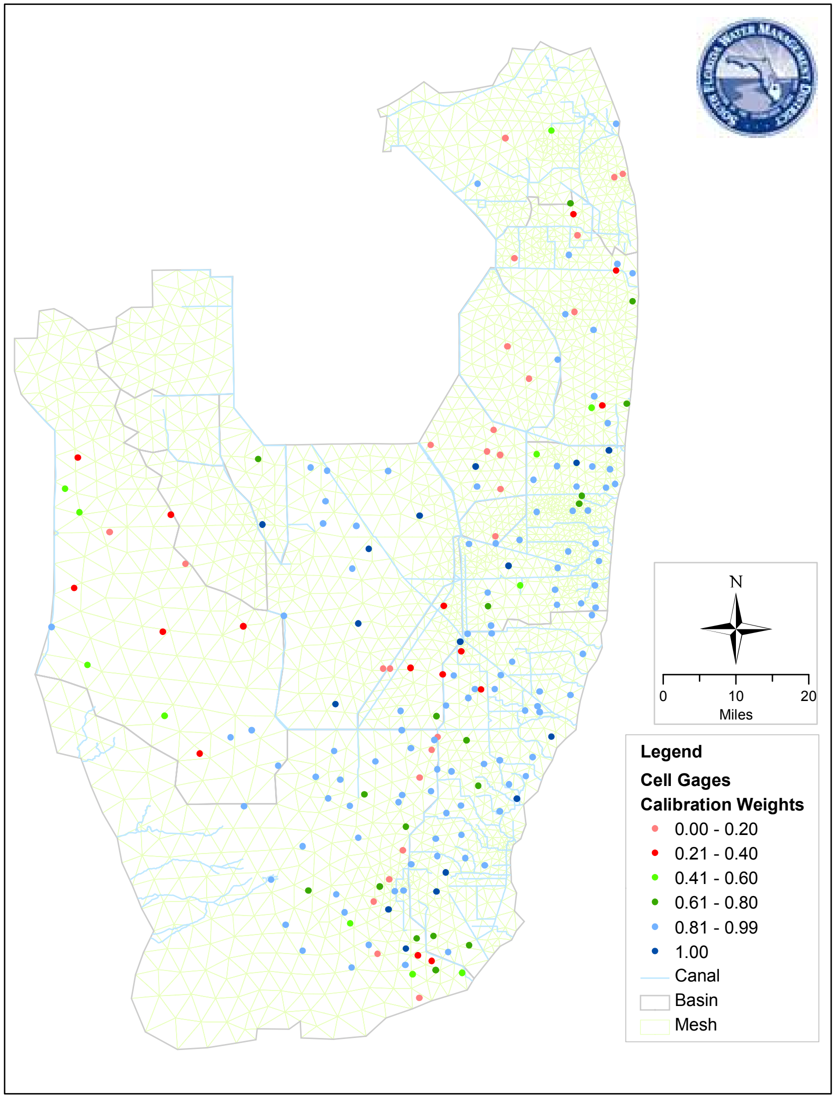
- The model was calibrated using manual methods and the traditional "parameter estimation mode" in PEST (Doherty, 2004).
- Historical daily stage and monthly flow data from 1984 to 1995 were used for the calibration of the Glades-LECSA model.
- Historical time-series data from 193 groundwater and marsh gages, 144 canal stage gages, 4 WCD gages, and 12 flow measurement gages were used for model calibration.
- Objective was to minimize the weighted sum of squares of the absolute bias and RMSE calculated at each measuring site.
- For groundwater levels or surface water stages at a given site the calibration was considered to be satisfactory if the absolute bias was less than 1.0 foot and the RMSE was less than 2.0 feet.
- Historical daily stage and monthly flow data from 1981 to 1983, and 1996 to 2000 were used for the verification of the model.

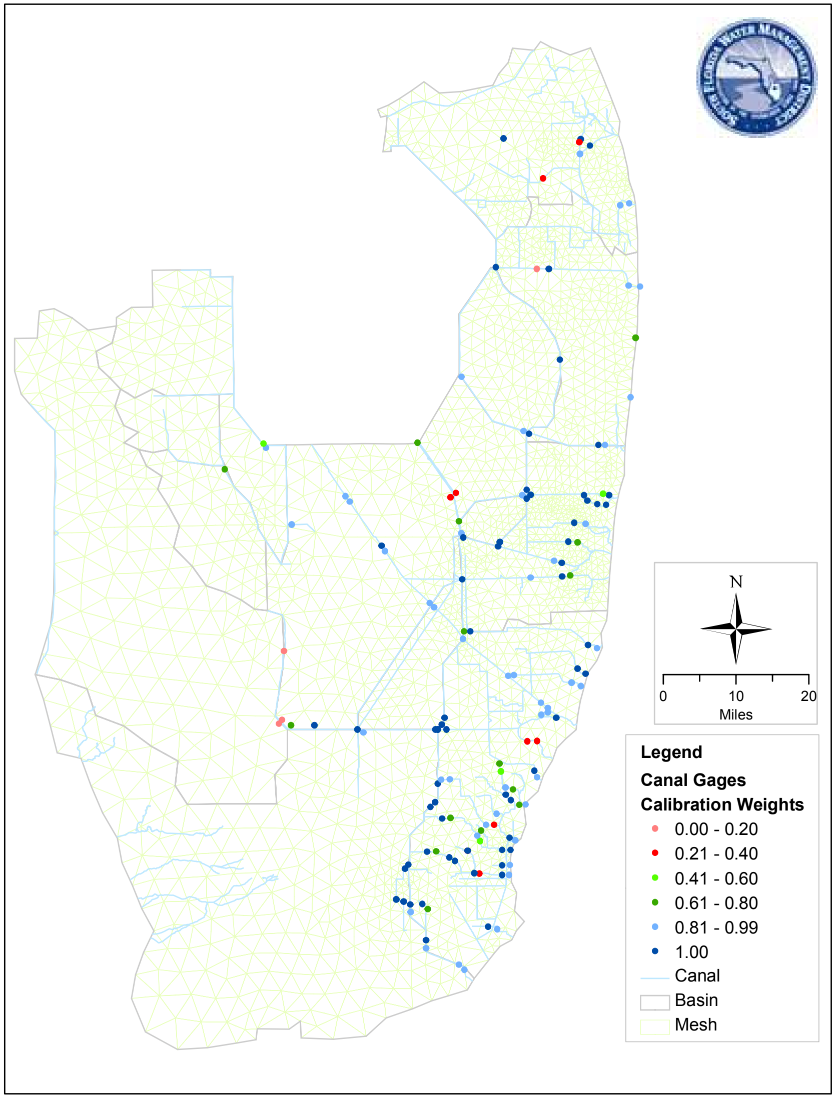
Calibration & Verification Gages





Calibration Weights





Goodness-of-Fit Statistical Estimators

$$Bias = \frac{\sum_{i=1}^{n} (\hat{x}_i - x_i)}{n}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\hat{x}_i - x_i)^2}{n-1}}$$

Objective Function for PEST Calibration

$$\Phi = \sum_{i=1}^{M} w_i (B_i)^2 + \sum_{i=1}^{M} v_i (RMSE_i)^2$$

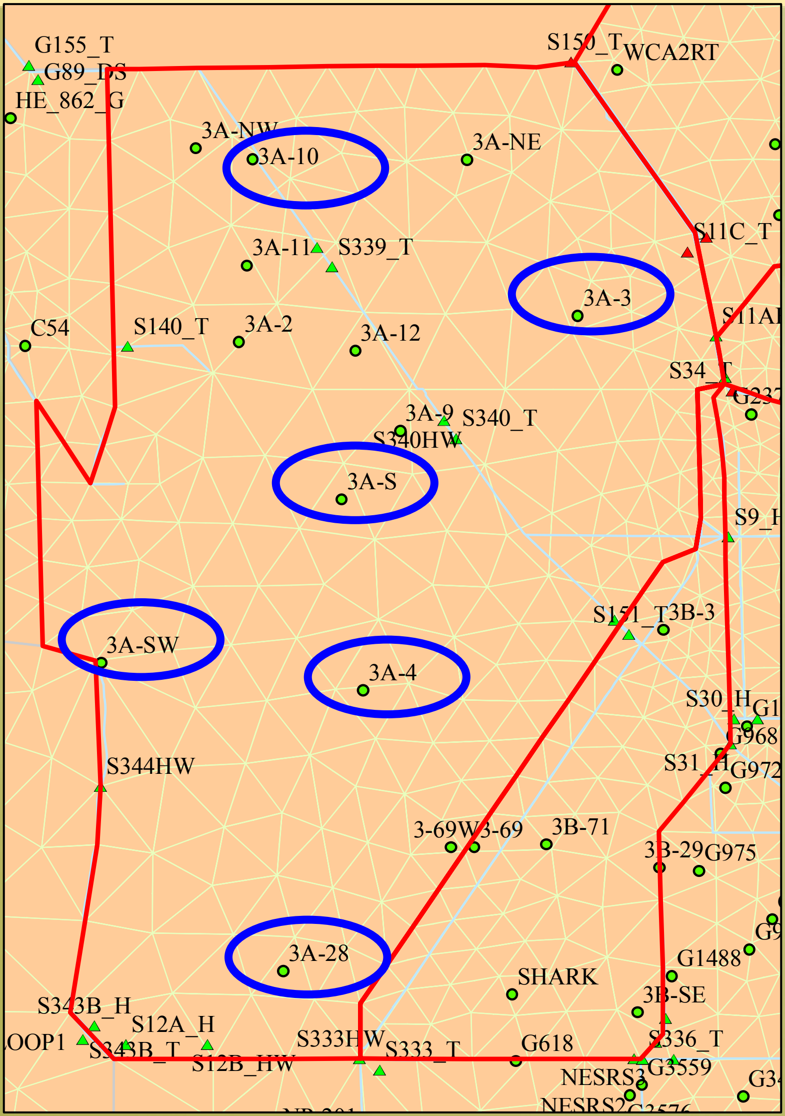
Φ = weighted sum of cumulative bias and root mean square error (RMSE) across all monitoring stations;
M = total number of monitoring sites;
w_i = weight assigned to data at site i that will be applied to bias;
v_i = weight assigned to data at site i that will be applied to RMSE;
B_i = bias at site i; and,
$RMSE_i$ = root mean square error at site i

Bias and RMSE values were computed on a daily basis and aggregated to a final
representative value for each gage.

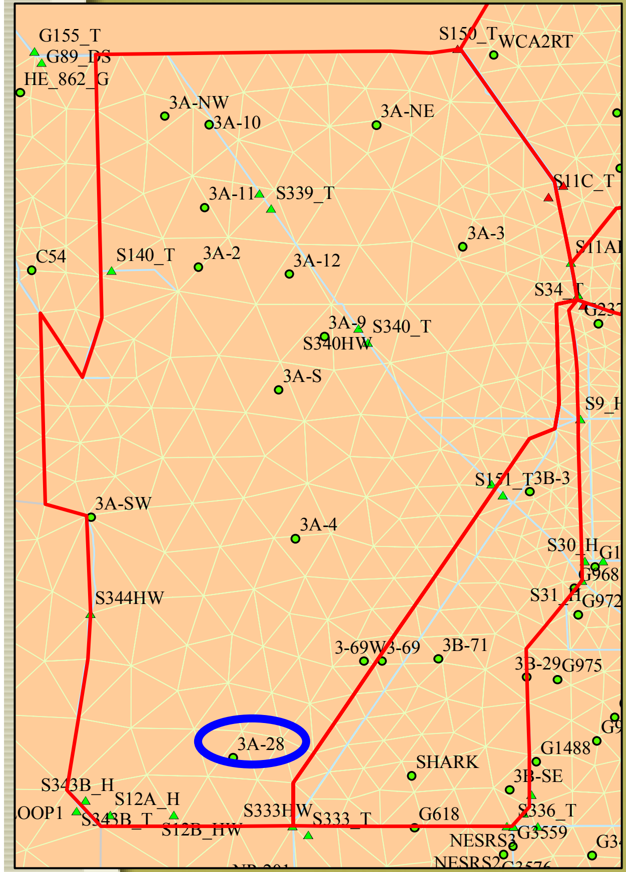
Major Model Calibration Parameters

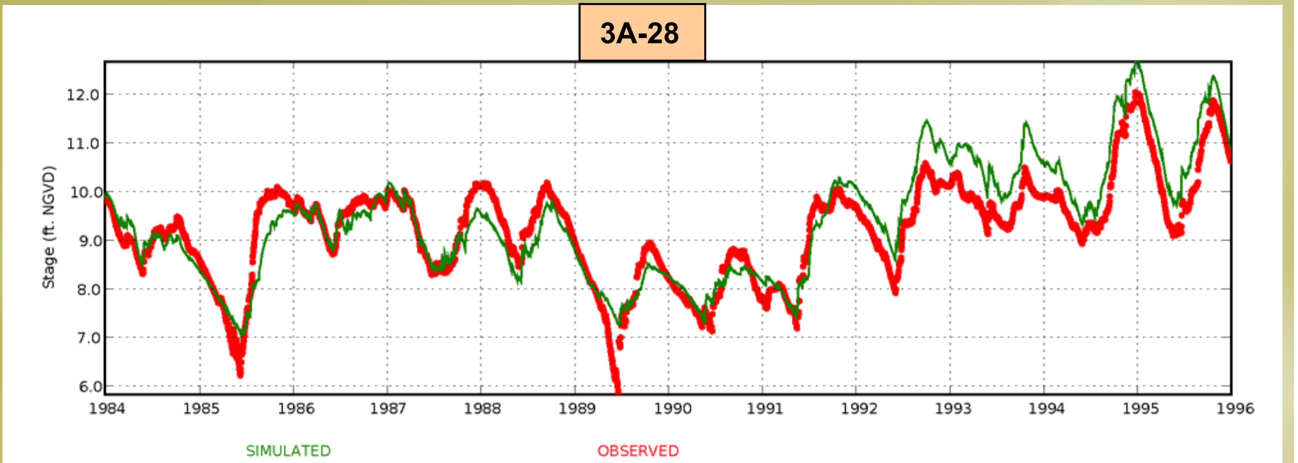
- Aquifer saturated hydraulic conductivity values
- Canal reach leakance values
- Levee seepage coefficients
- Overland Manning's roughness coefficients
- Overland Kadlec roughness coefficients
- General head boundary conductance values
- Water control district canal leakance values
- Evapotranspiration coefficients
- Canal bank heights

Calibration & Verification of Marsh Stages in WCA-3A

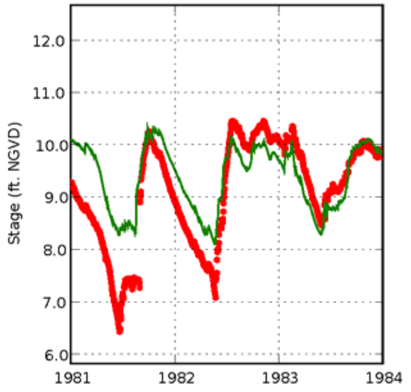


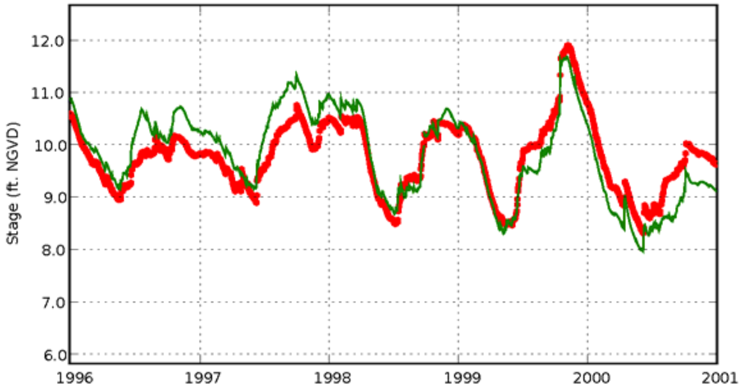
Gage 3A-28: Calibration & Verification



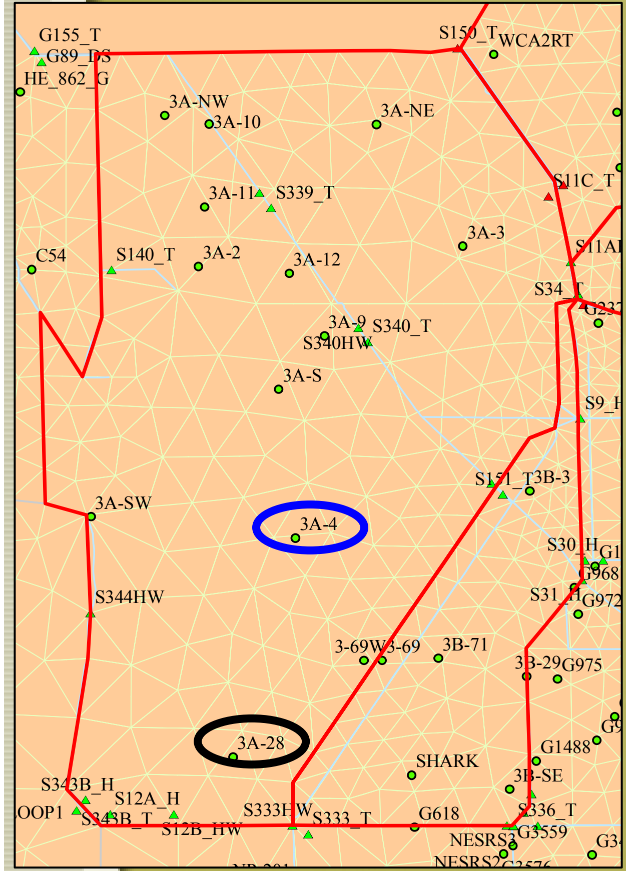


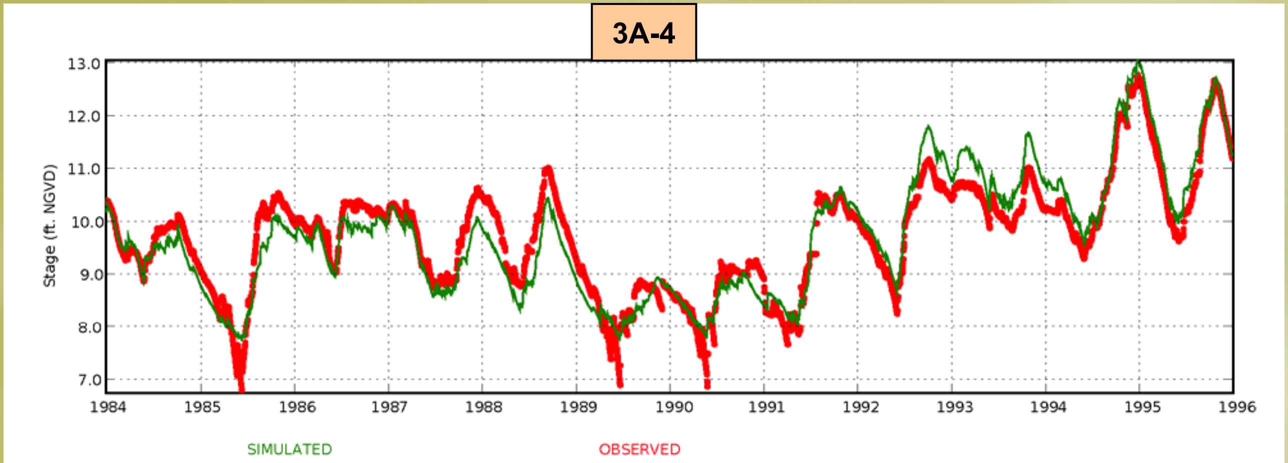
Calibration Period: Bias = 0.17 ft; RMSE = 0.49 ft	Verification Period: Bias = 0.15 ft; RMSE = 0.51 ft



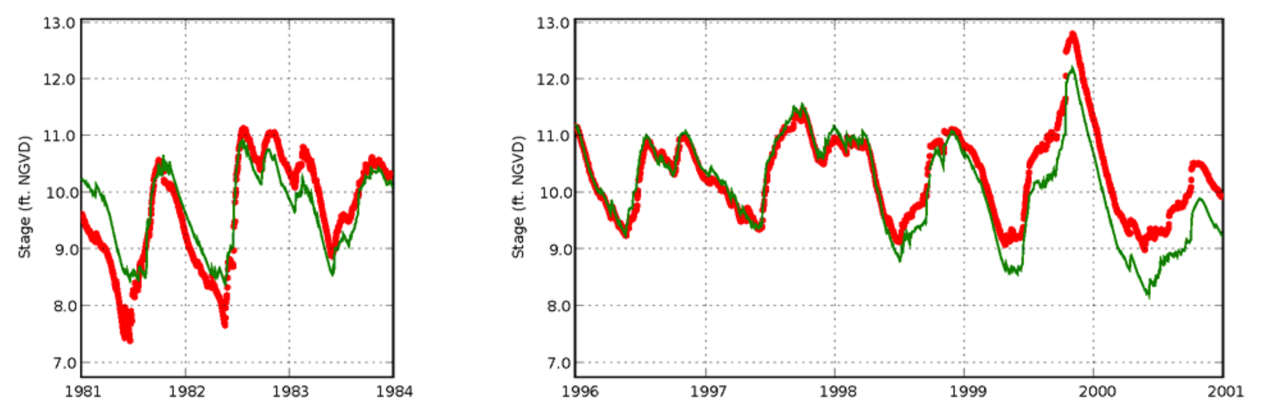


Gage 3A-4: Calibration & Verification

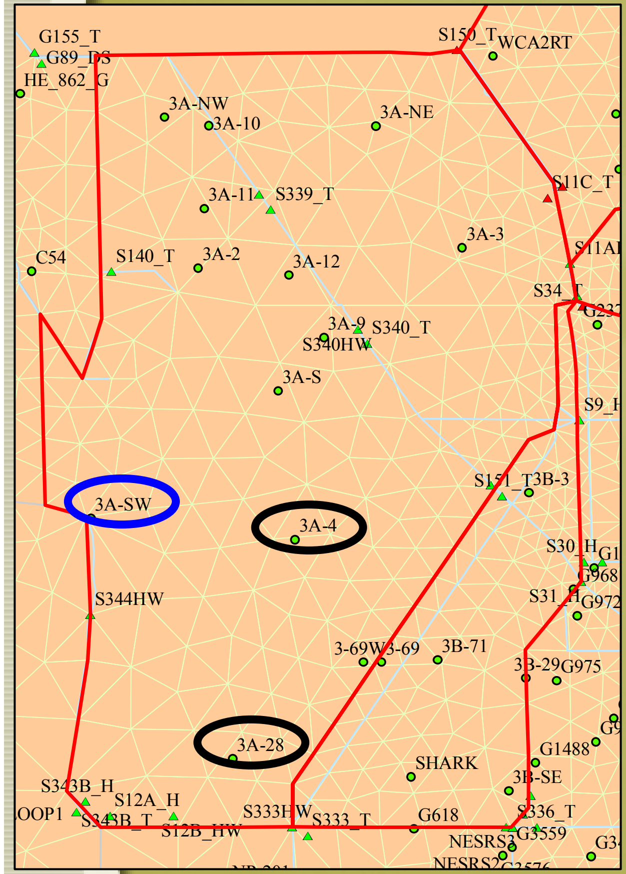


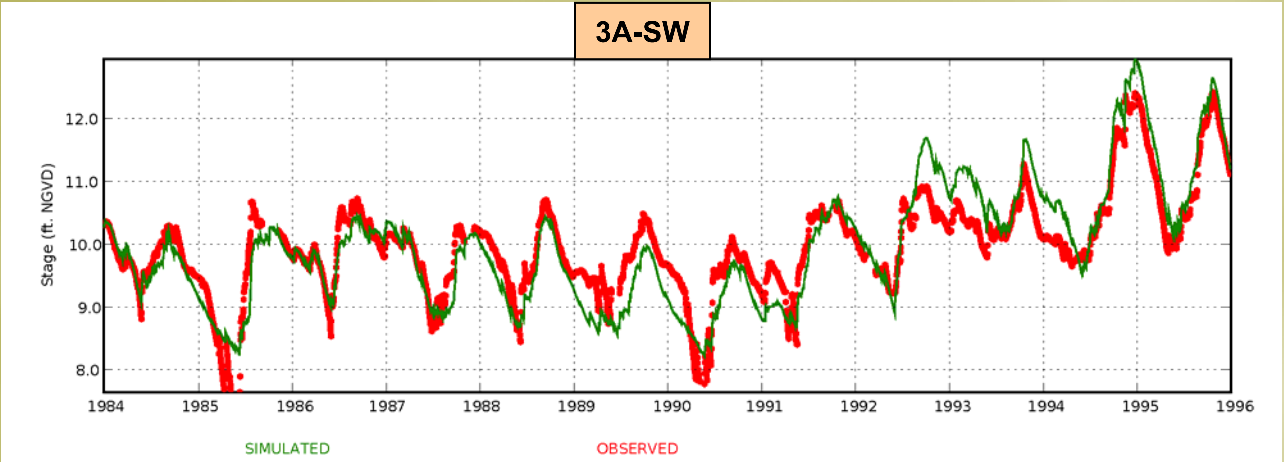


Calibration Period: Bias = 0.00 ft; RMSE = 0.37 ft	Verification Period: Bias = -0.13 ft; RMSE = 0.43 ft

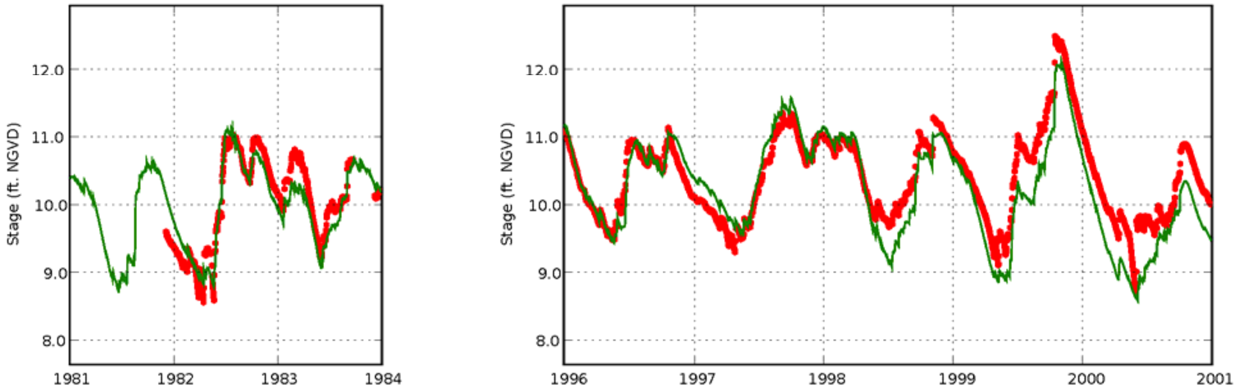


Gage 3A-SW: Calibration & Verification

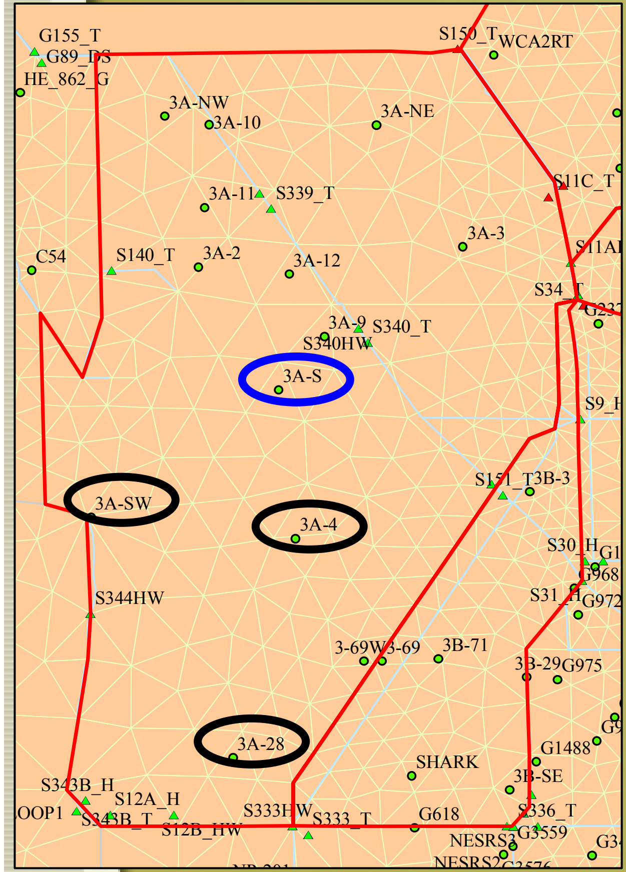


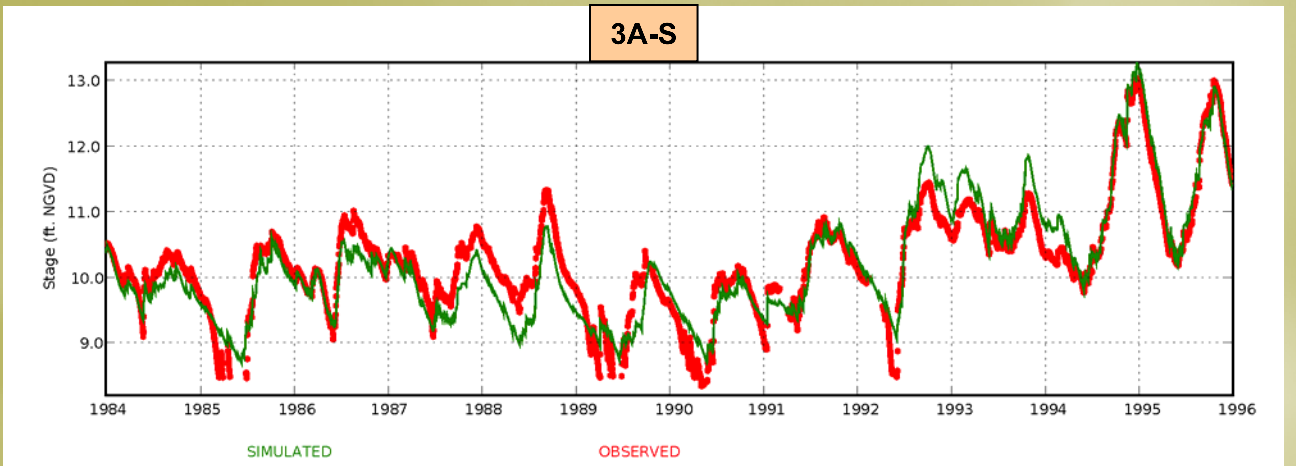


Calibration Period: Bias = -0.01 ft; RMSE = 0.38 ft	Verification Period: Bias = -0.15 ft; RMSE = 0.33 ft



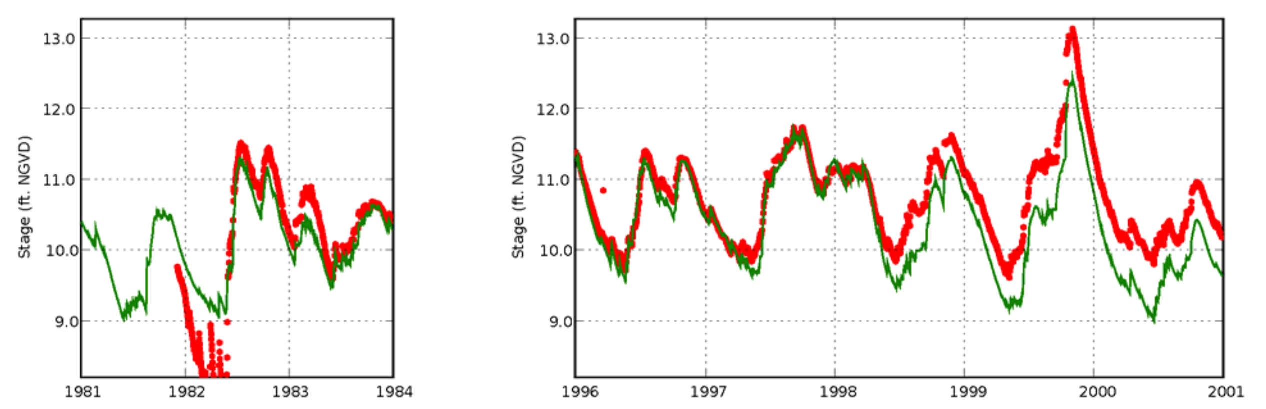
Gage 3A-S: Calibration & Verification



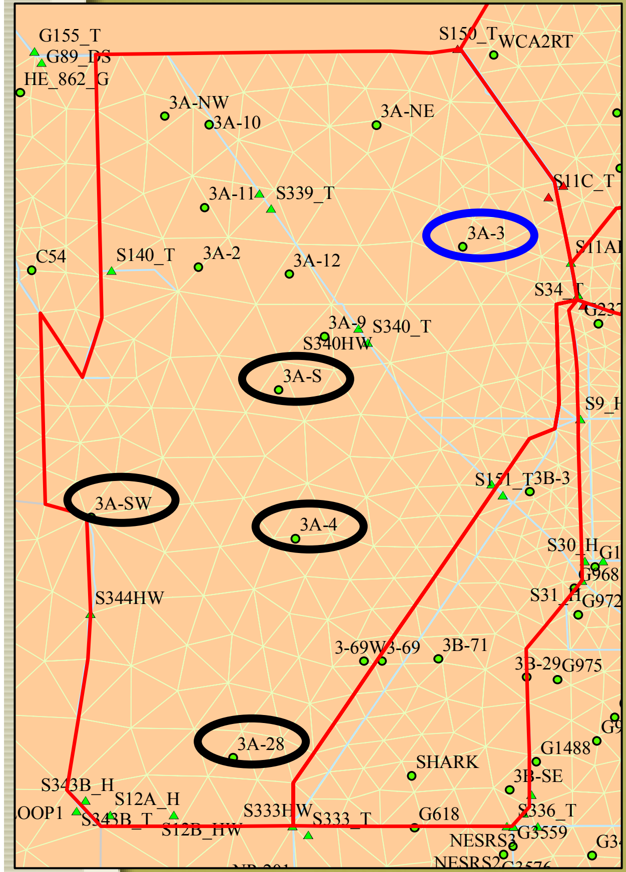


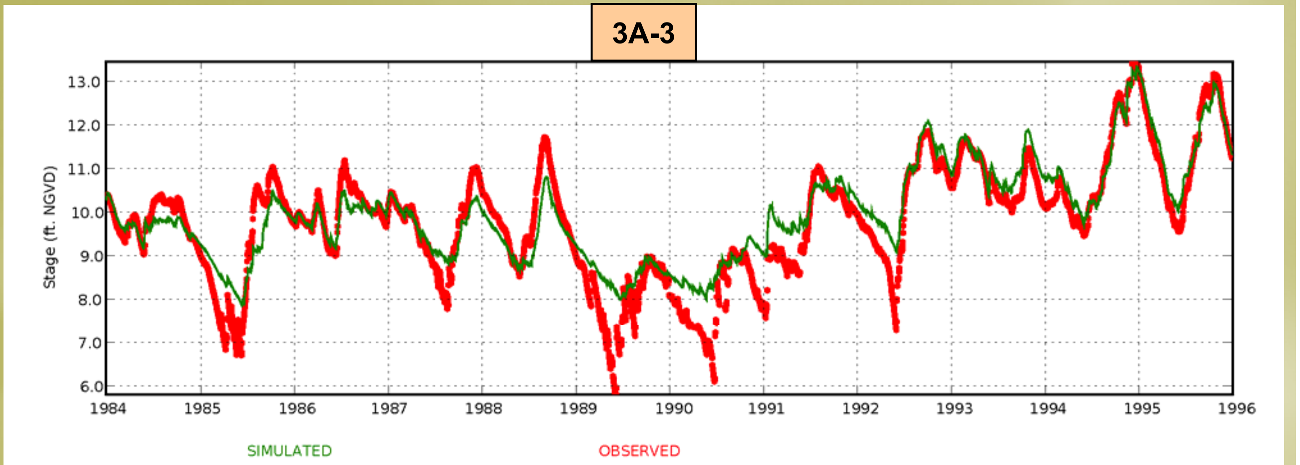
Calibration Period: Bias = -0.02 ft; RMSE = 0.31 ft

Verification Period: Bias = -0.26 ft; RMSE = 0.42 ft



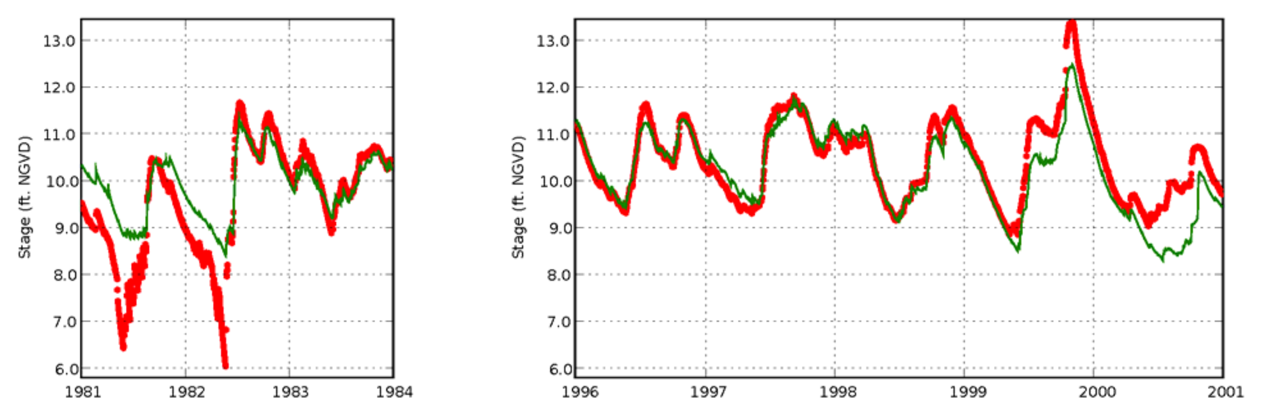
Gage 3A-3: Calibration & Verification



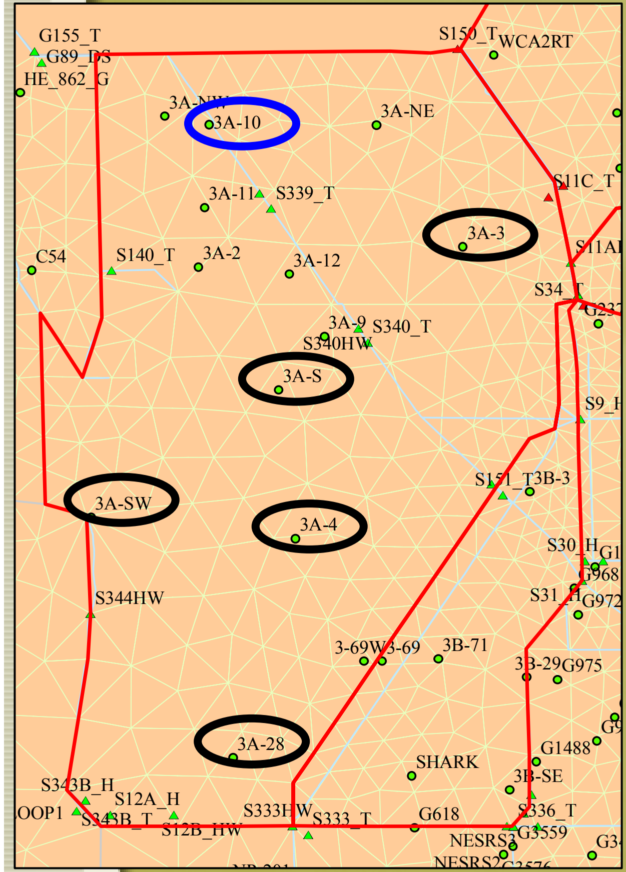


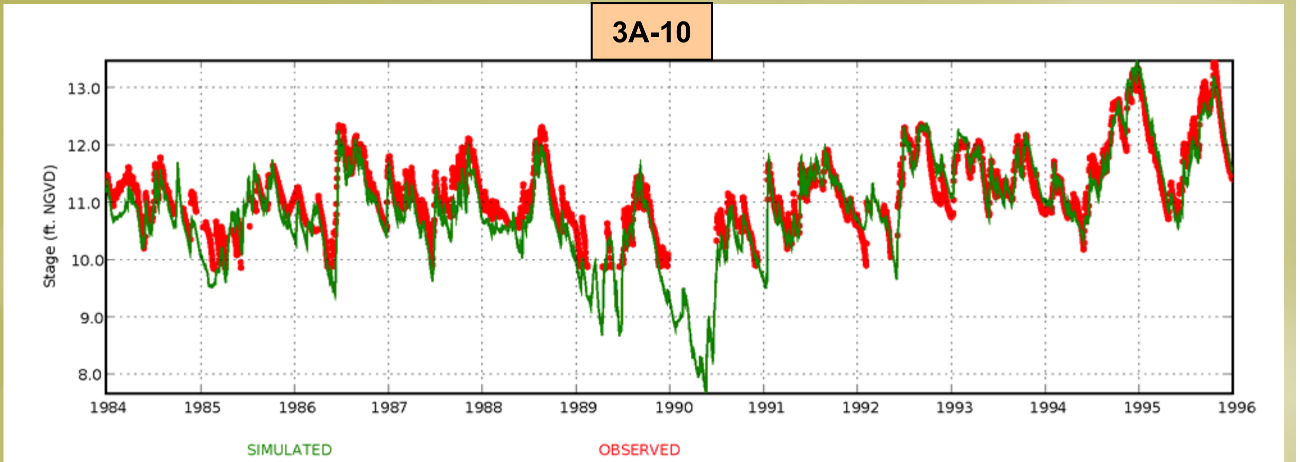
Calibration Period: Bias = 0.18 ft; RMSE = 0.55 ft

Verification Period: Bias = -0.01 ft; RMSE = 0.56 ft



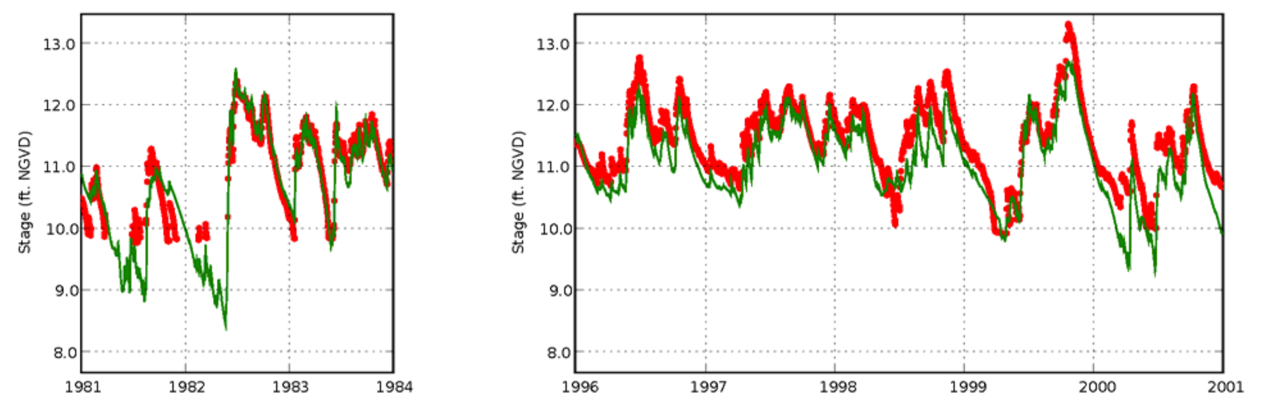
Gage 3A-10: Calibration & Verification



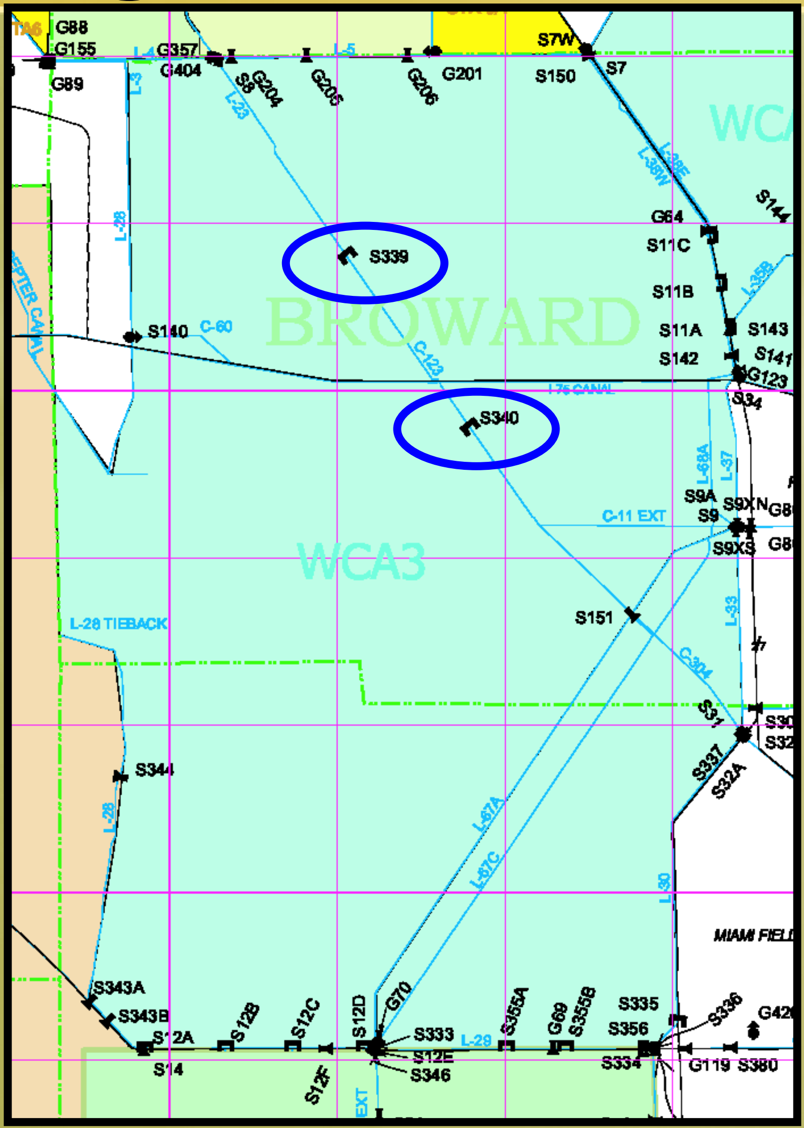


Calibration Period: Bias = -0.14 ft; RMSE = 0.29 ft

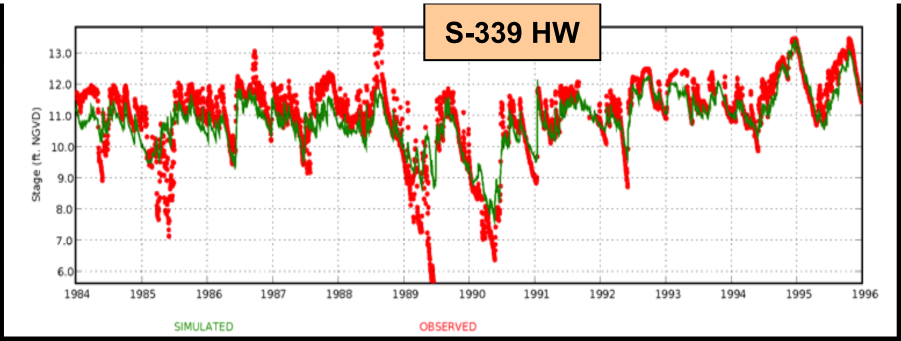
Verification Period: Bias = -0.20 ft; RMSE = 0.33 ft



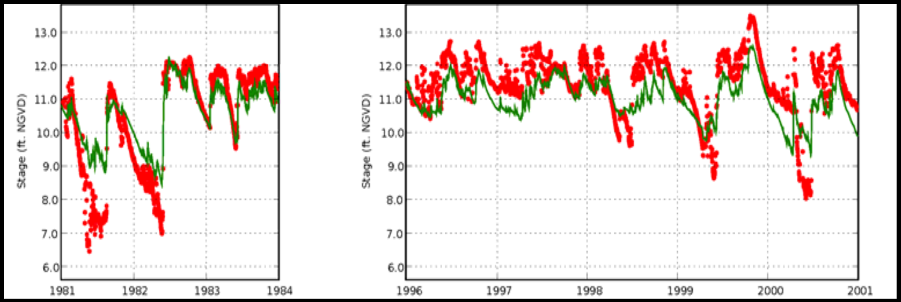
Calibration & Verification of Canal Stages in WCA-3A



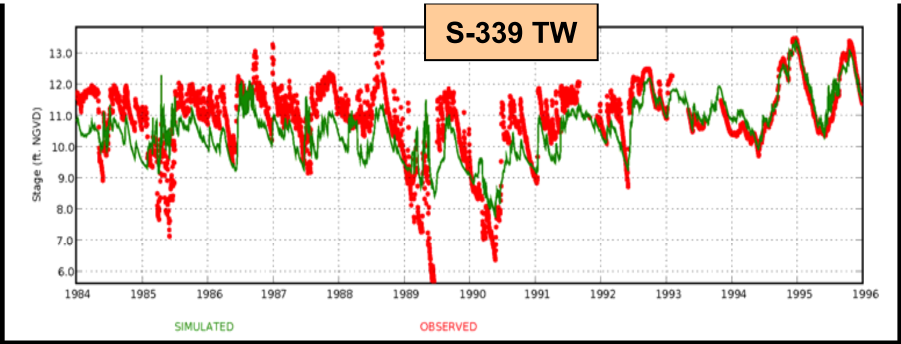
S-339 HW



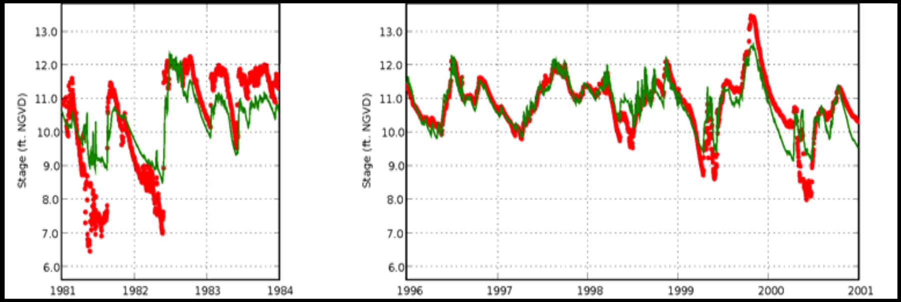
Calibration Period: Bias = -0.18 ft; RMSE = 0.68 ft	Verification Period: Bias = -0.21 ft; RMSE = 0.73 ft



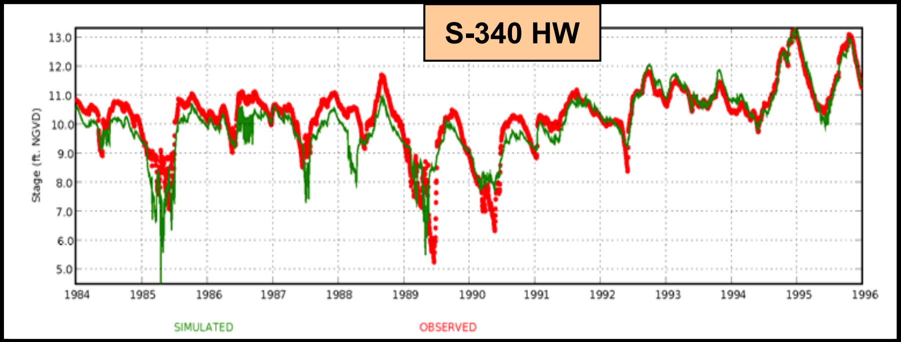
S-339 TW



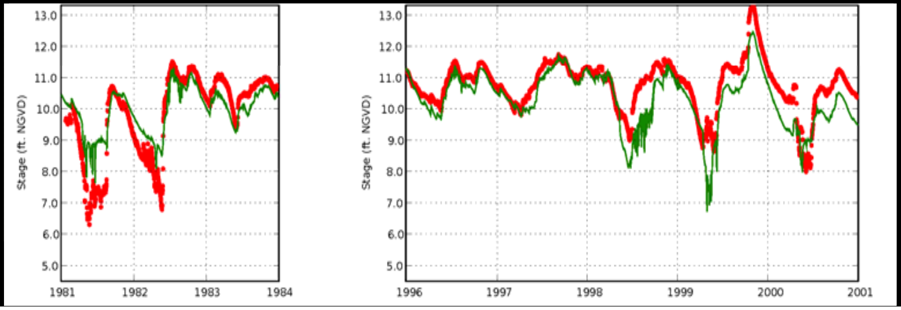
Calibration Period: Bias = -0.36 ft; RMSE = 0.90 ft	Verification Period: Bias = -0.05 ft; RMSE = 0.59 ft



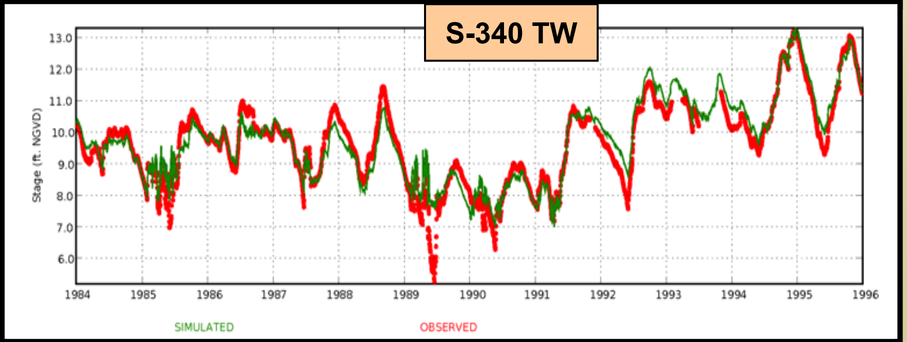
S-340 HW



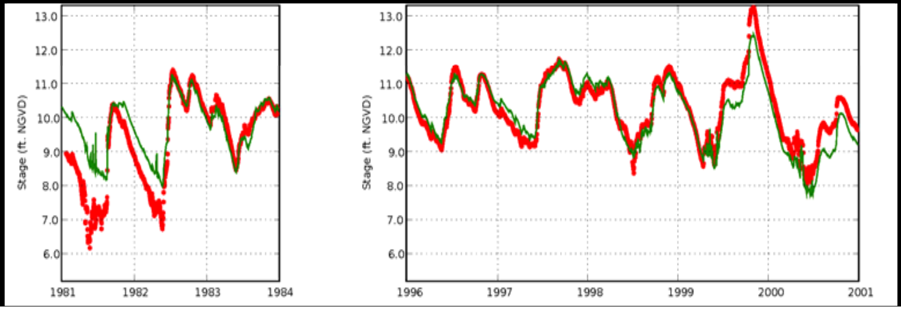
Calibration Period: Bias = -0.21 ft; RMSE = 0.62 ft	Verification Period: Bias = -0.22 ft; RMSE = 0.67 ft



S-340 TW

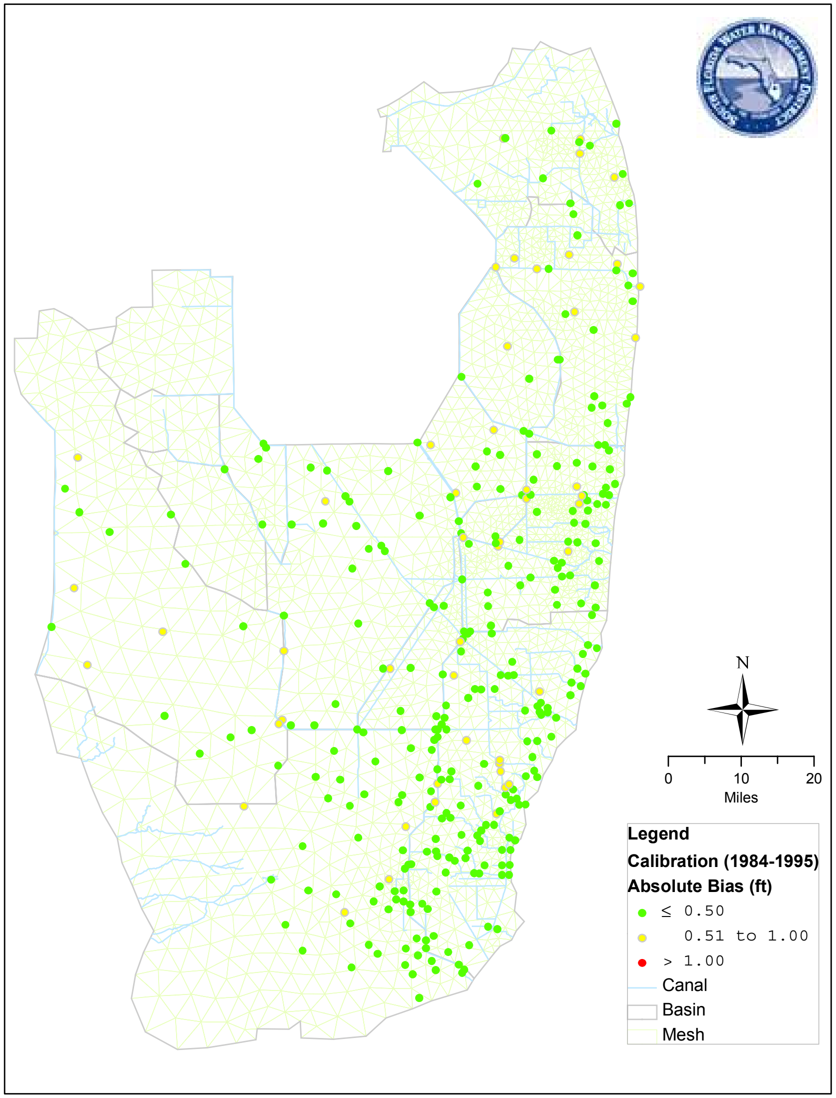


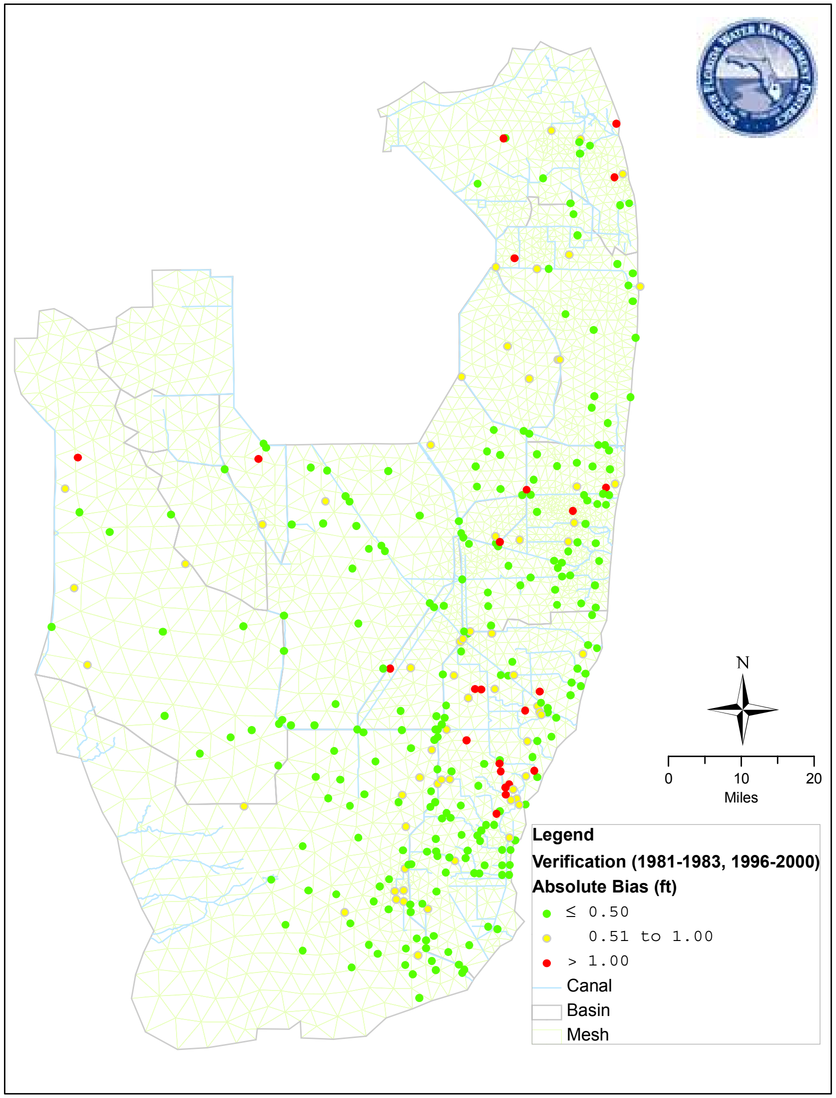
Calibration Period: Bias = 0.08 ft; RMSE = 0.43 ft	Verification Period: Bias = 0.07 ft; RMSE = 0.51 ft



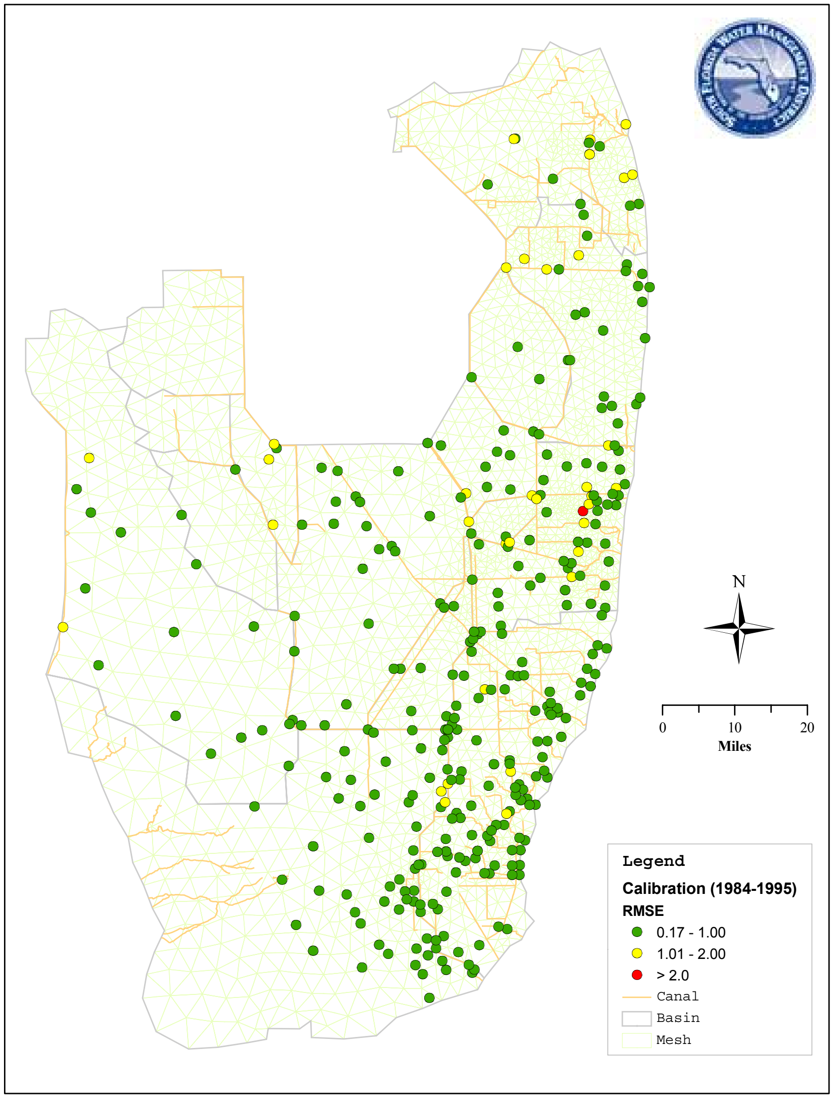
E

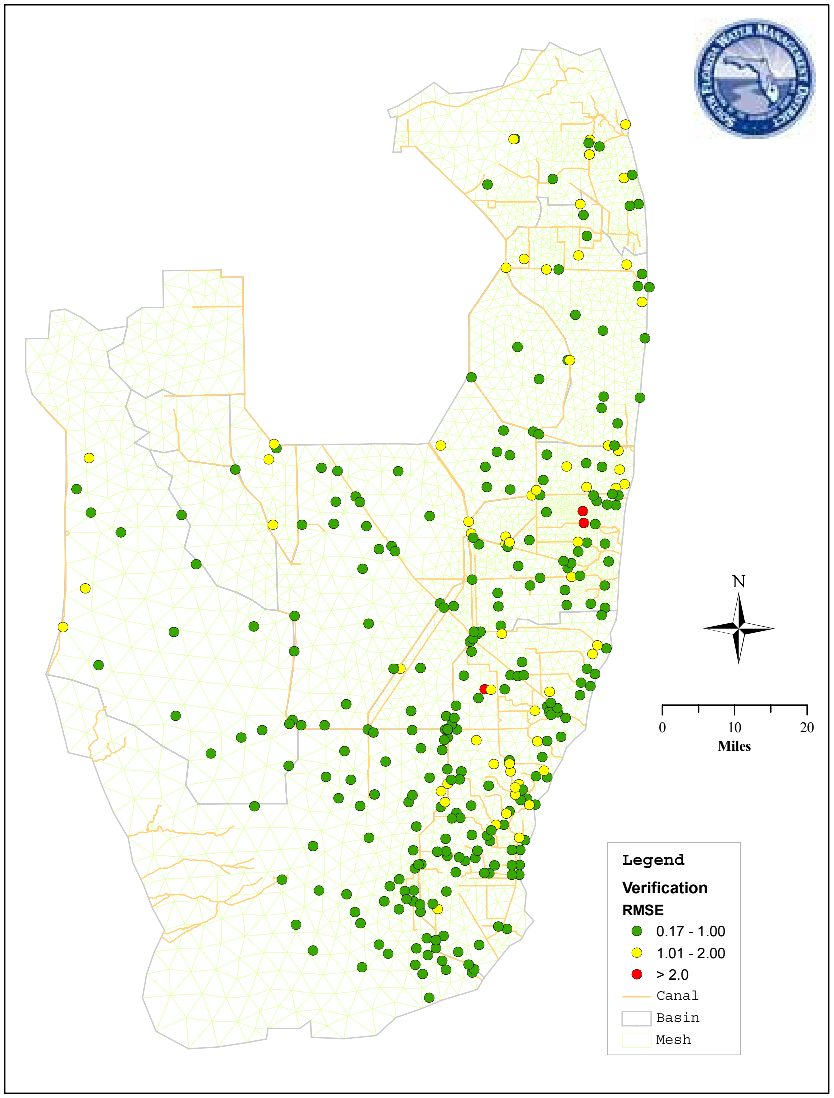
Bias (Calibration vs. Verification)





RMSE (Calibration vs. Verification)





Summary Statistics per Basin

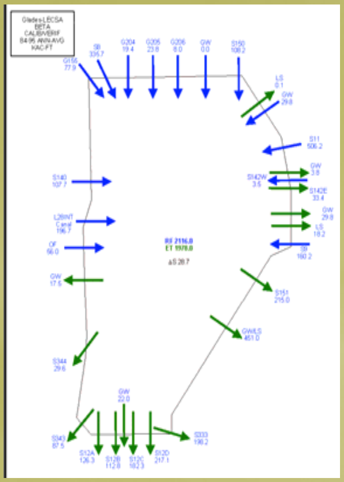
Basin Name	Calibration			Verification		
	No. of Gages	Bias (ft)	RMSE (ft)	No. of Gages	Bias (ft)	RMSE (ft)
Big Cypress	16	-0.05	0.64	16	-0.02	0.78
ENP	45	0.01	0.50	45	-0.20	0.49
L-28 Interceptor	2	-0.20	1.30	2	1.02	1.59
LEC NSA	7	-0.27	1.06	7	-0.45	1.17
LEC SA-1	16	-0.05	0.71	12	0.03	0.84
LEC SA-2	31	-0.02	0.80	28	0.24	0.90
LEC SA-3	44	-0.09	0.61	44	-0.32	0.78
WCA-1	3	-0.48	0.60	3	-0.62	0.73
WCA-2A	7	-0.15	0.61	7	-0.06	0.61
WCA-2B	2	0.10	0.88	2	-0.42	1.12
WCA-3A	13	0.03	0.49	13	-0.11	0.48
WCA-3B	7	0.06	0.51	7	-0.19	0.60

Calibration & Verification Summary

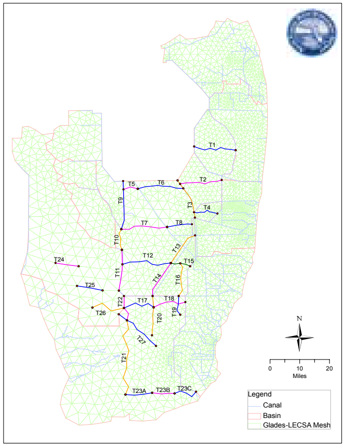
- Out of the 341 gages used for stage calibration, 100.0% and 99.7% of the gages met the acceptability criterion for bias (absolute bias ≤ 1.0’) and RMSE (≤ 2.0’), respectively.
- For the verification period, the bias and RMSE acceptability criterion matching percentages were 93.3% and 99.1%, respectively.
- In WCA-3A, the average bias and RMSE were less than 0.5 ft for both calibration & verification periods.

Output Options

Water Budgets



Transect Flows



Ponding Depths

Heads & Velocity Vectors

Monthly Average Computed Head and Overland Flow Vectors
January-December