Modeling and Optimizing Multi-reservoir System for Carolinas using GRAPS

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Motivation

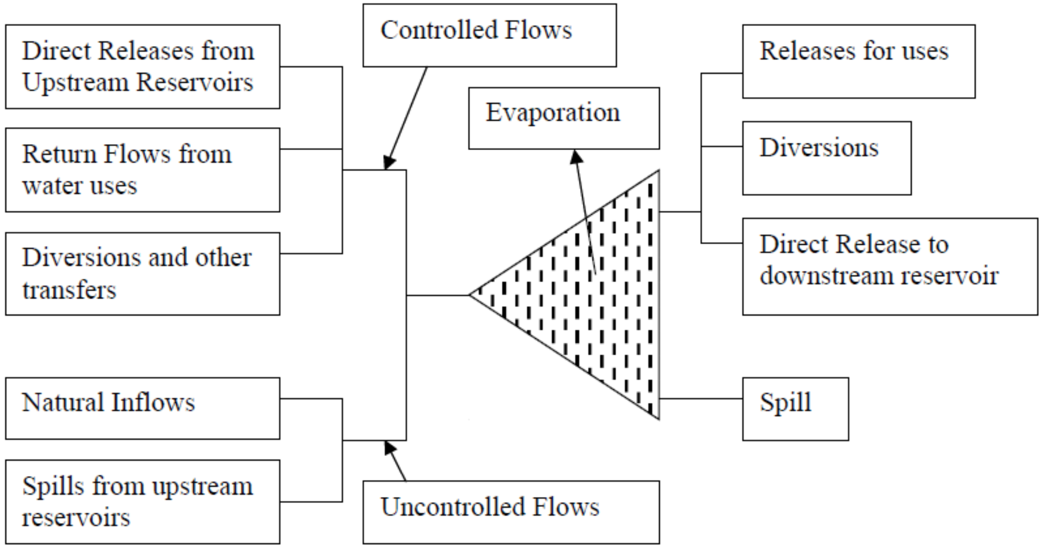
- Changes (technology, land use, population, ect.)
- Many considerations
- Complex interactions
- Need for effective allocation and management of reservoirs
- For water resources manager:
  - Goals
  - Tools to simulate changes
  - Testing different management policies

GRAPS

- GRAPS (Generalized Reservoir Analyses using Probabilistic Streamflow Forecasts)
- FORTRAN
- A generic model
- Simulation capabilities
- FORTRAN
- Can be used for:
  - Preliminary analysis
  - Detailed analysis

Modeling Capabilities

- Forecast future demand
- Water supply
- Water users
- Withdrawals
- Losses
- Connections
- Acyclic graph and tree structure
- Simulation



$$Maximize \sum_{r=1}^{Nr}\sum_{i=1}^{n}\Phi_i^r R_i^r - \sum_{r=1}^{Nr}\left[\sum_{i=1}^{n}\sum_{j=1}^{nl}\gamma_{ij}^r W_{ij}^r + \sum_{i=1}^{n} v_i^r \nabla(W_i^r - W_{i,\max}^r)\right] - a\sum_{r=1}^{Nr}\Delta(P(S_T^r \le S_{Tend}^r) - p_s^r) - b\sum_{j=1}^{n}\Delta(P(w_i^r \ge w_{i,\max}^r) - p_{wi}^r) - c\sum_{l=1}^{nl}\Delta(P(RL_l^r) - pr_l^r)$$

$subject\ to:$

$$DI_t^r = \sum_{r'=1}^{Ur}\alpha_{rr'}\beta_t^{rr'} RE^{r'} \text{ (direct inflow)}$$

$$RF_t^r = \sum_{r'=1}^{Ur}\sum_{i=1}^{nr}\sum_{t'=t}^{t-NL} f_{t',i}^{rr'}\beta_{t',i}^{r'} R_i^{r'} \text{ (return flow)}$$

$$NI_{t,k}^r = DI_t^r + RF_t^r + Sp_{t,k}^r + q_{t,k}^r \text{ (net inflow)}$$

$$CF_{t,k}^r = DI_t^r + RF_t^r + Sp_{t,k}^r - R \text{ (controlled flow)}$$

$$R_{i,\min}^r \le R_i^r \le R_{i,\max}^r \text{ (release)}$$

$$o \le Sp_t^r \le Sp_{\max}^r \text{ (spillage)}$$

$$P(w_i^r \ge w_{i,\max}^r) \le p_{wi}^r \text{ (user restriction)}$$

$$P(S_T^r \le S_{Tend}^r) \le p_s^r \text{ (end storage)}$$

$$P(RL_l^r) \le pr_l^r \text{ (restriction level)}$$

$$S_t^r = S_{t-1}^r + NI_t^r - E_t^r - \sum_{i=1}^{nr} R_{it}\ (storage)$$

$$S_t^r = \min(S_t^r, S_{\max}^r) \text{ (max storage)}$$

$$S_t^r = \max(S_t^r, 0) \text{ (min storage)}$$

$$E_t^r = \Psi_t^r \delta_1^r ((S_t^r + S_{t-1}^r)/2)^{\delta_2^r} \text{ (evaporation)}$$

a, b, c = penalties for violating constraints
CF = controlled flow
DI = direct inflow
E = *evaporation*
f = fraction of monthly release that contributes to current reservoir
n = number of uses
NB = net benefits
NI = net inflow
NL = number of lags
p_s = failure probability
q = natural inflow
R = release
RE = upstream direct release
RF = return flow
RL = restriction level
S = storage
Sp = spillage from upstream reservoirs
v = restriction compensation
W = restriction to user
w = user restriction
α = loss fraction
β = within year distribution factor/monthly demand fraction
γ = penalty compensation
δ = storage-elevation curve coefficient
Φ = *value of each use*
Ψ = evaporation rate
$\nabla(x)$ = 1 if x >0, 0 otherwise
$\Delta(x) = x$ if x >0, 0 otherwise

Climate-based streamflow forecast

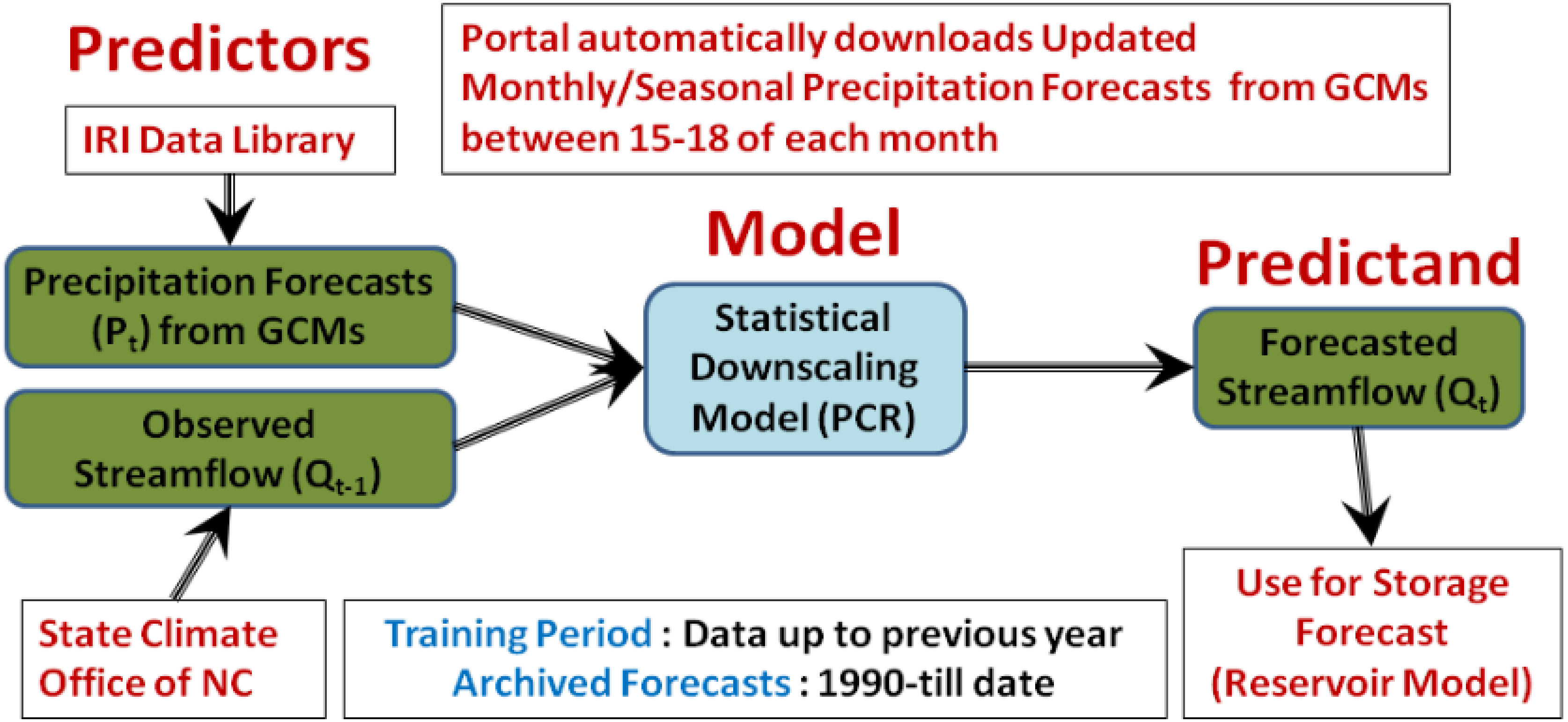


Image source: https://climate.ncsu.edu/inflow/index.php

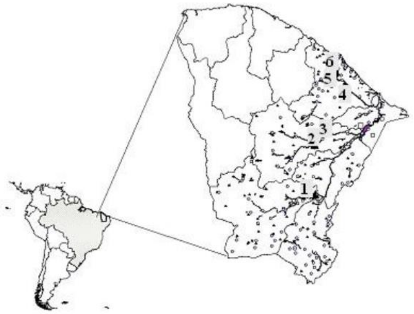
PSO(Particle Swarm Optimization)

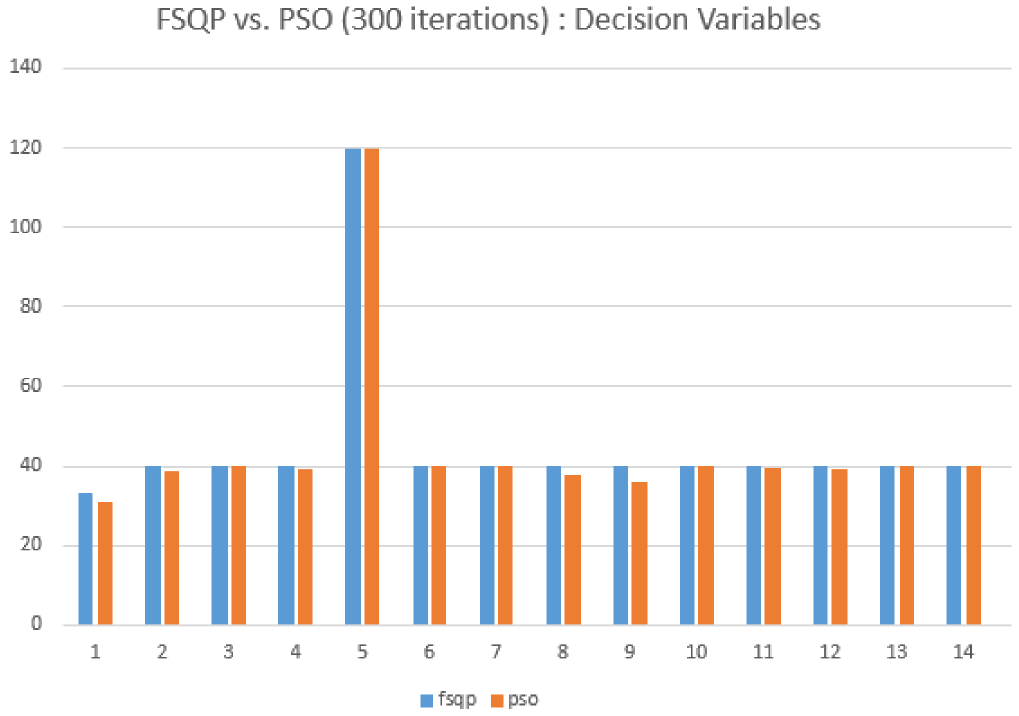
- Heuristic optimization
- Swarm intelligence
- Swarms of animals in nature
- Candidates are represented as particles
- During each iteration
- high-dimensional, non-linear problems

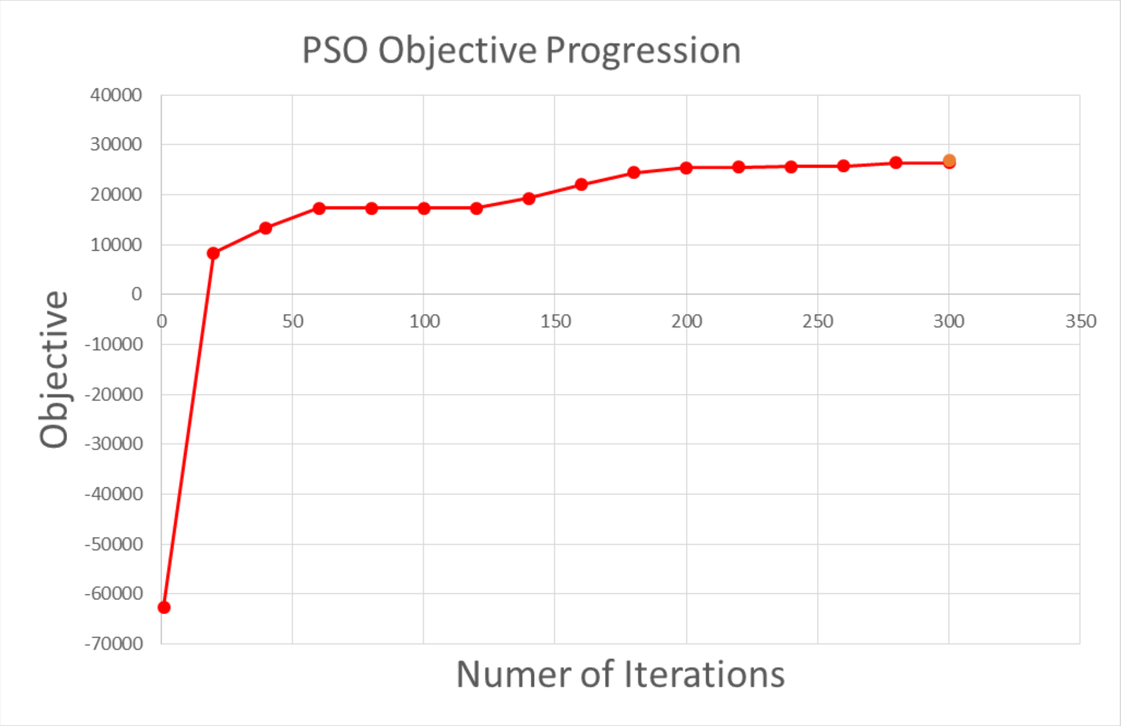
Flock of birds in Italy forming curious shapes
Courtesy: National Geographic

- FSQP (Feasible Sequential Quadratic Programming)
  - SQP (Sequential Quadratic Programming)

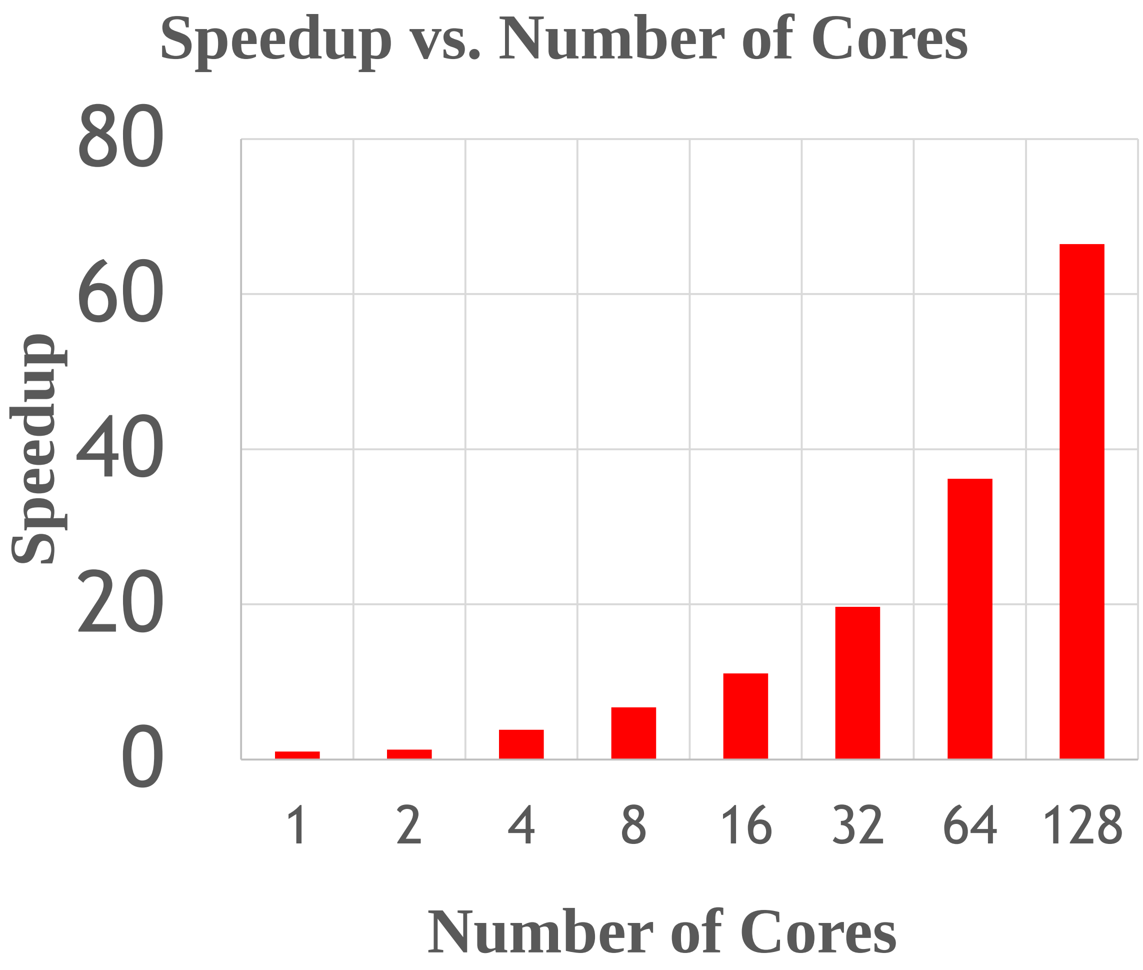
Penalty Method

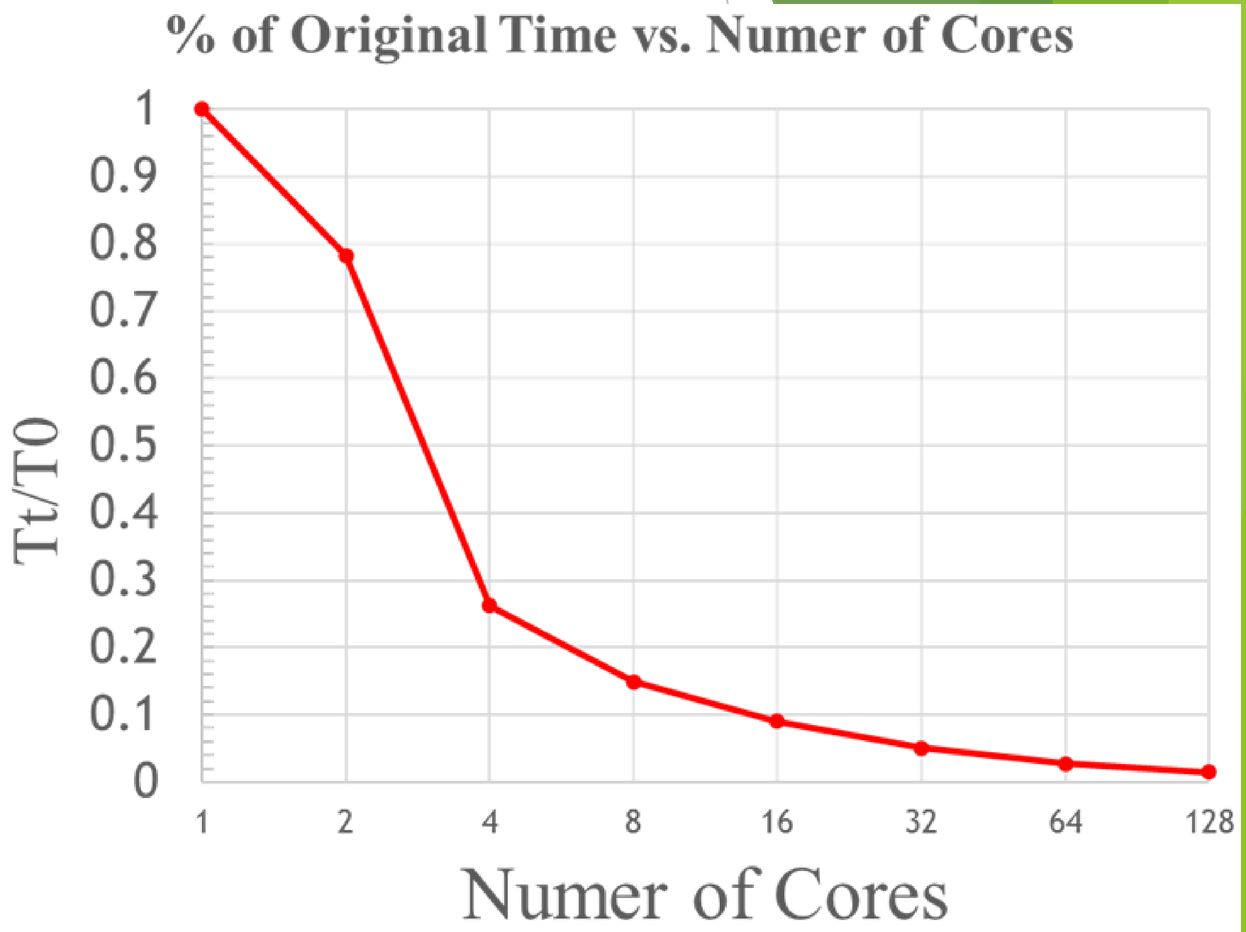




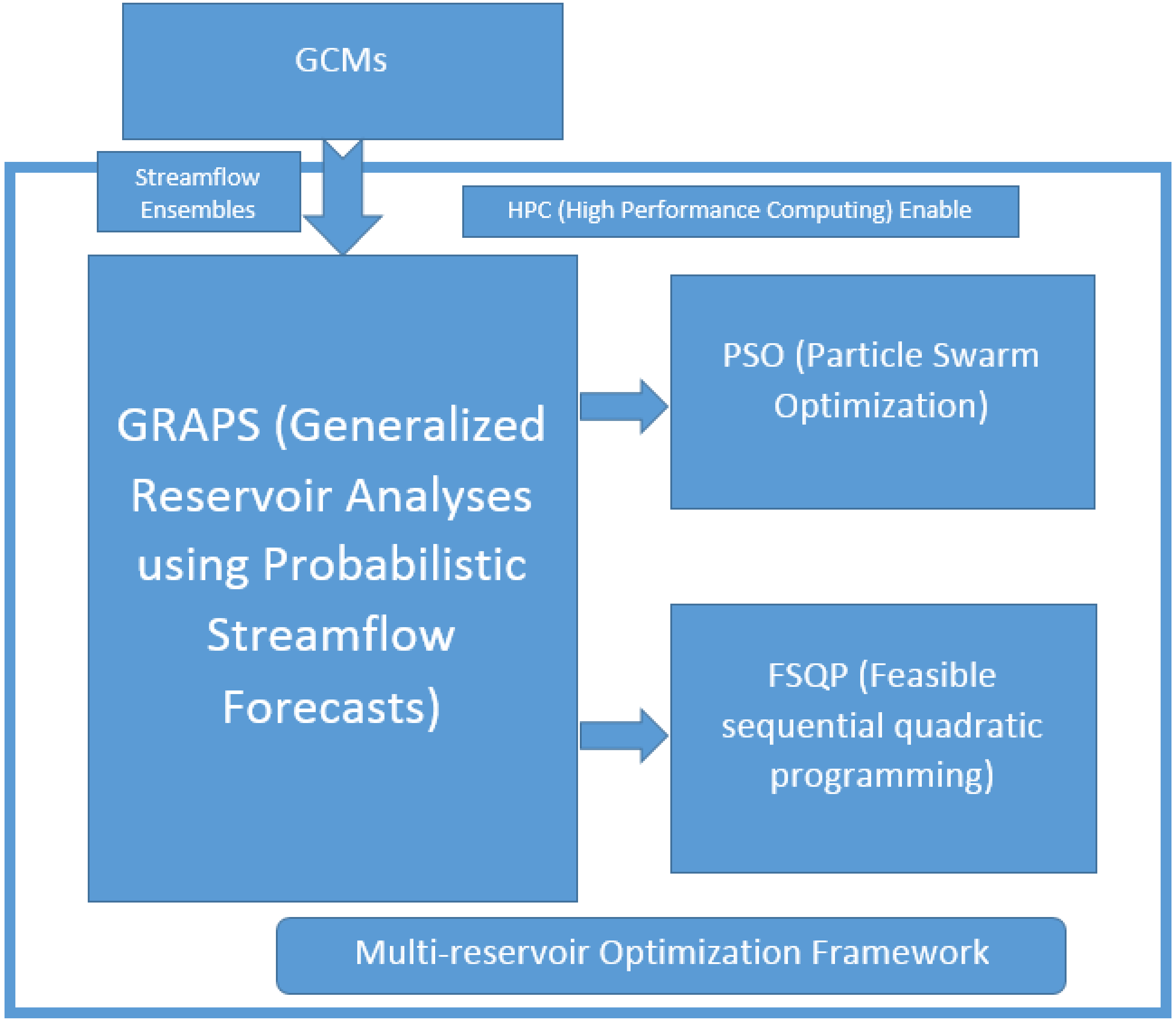


HPC Enable





speedup $S = \frac{T_{serial}}{T_{parallel}}$


GCMs
Streamflow Ensembles
HPC (High Performance Computing) Enable
GRAPS (Generalized Reservoir Analyses using Probabilistic Streamflow Forecasts)
PSO (Particle Swarm Optimization)
FSQP (Feasible sequential quadratic programming)
Multi-reservoir Optimization Framework

Study Area: Savannah River Basin

- Savannah River Basin Size by State:
- - 179 square miles in North Carolina
- - 4,530 square miles in South Carolina
- - 5,870 square miles in Georgia
- - 10,579 square miles total
- Cumulative Watershed/Basin Size:
- - Hartwell = 2,088 square miles
- - Russell = 2,890 square miles
- - Thurmond = 6,144 square miles

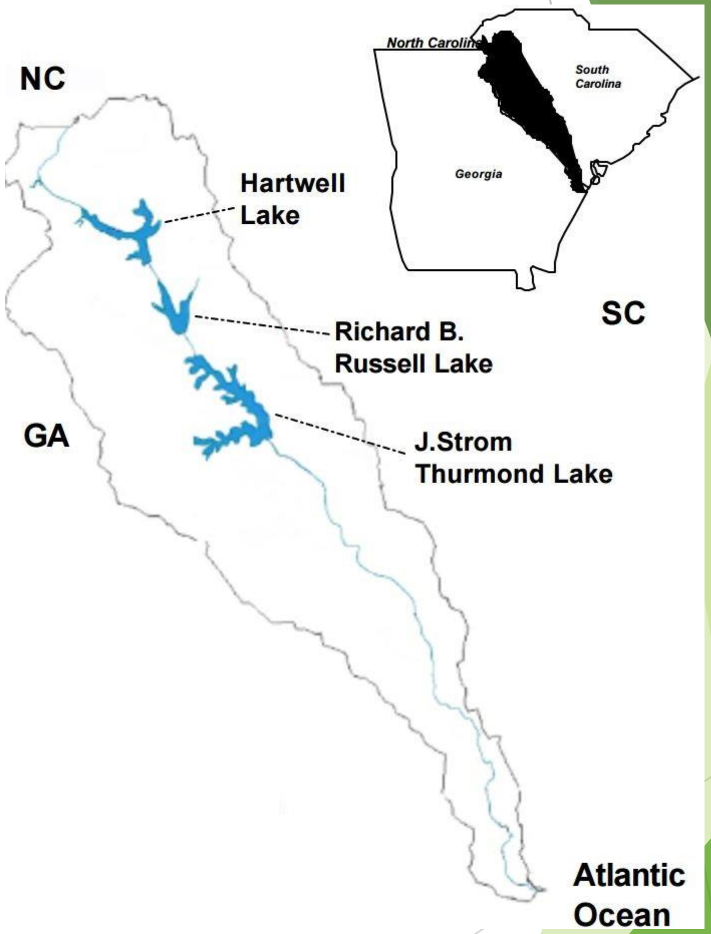
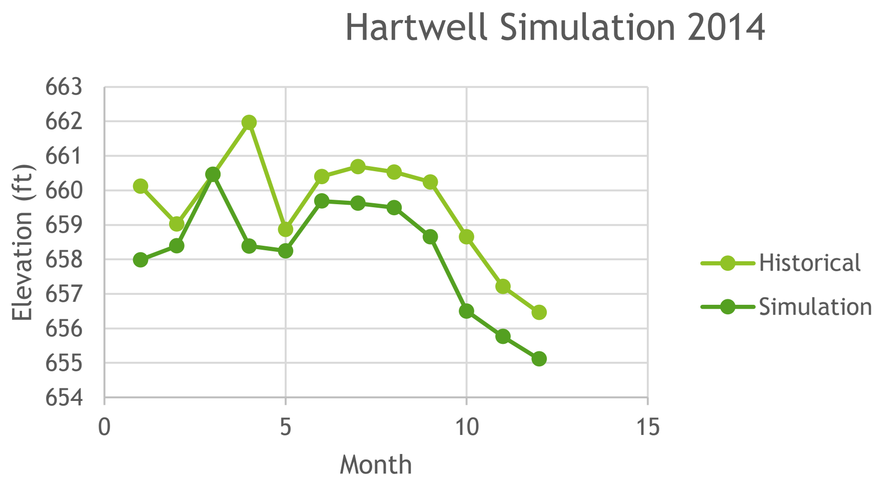
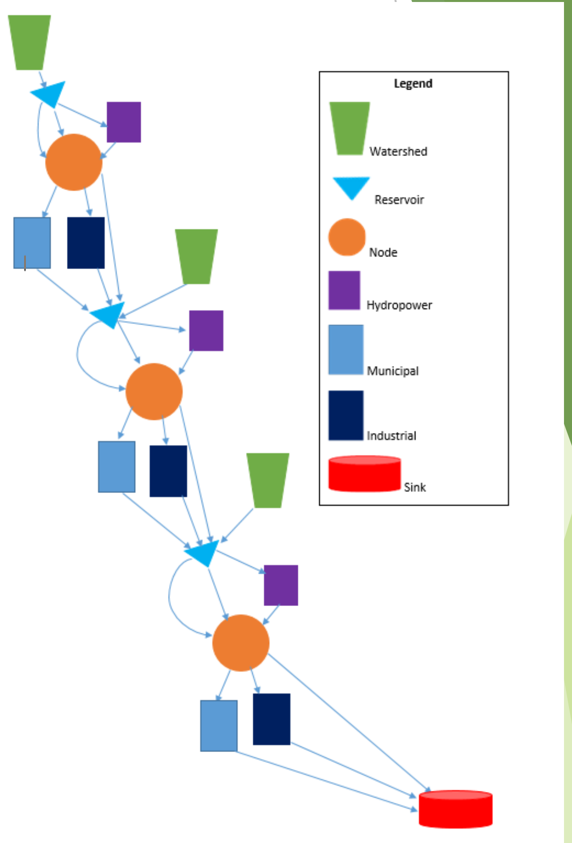


Image source : http://www.sas.usace.army.mil/Portals/61/docs/lakes/hartwell/PlanaVisit/LakeLevelMngt/DrainageBasins.pdf

Modeling and Simulation

- 1000 ensembles of streamflow for each reservoir
- 1 year, monthly time step
- 3 watersheds
- 3 reservoirs
- 9 users
  - Hydropower
  - Municipality
  - Industrial





Future Works

- User details
- GUI

Questions?

Anyone from Duke Energy or USACE?