# Lecture I

# Hydrological modeling requirements for Water Resources Applications - Model Calibration and parameter Estimation Issues


***Soroosh Sorooshian***

*Center for Hydrometeorology and Remote Sensing*

*University of California Irvine*


***The Abdus Salam ICTP Workshop on:***

***Water Resources in Developing Countries - Planning and Management in a Climate Change Scenario***

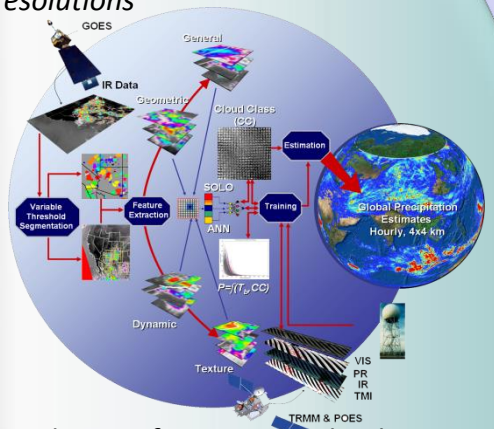
***Trieste, Italy: May 6th – 17th 2013***

# University of California Irvine (UCI) Past

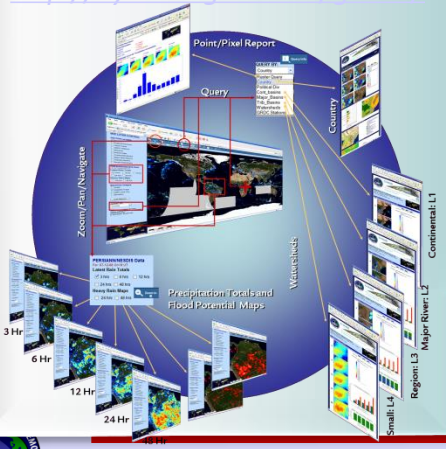
***and many more …***

# Center for Hydrometeorology and Remote Sensing

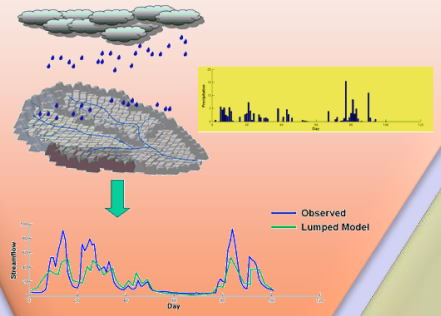
*Develop state-of-the-art systems to estimate rainfall from satellite observations at global scale and high spatial and temporal resolutions*




*Utilizing Information Technology to provide world-wide access to real-time global precipitation products:*
http://hydis.eng.uci.edu/gwadi/




*Improve the performance and reliability of hydrologic, flood, and water supply forecasting models, particularly those used by the National Weather Service and other operational agencies.*





*Improve California's water supply management through:*

- *Forecast system (CaliForecast)*
- *Improved decision optimization*


*Nearly 70% of our supply is in Northern half*

*Almost 75% of our demand is in the Southern half*

*Prepare the next generation of hydrologists and water resources engineers*

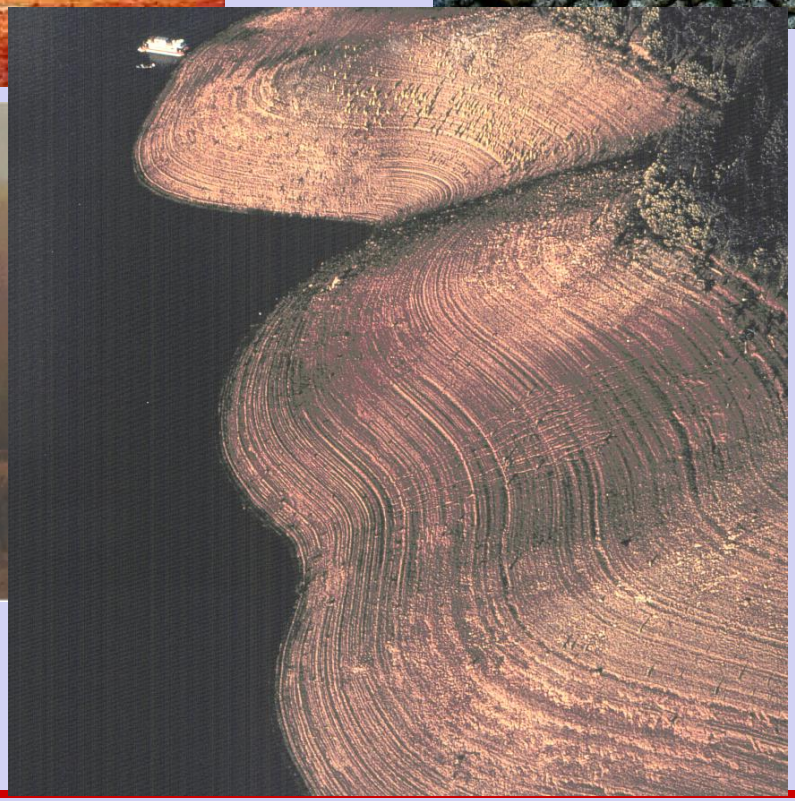

# Two Primary Water Resources/Hydrology Challenges:

- ***Hydrologic Hazards ( Floods and Droughts)***

- ***Water Supply Requirements ( Quantity and Quality)***

# Hydrologic Forecasting Needs: Flash Floods

# Droughts: The Other hydrologic Extreme



SAHRA

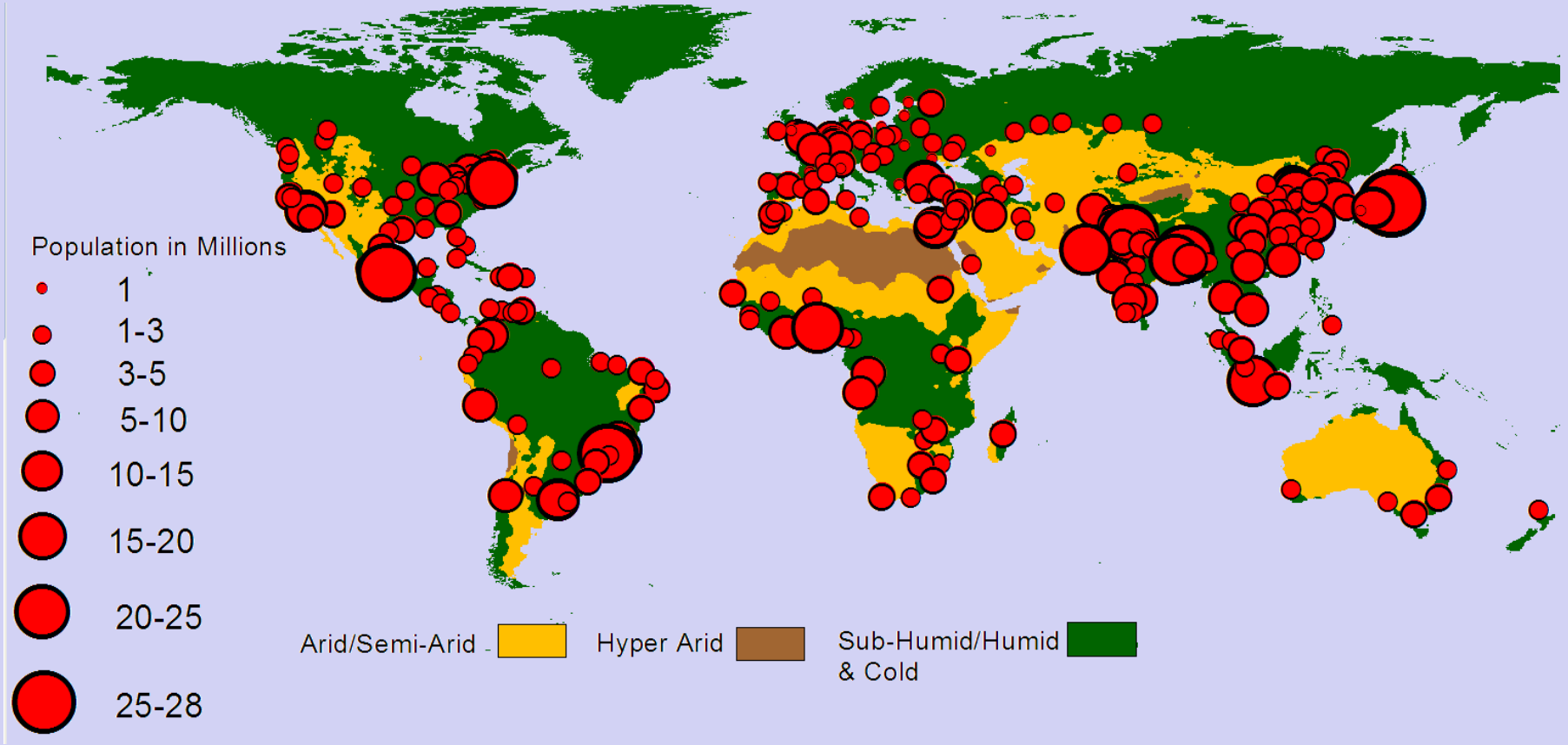

# Two Primary Water Resources/Hydrology Challenges:

- ***Hydrologic Hazards ( Floods and Droughts)***

- ***Water Supply Requirements ( Quantity and Quality)***

# Increasing Population: Number of Mega Cities

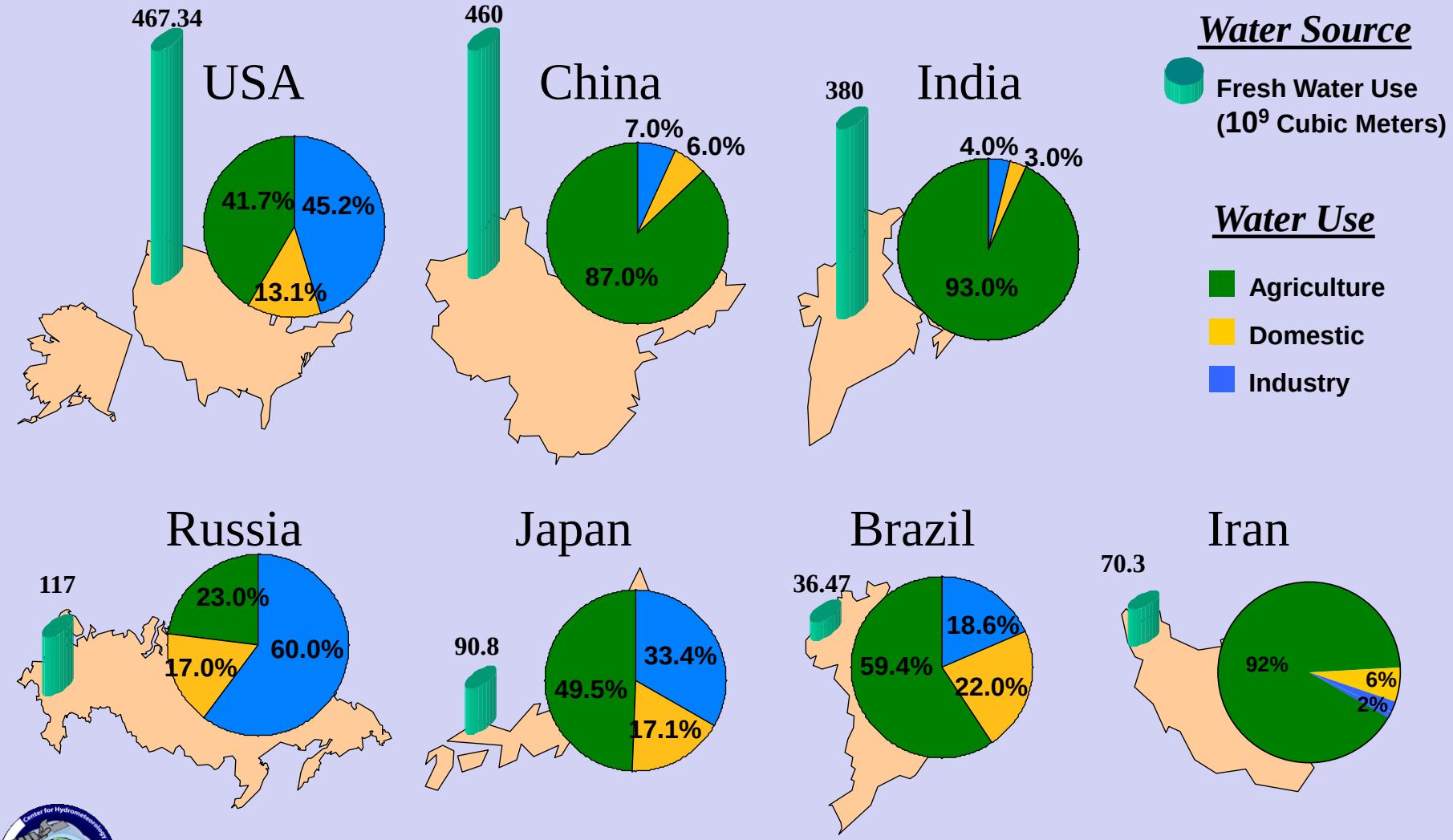
**Projected Global Population: 8.3 Billion by 2025**




***Global Urban population 1970: ~37%***

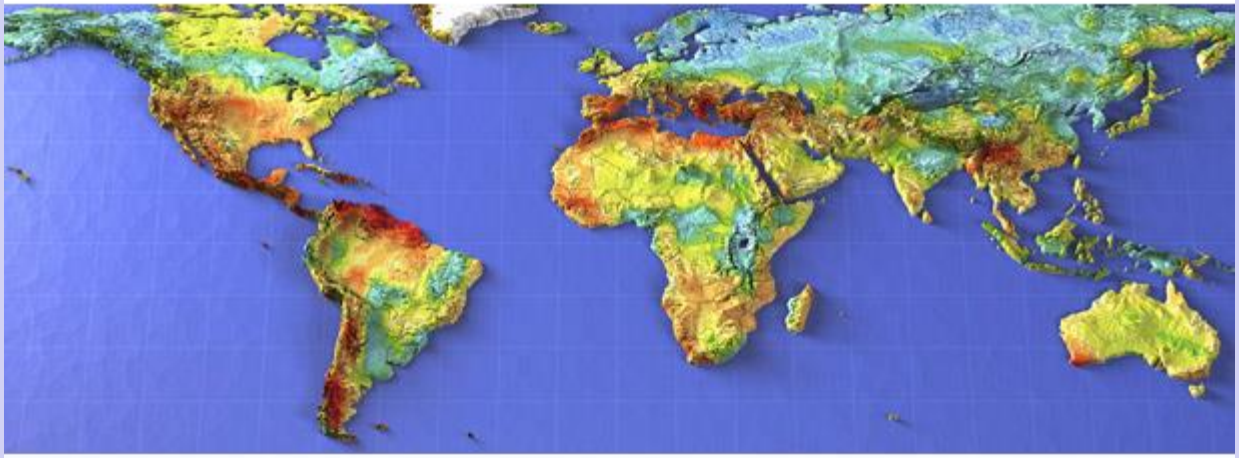
***2010: ~53%***

# Distribution of Fresh Water Use



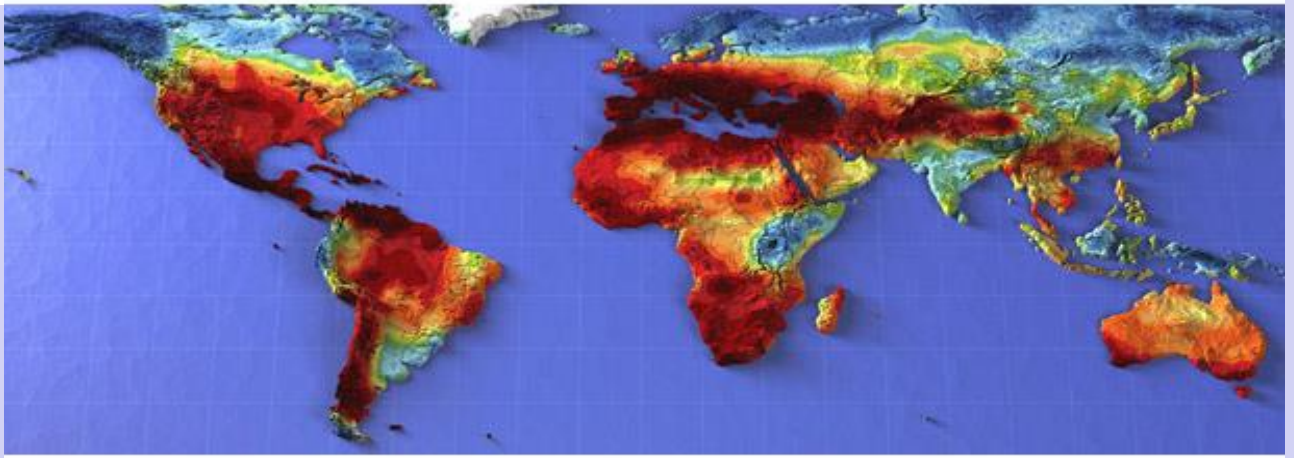
# *Global Climate: Past Decade and Prediction of End of 21st Centaury*

2000-2009



DRY COND

2090-2099



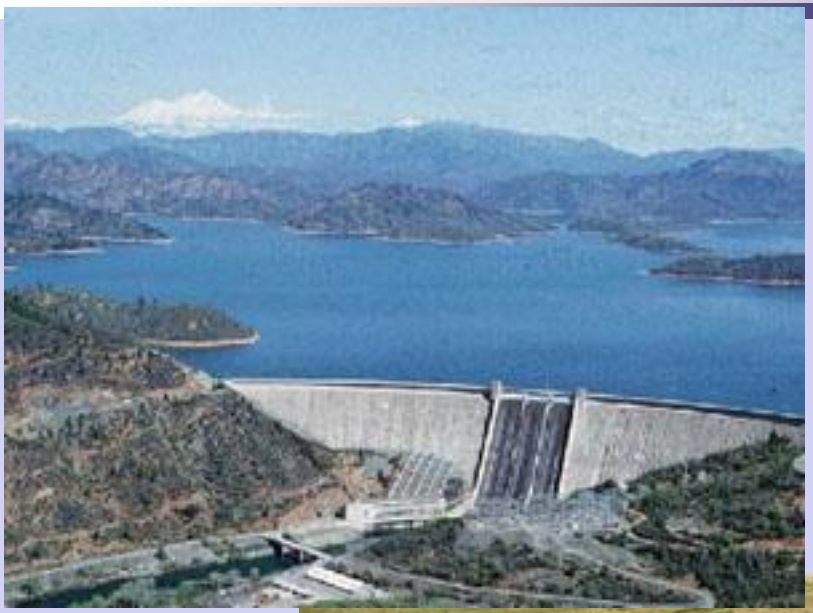
DRY CONDITION WET


# *Primary Solution To Meet Hydrologic Extremes and Water Resources Needs*

## *Engineering Approach:*

## *Control, Store, Pump and Transfer*

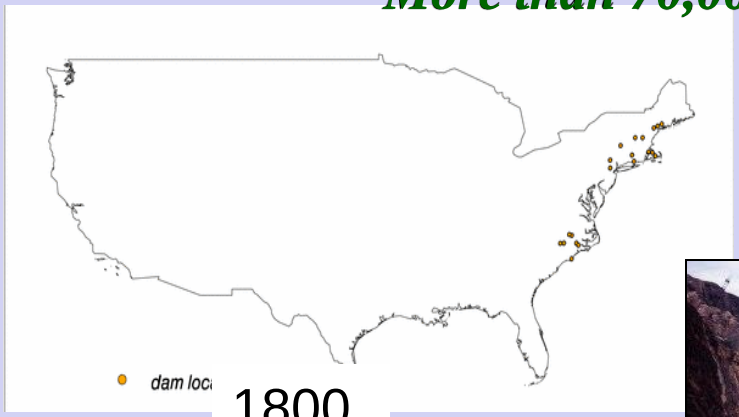
# A Century of Water Resources Development: Engineering success



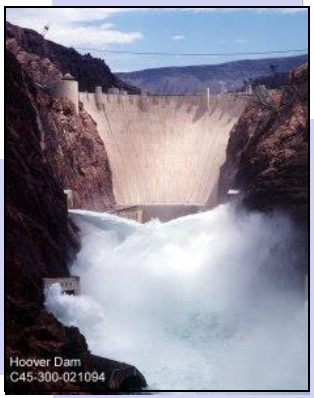
t Aqueduct

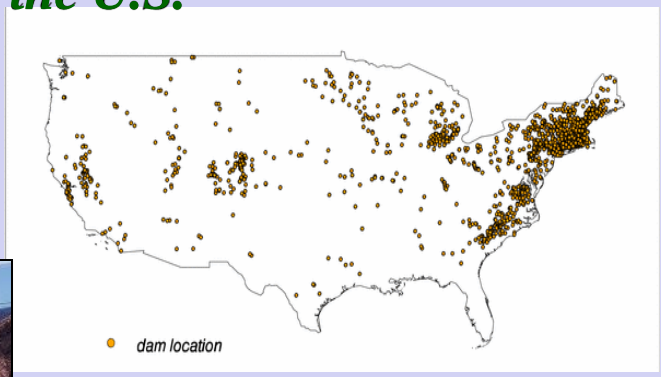
# Impact on Design and Operation of Global Infrastructure

## More than 70,000 Dams in the U.S.

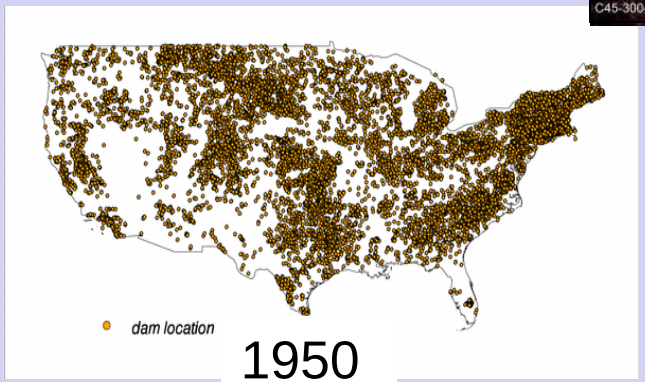



1800

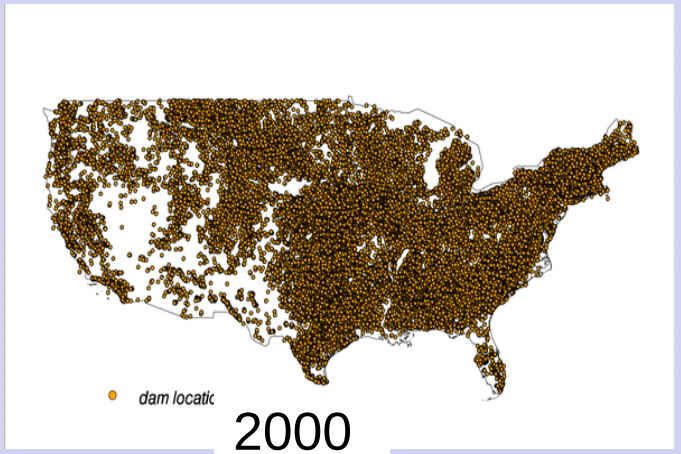



1900




1950



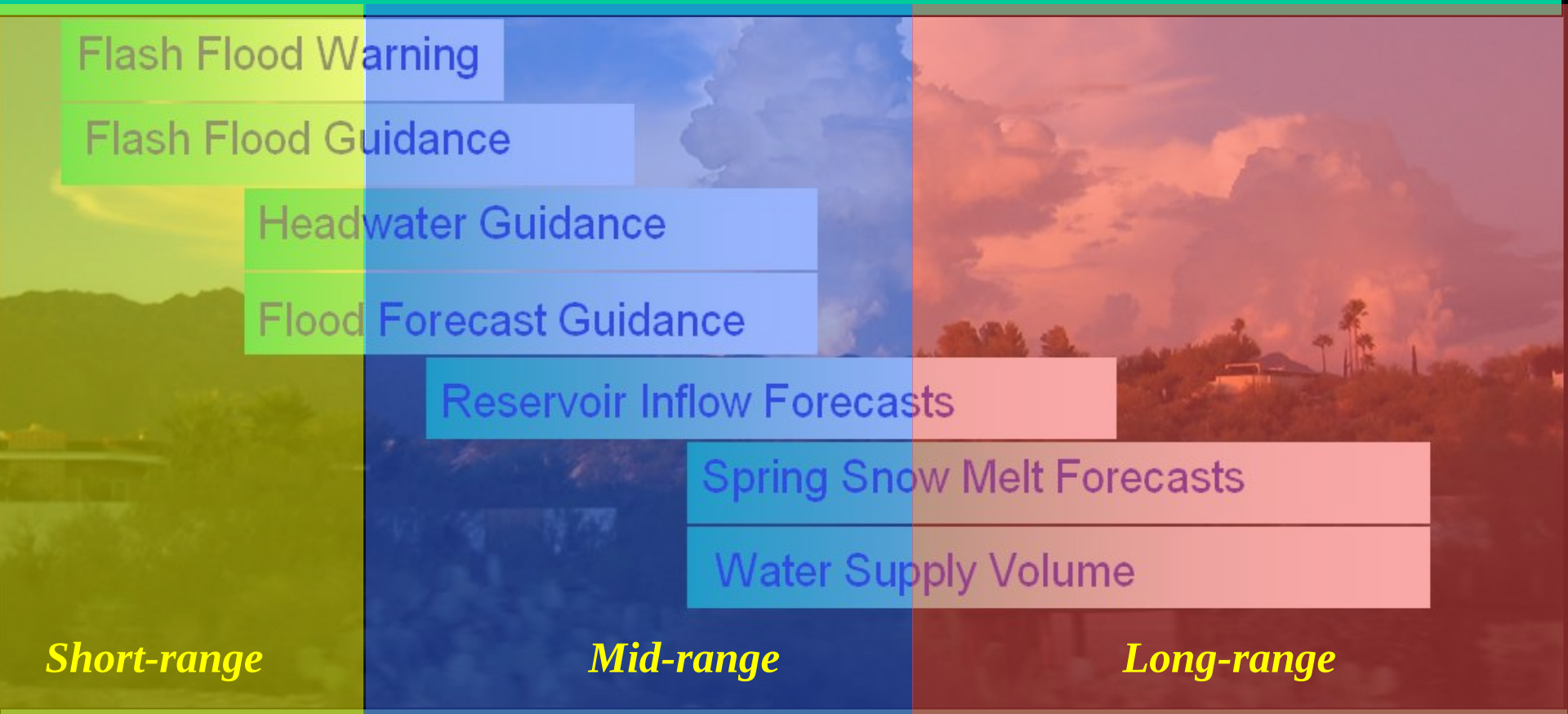

2000

**Provided by: C. J. Vörösmarty**

# Required Hydrometeorologic Predictions

**Short Range → Long Range**

**hours → days → weeks → months → seasons → years → decades**

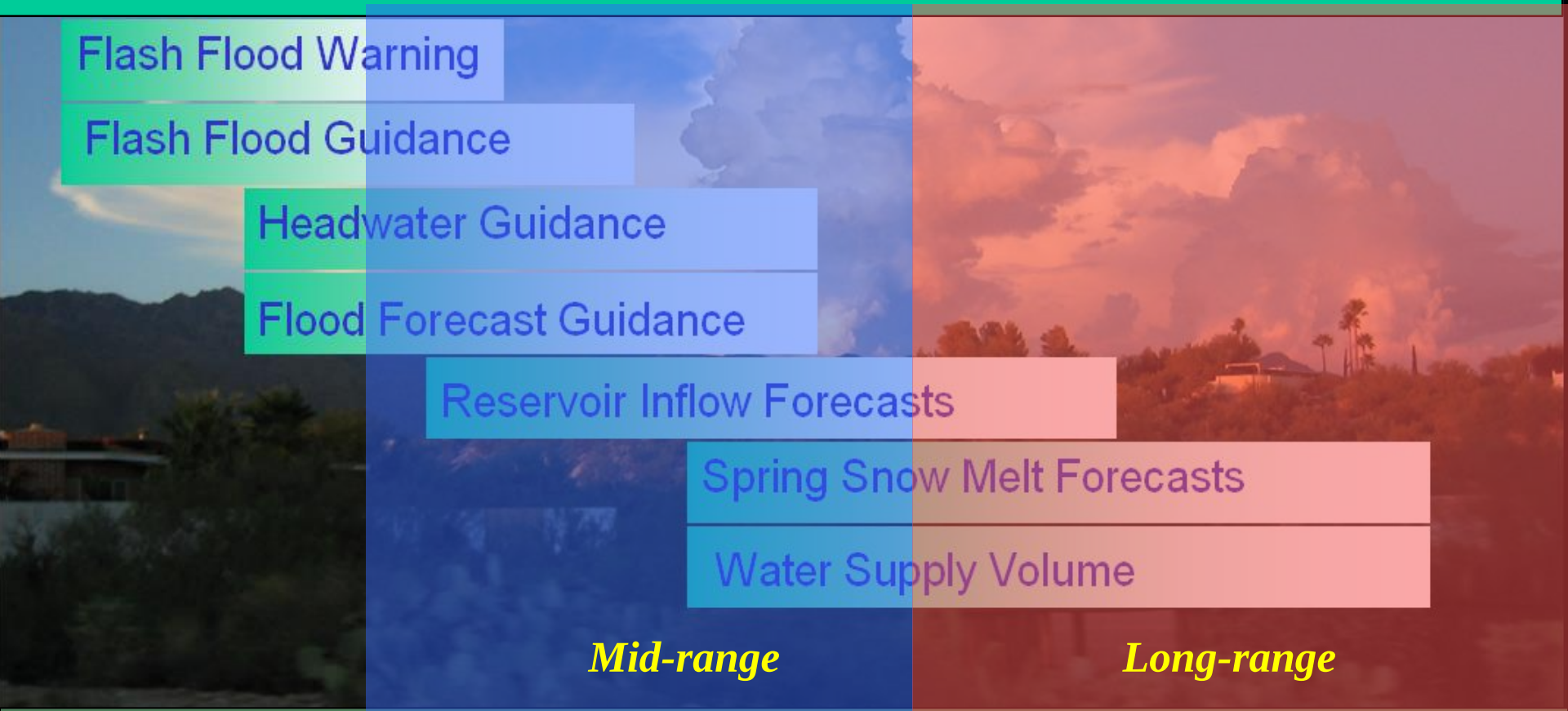



*Forecast Requirements*

# Required Hydrometeorologic Predictions

**Short Range** ← · — · — · — · — · — · — · — · — · — · — · — · — · — → **Long Range**

**hours** ----→ **days** ----→ **weeks** ---→ **months** --→ **seasons** --→ **years** ------→ **decades**

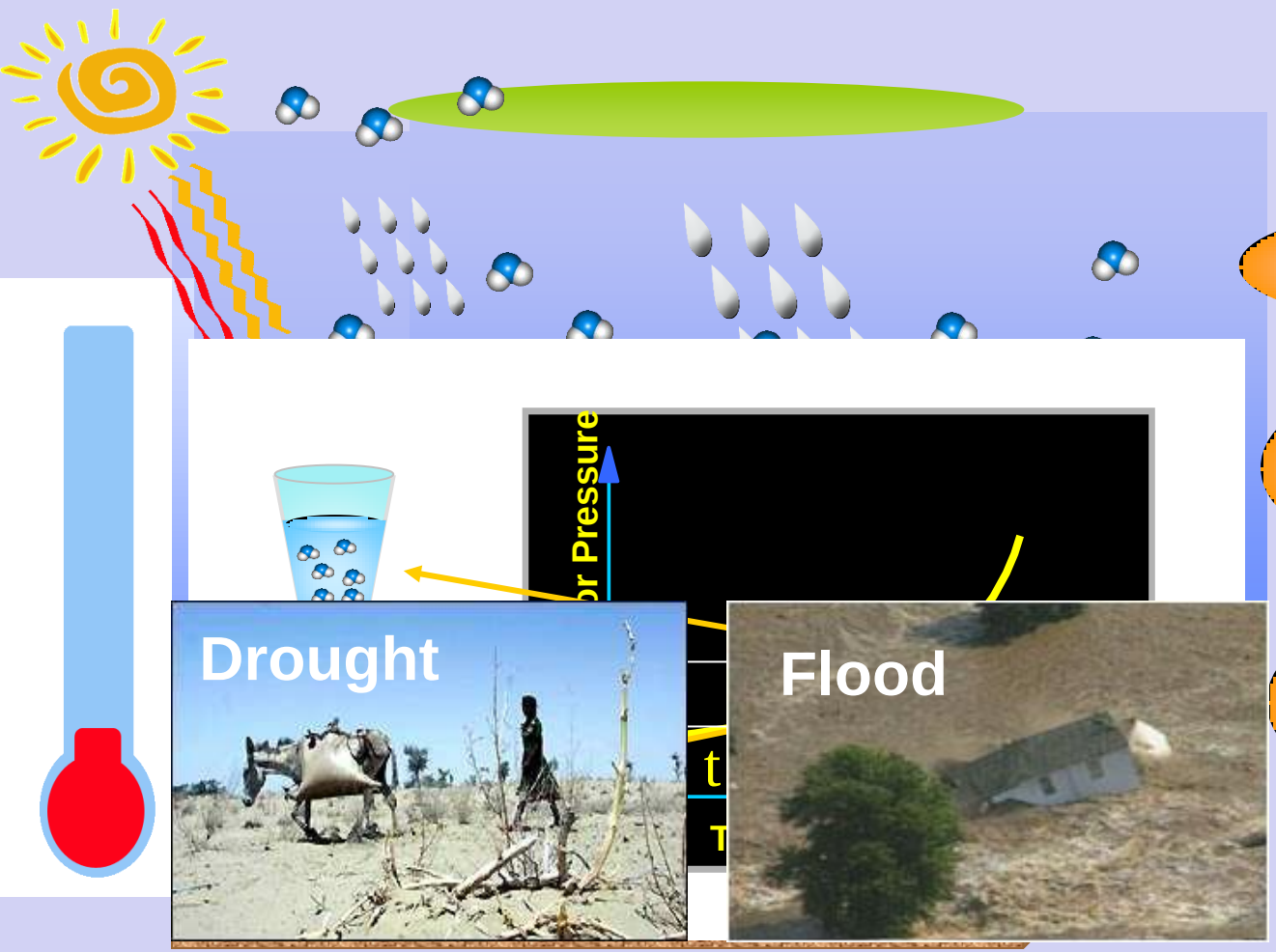


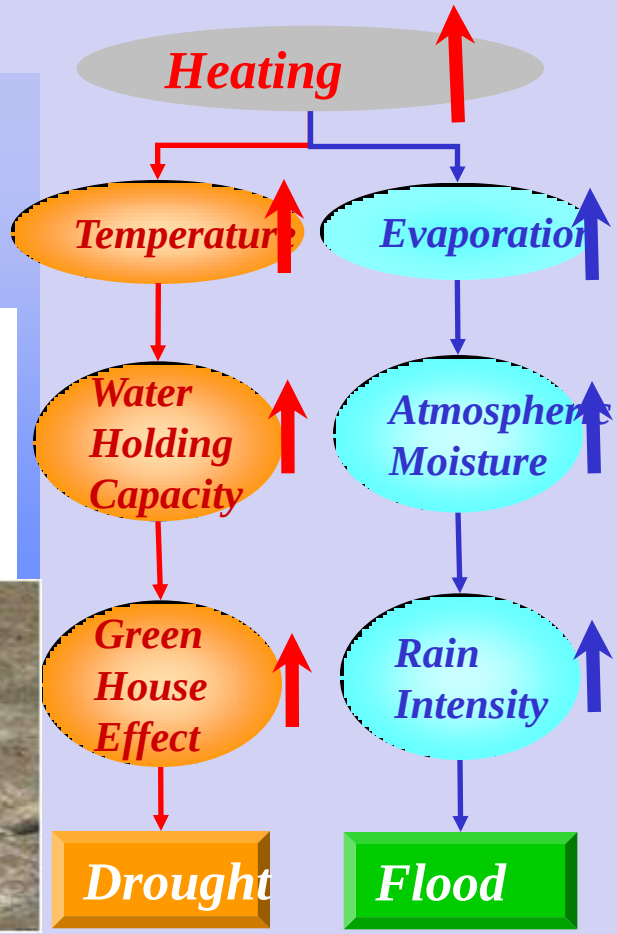

*Forecast Requirements*

# *A Key Consideration:*

# *The Link Between Climate and Hydrology*

# Global Warming And Hydrologic Cycle Connection

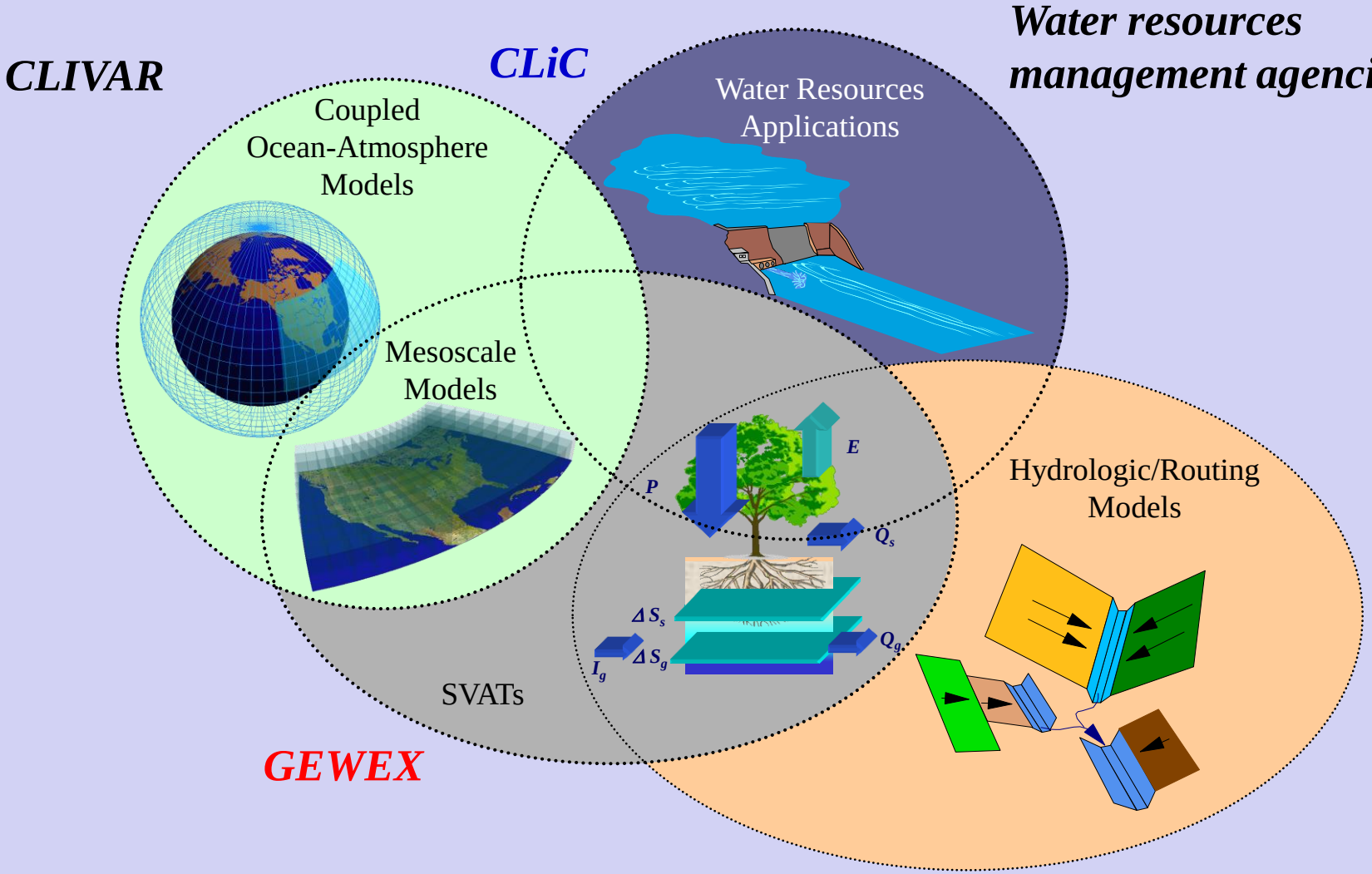



*Created by: Gi-Hyeon Park*

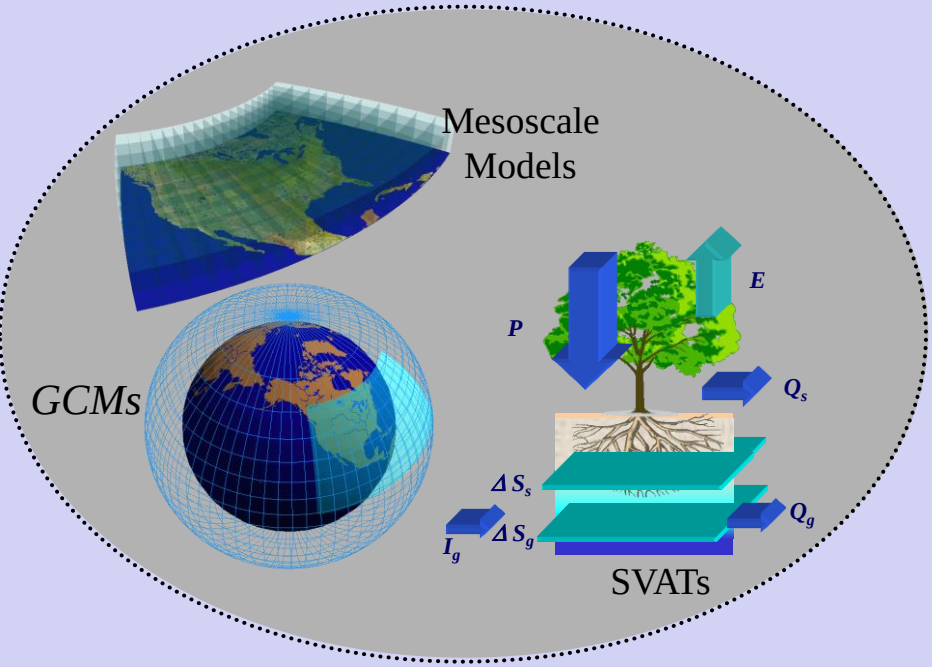
*Center for Hydrometeorology and Remote Sensing, University of California, Irvine*

# From the Global- to Watershed-Scale

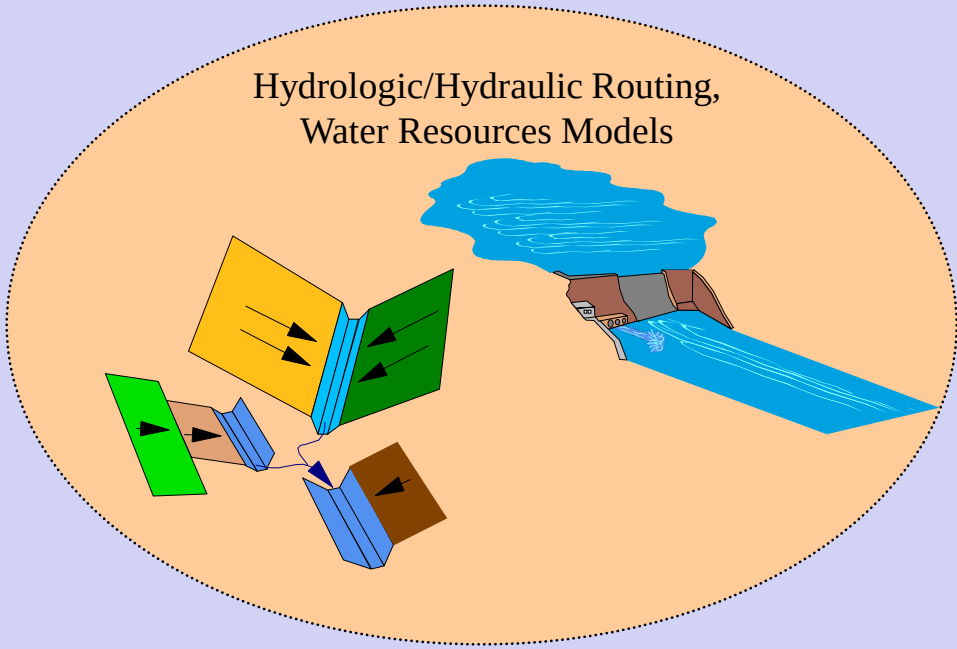


# Hydroclimate Science and Hydrologic/Water Resources Engineering

## SCIENCE




## ENGINEERING




***Hydroclimate Science***

***Hydrologic/Hydraulic and Water Resources Engineering***

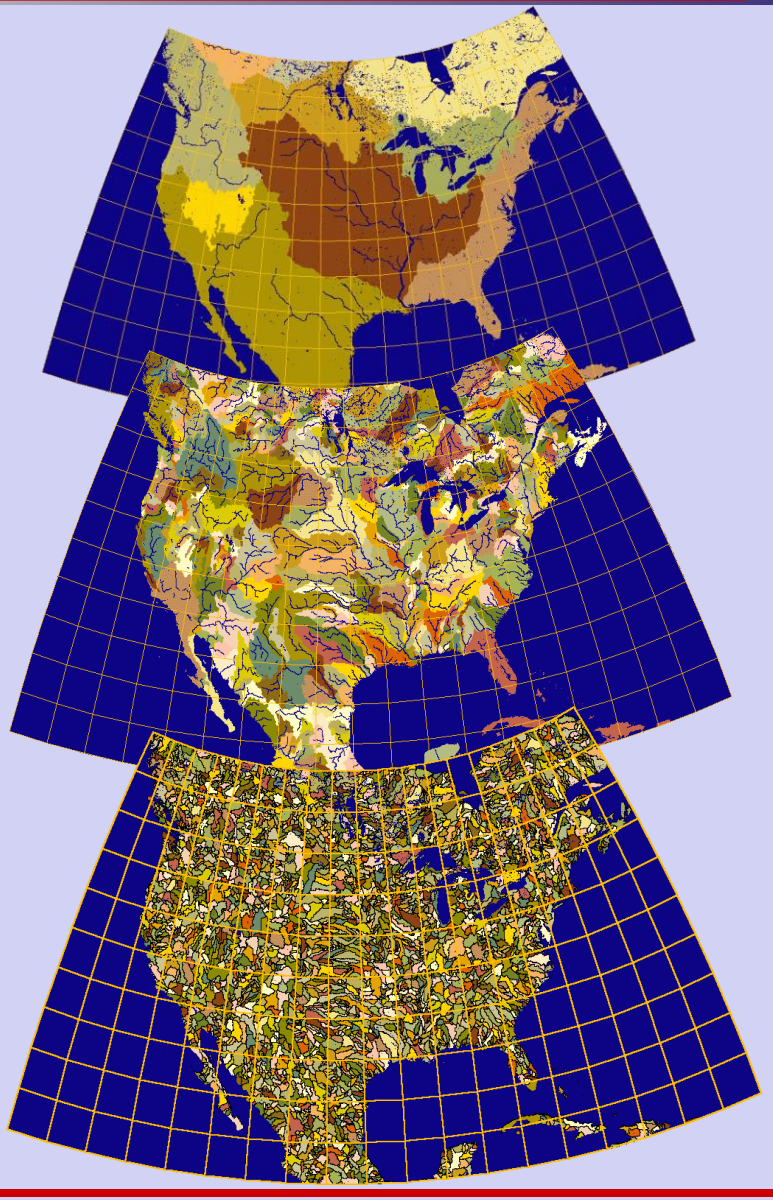
# River Basins and Watersheds

*Continental Scale:*

*Different Scales*
*Different Issues*

*Watershed Scale:*

*Where hydrology happens*
*Where stakeholders exist*



# *Climate-Scale approaches to addressing hydrologic extremes*

**Short Range → Long Range**

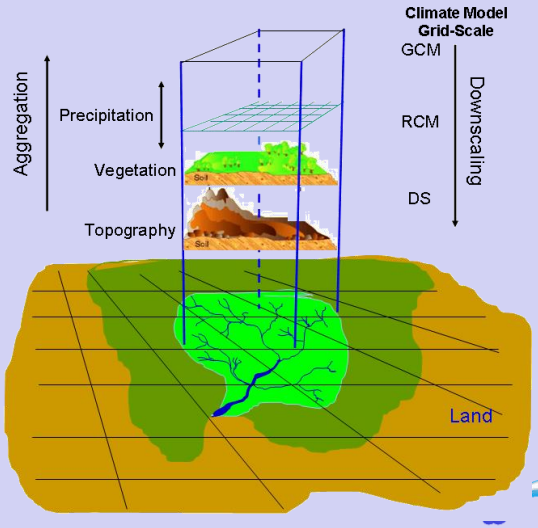
**hours → days → weeks → months → seasons → years → decades**

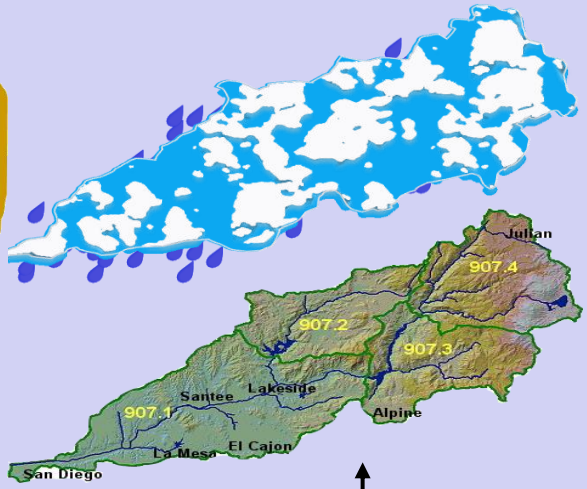
- ***Use of climate models: down-scaling and ensemble schemes***

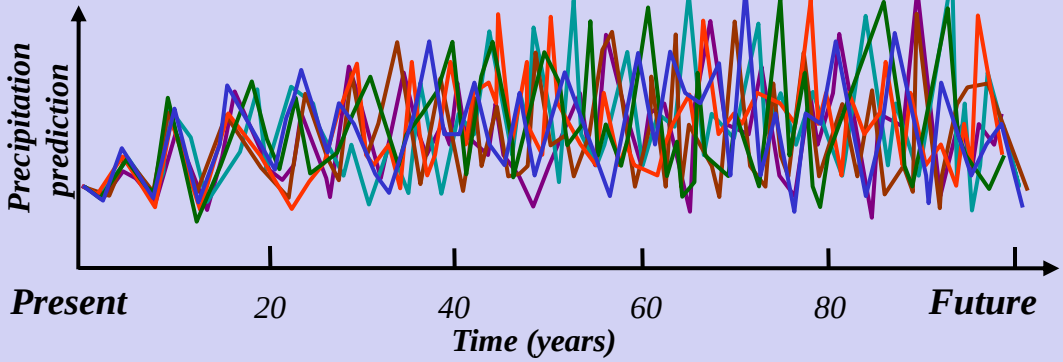
- ***Traditional statistical hydrology methods:***

# Climate Model Downscaling to Regional/Watershed Scales

## Generation of Future Precipitation Scenarios

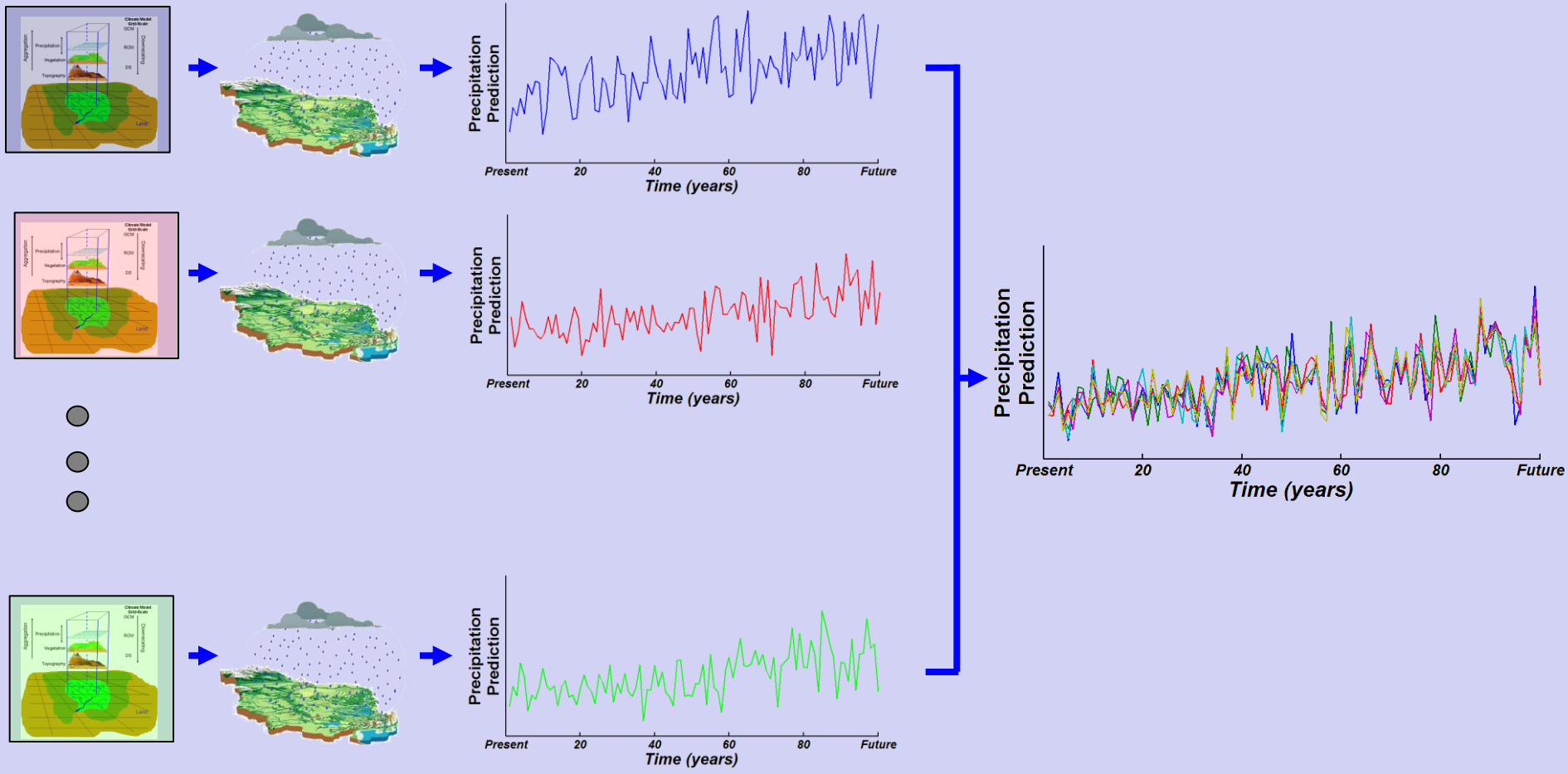


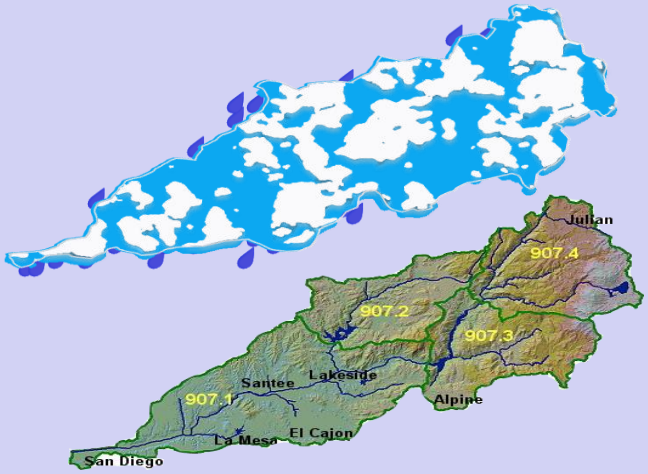
# Ensemble Approach

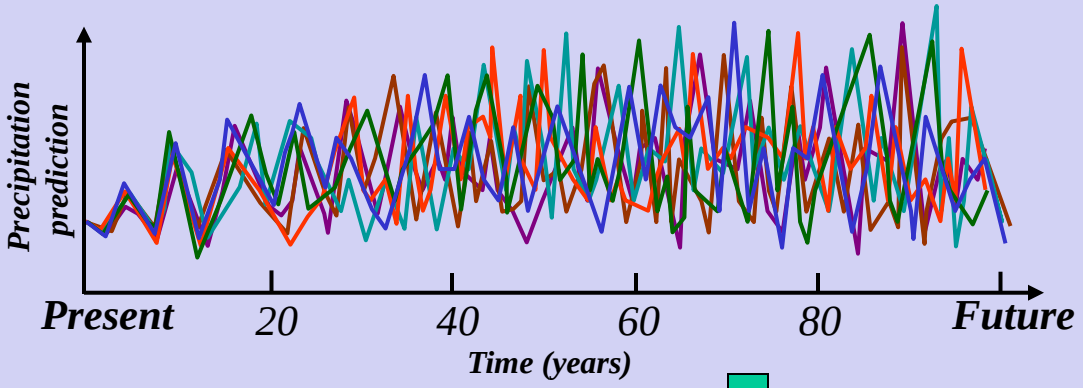
## Generation of Future Precipitation Scenarios

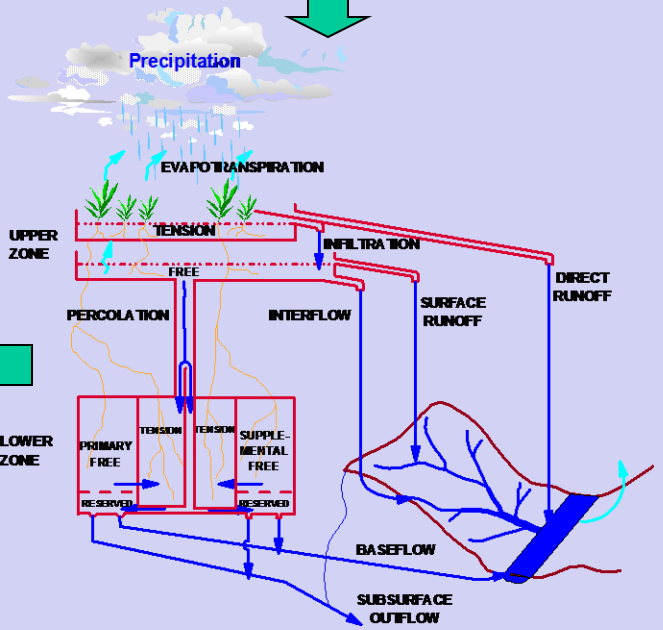


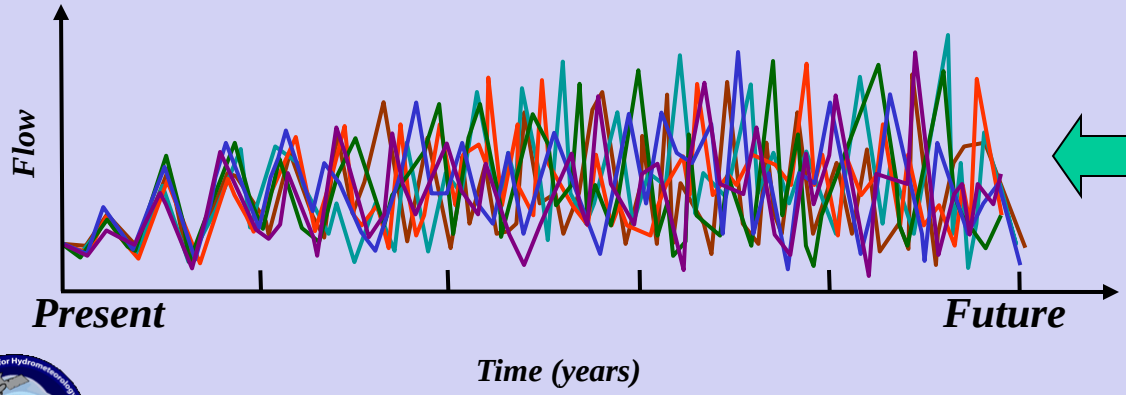
# Downscaled Precipitation to Runoff Generation

## Generation of Future Runoff Scenarios

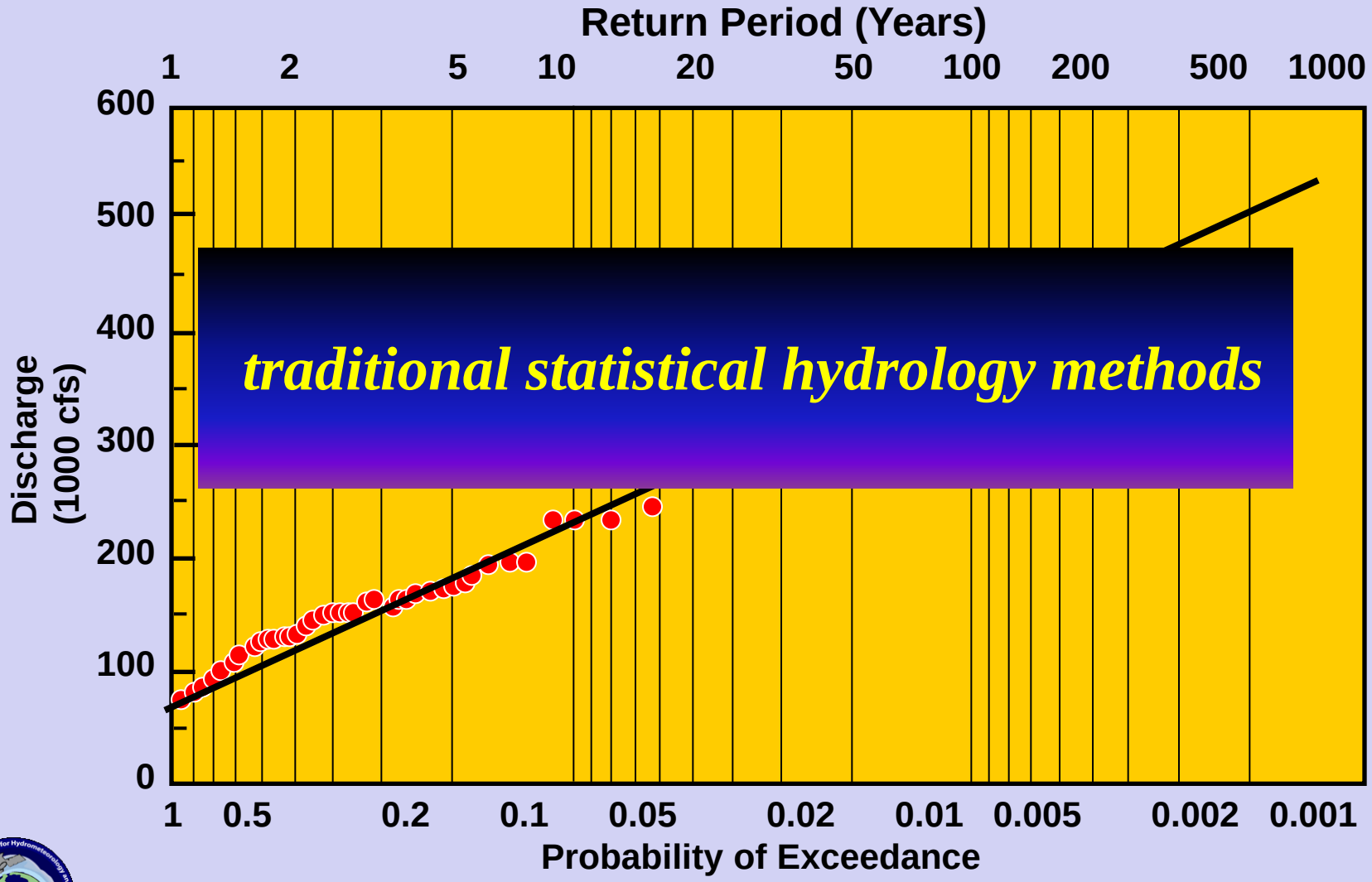


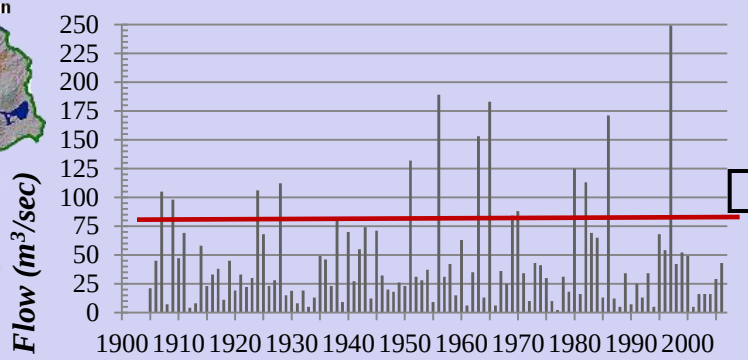



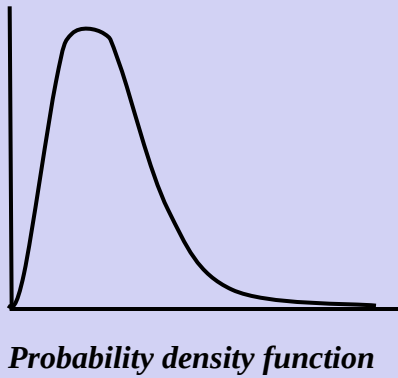



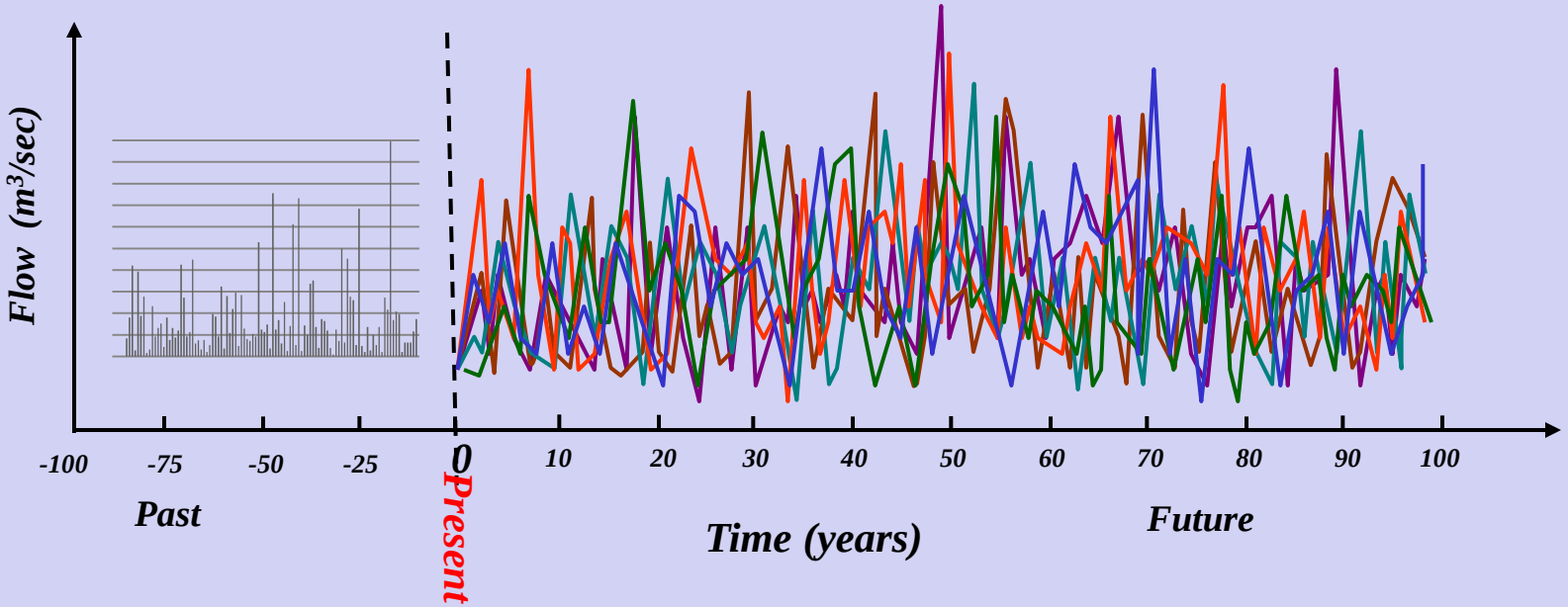
# Alternative Approach to Climate Model Downscaling



# Statistical Hydrology: "synthetic" stream flow Generation

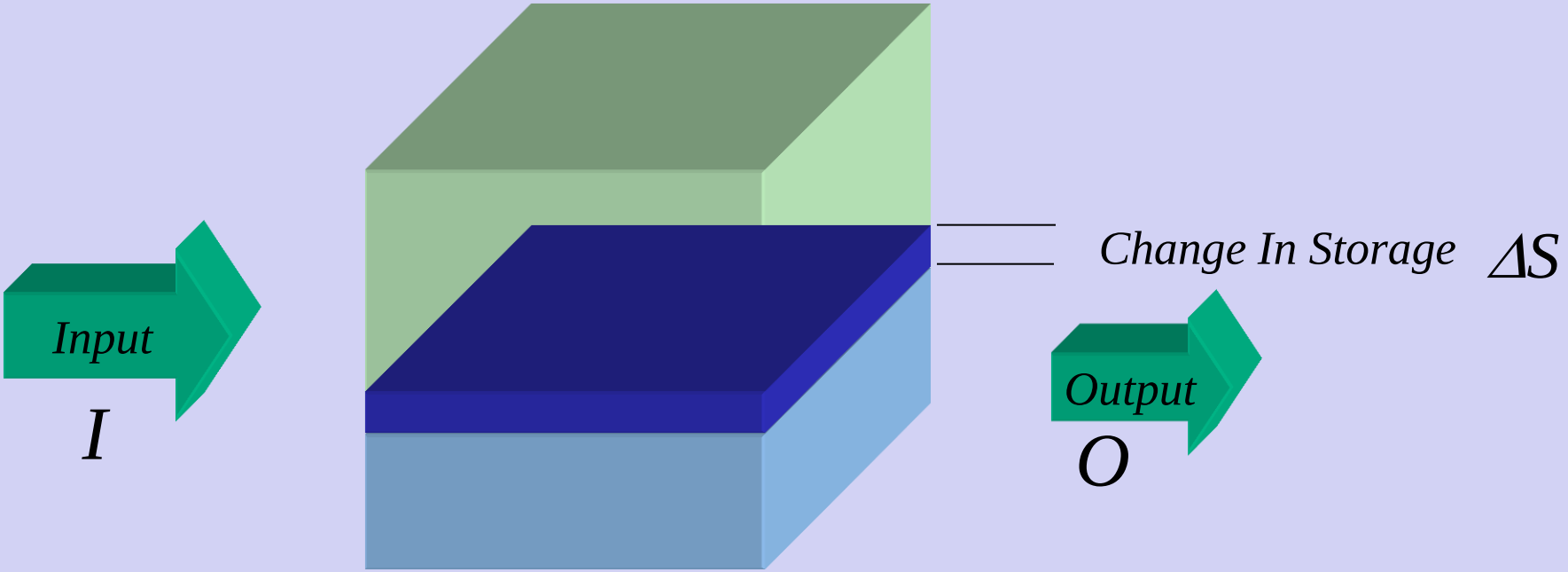



# *Brief Review of Rainfall Runoff modeling:*

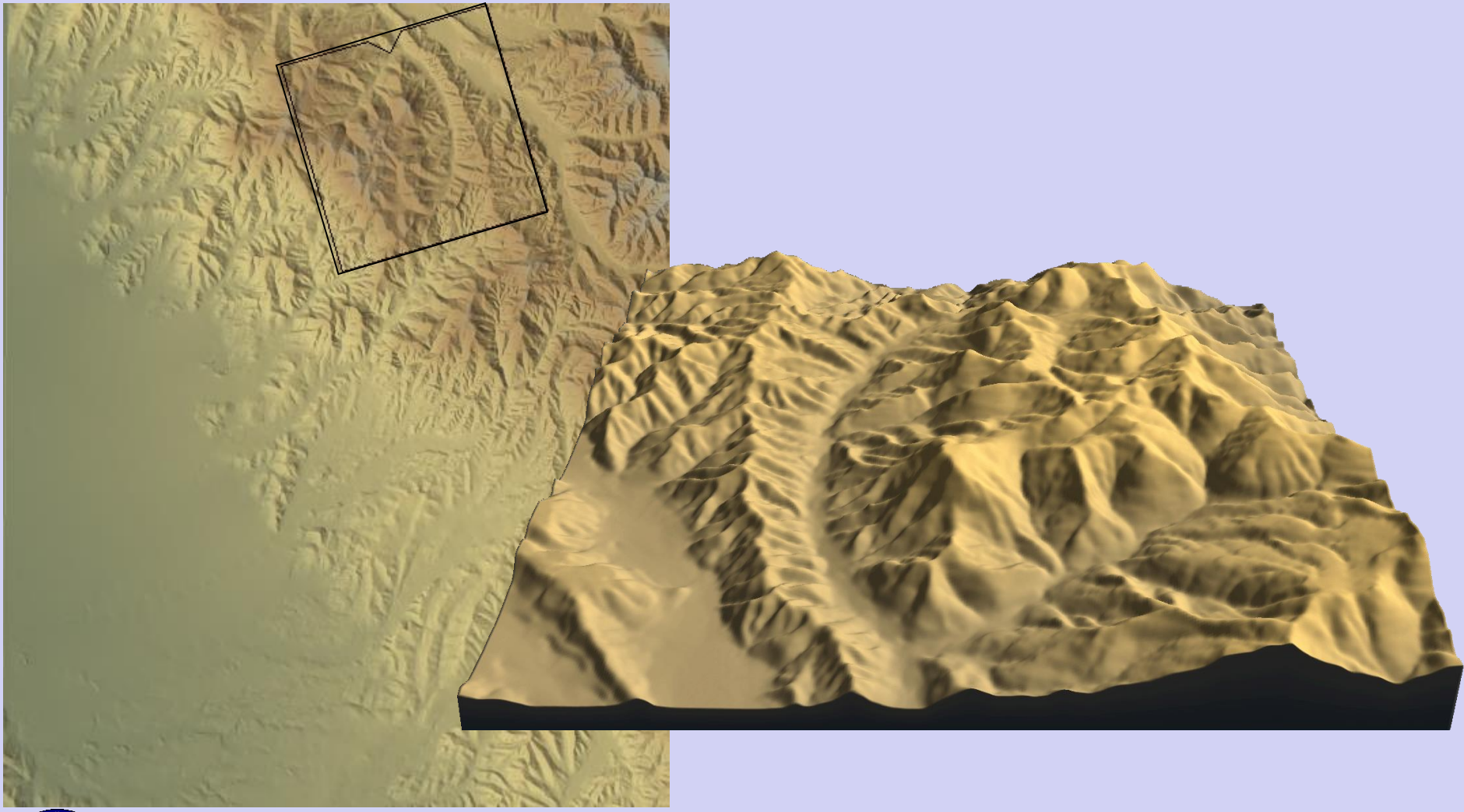
# *Progress in Hydrologic Modeling*

# Fundamental Law



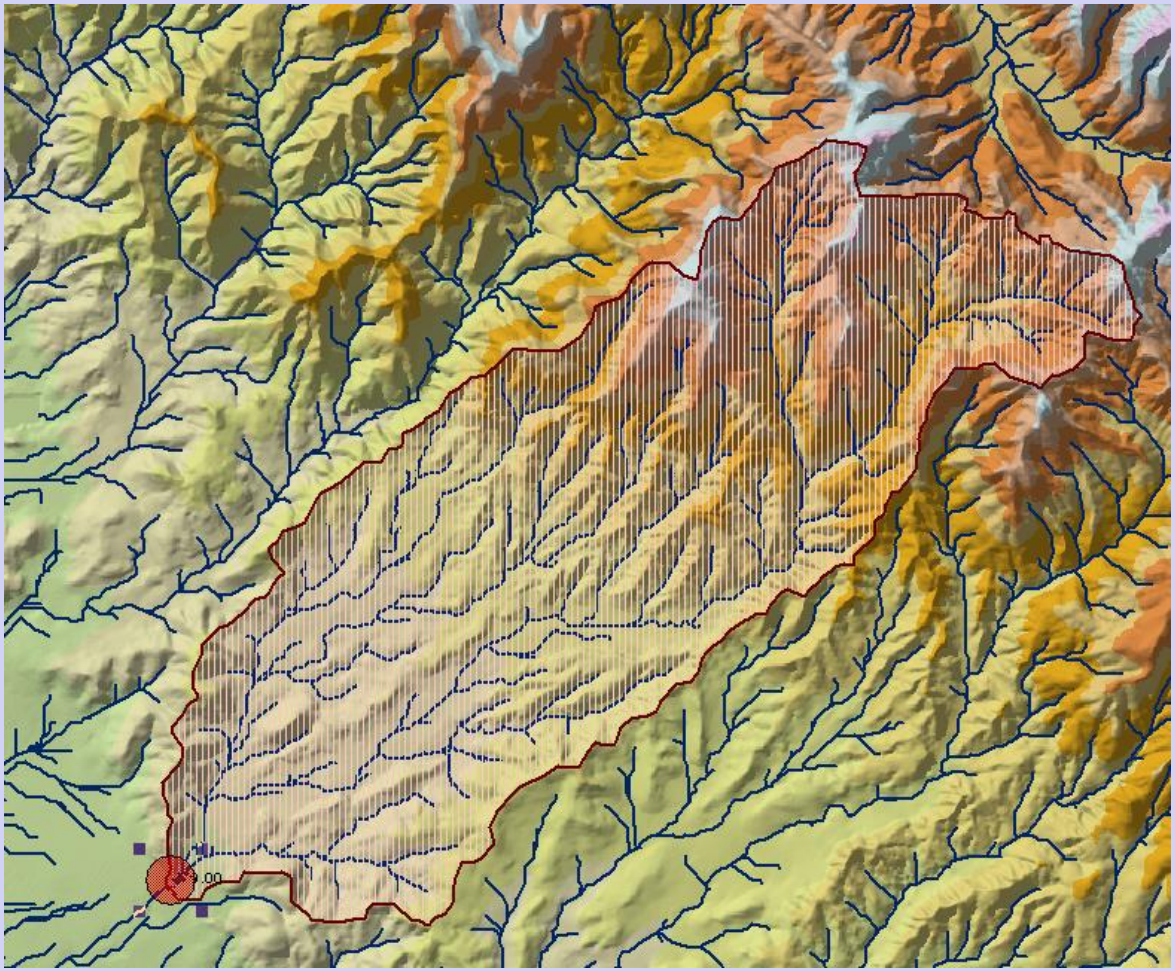

$$I - O = \Delta S$$

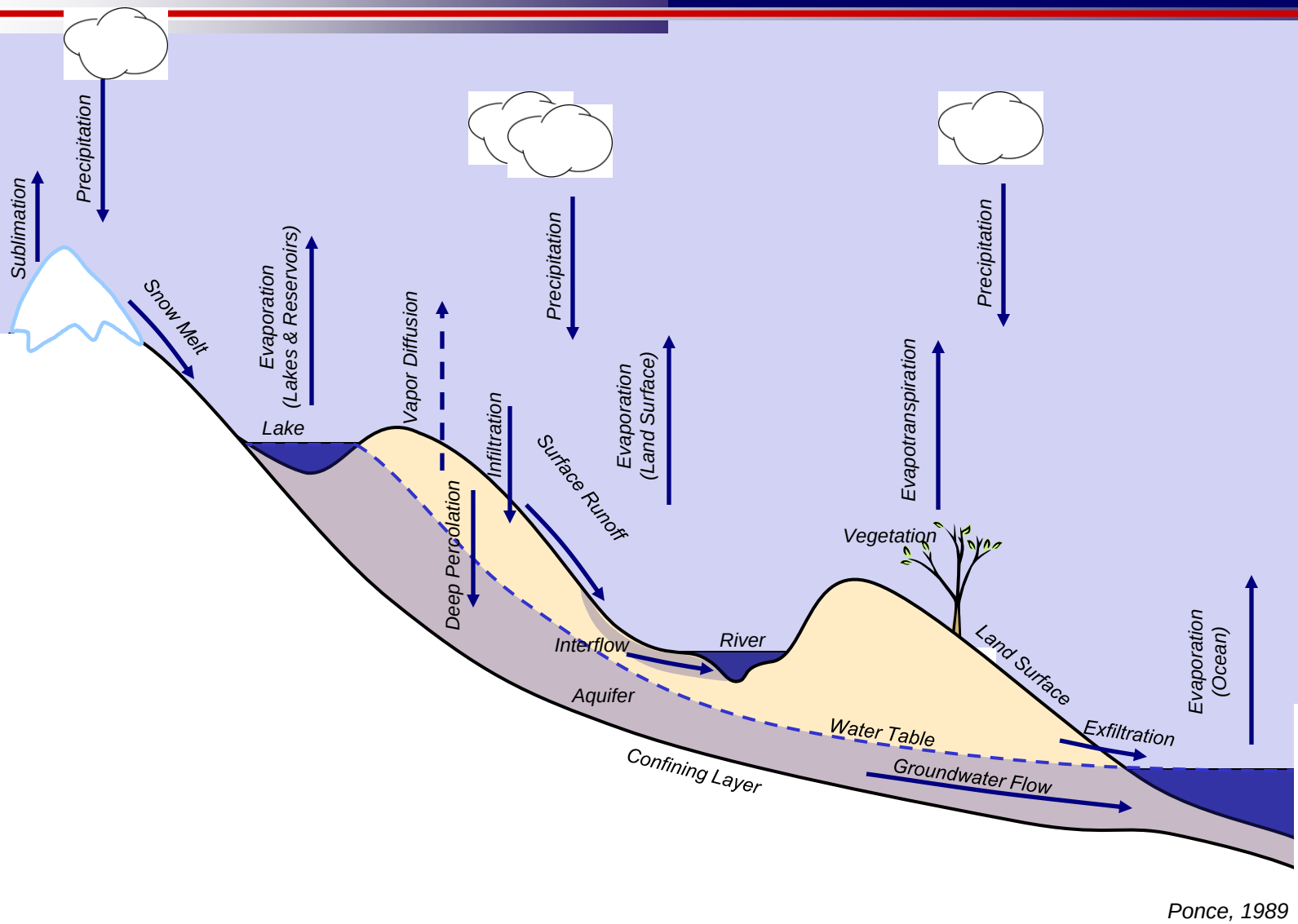
# *Nature's Way → Terrain*



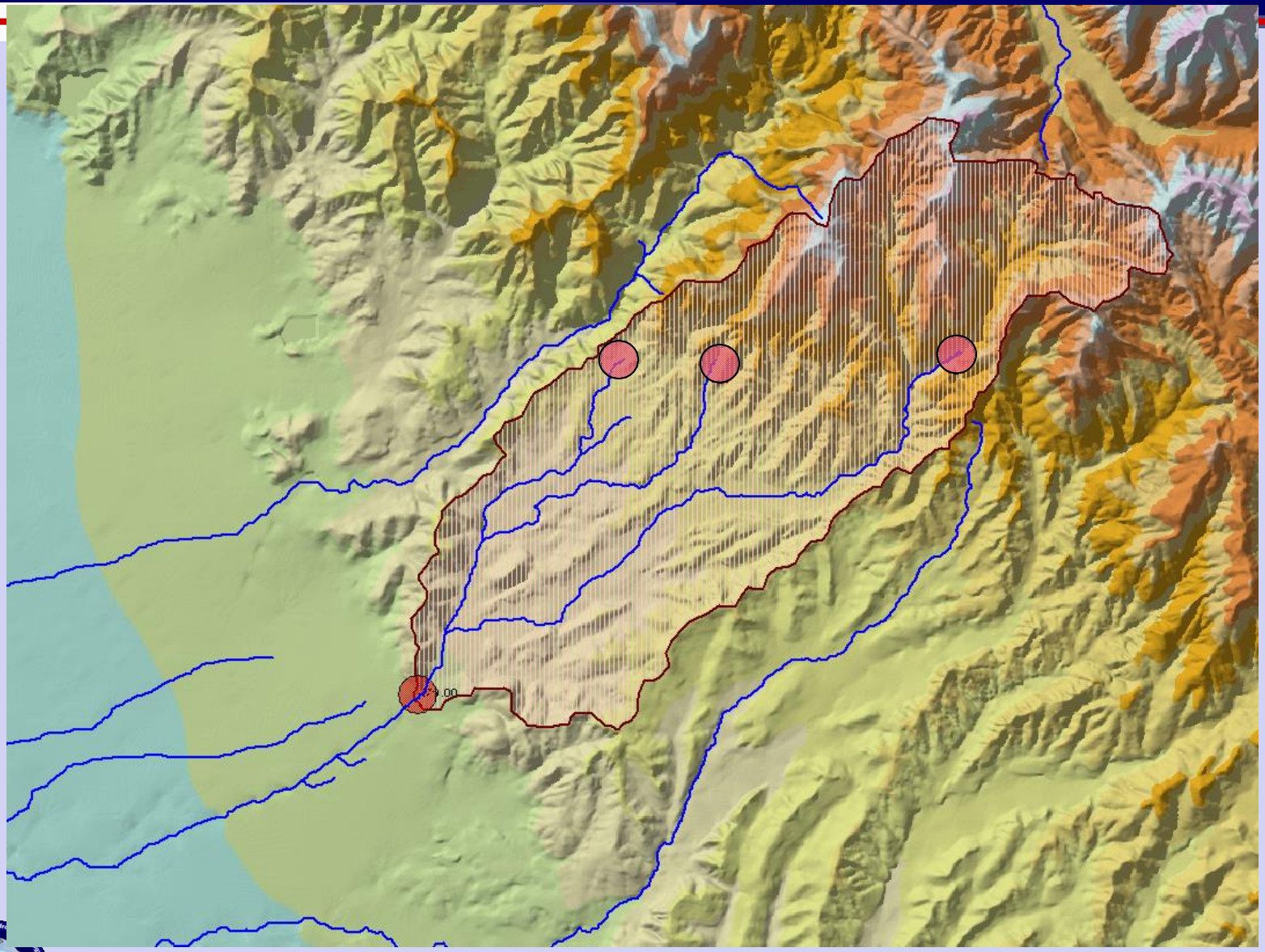
# The Watershed

| | |
|---|---|
| Area km2 | 12.78 |
| Perimeter km | 19.344 |
| Min Elevation m | 478.00 |
| Max Elevation m | 1756.00 |
| Mean Elevation | 930.34 |
| Max Flow Length | 8.878 |

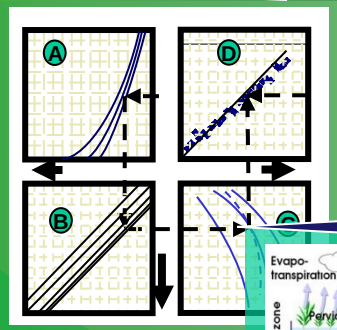



Precipitation
Sublimation
Snow Melt
Evaporation (Lakes & Reservoirs)
Lake
Vapor Diffusion
Infiltration
Deep Percolation
Surface Runoff
Precipitation
Evaporation (Land Surface)
Evapotranspiration
Vegetation
Precipitation
Interflow
River
Land Surface
Evaporation (Ocean)
Aquifer
Water Table
Exfiltration
Confining Layer
Groundwater Flow
Ponce, 1989

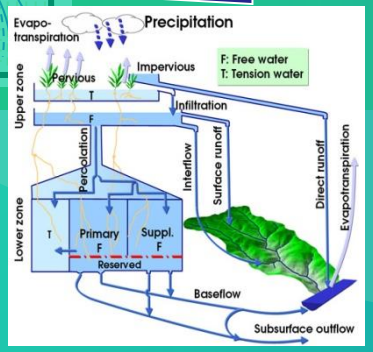
# *Trace The Water Drop*



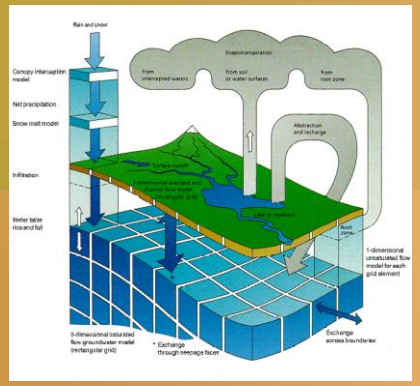
# Evolution of Hydrologic R-R Models



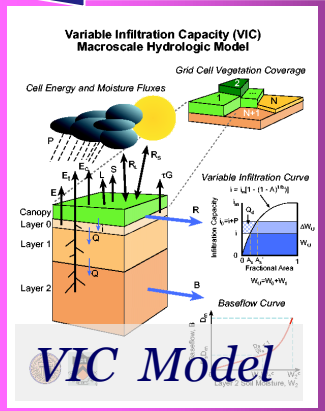

API Model




Lumped Conceptual



Distributed (Mike SHE)




VIC Model

Lumped

"Simple"

Time

Distributed

Physically-based

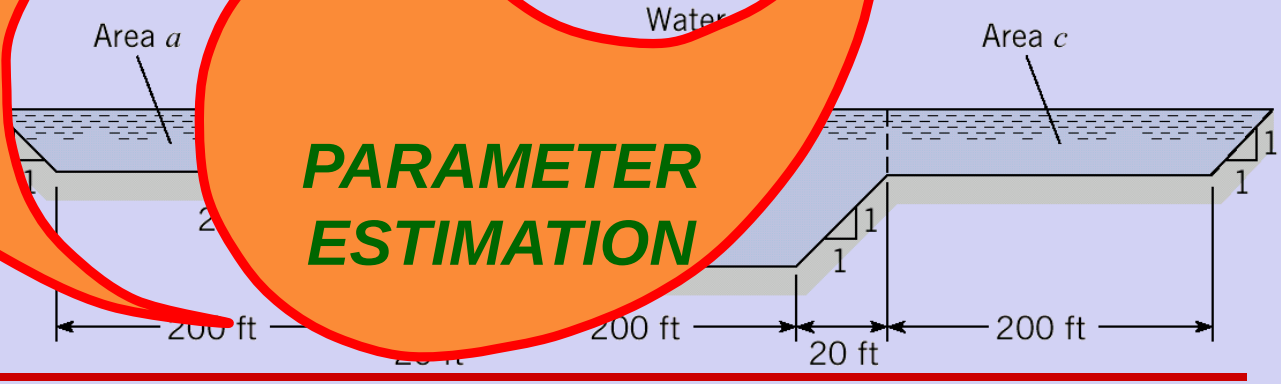
# Hydrologic Modeling: 3 Elements!

**If the "World" of Watershed Hydrology Was Perfect!**

DATA

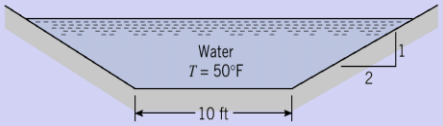
MODEL

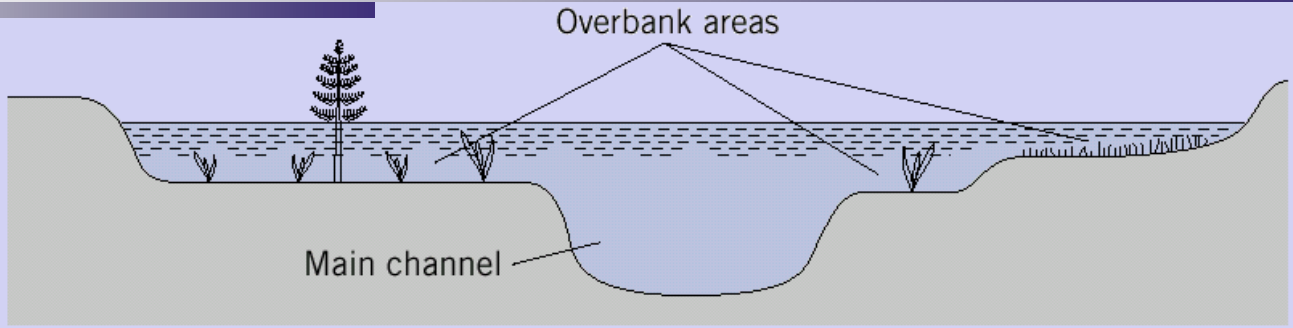
PARAMETER ESTIMATION

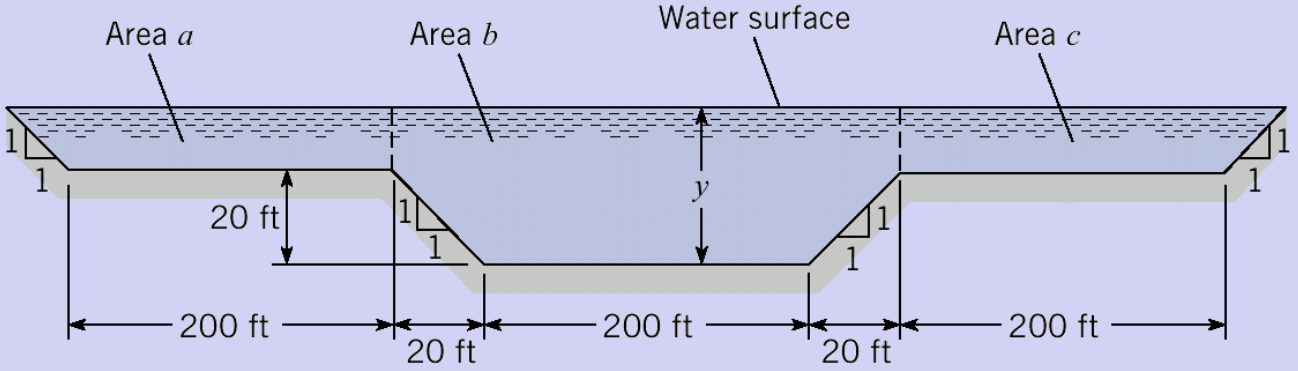


# Flow in Channels: How far can we go simplifying?

$$V = n^{-1} R^{2/3} S^{1/2}$$



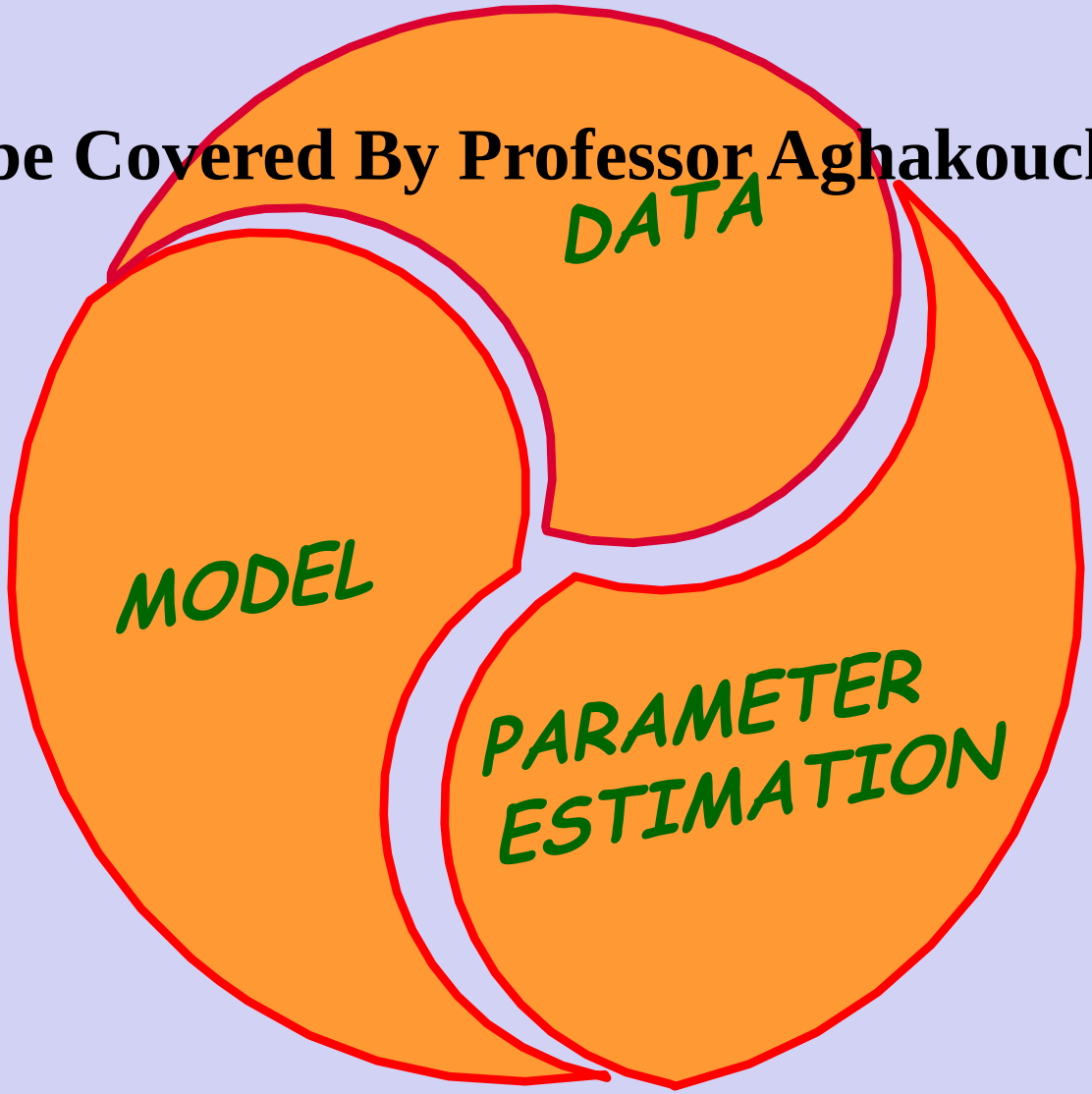



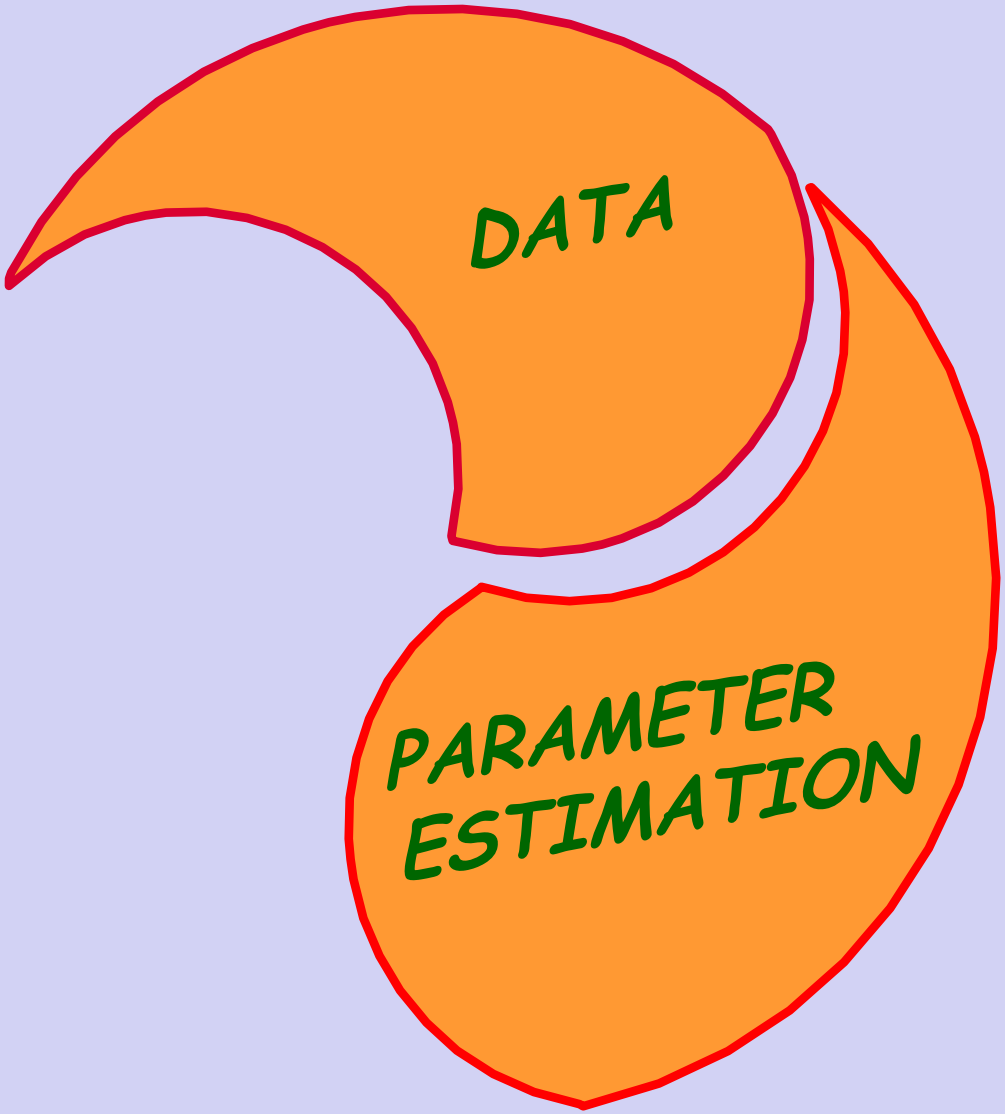

*n – Manning Coefficient*
*R – Hydraulic Radius*
*S – Energy Slope*

# Hydrologic Modeling

**Will be Covered By Professor Aghakouchak**



# Model Calibration



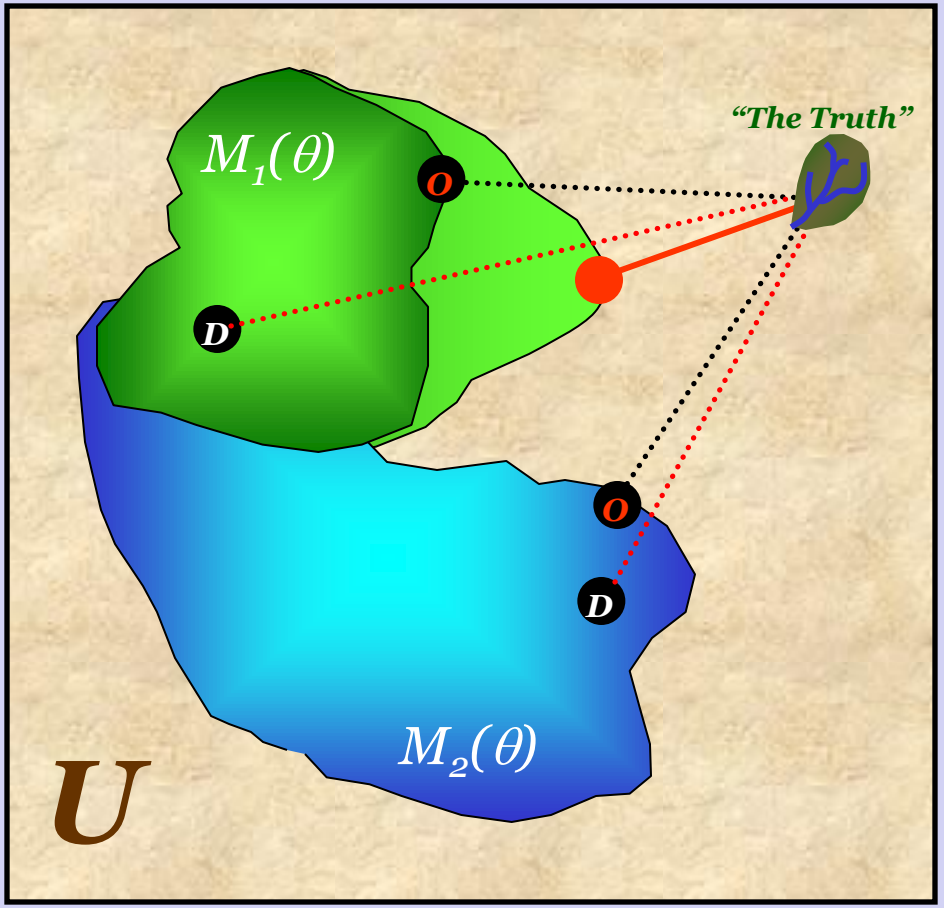
# The Identification Problem

1. **Select a model structure** (Input-State-Output equations)
2. **Estimate values for the parameters**

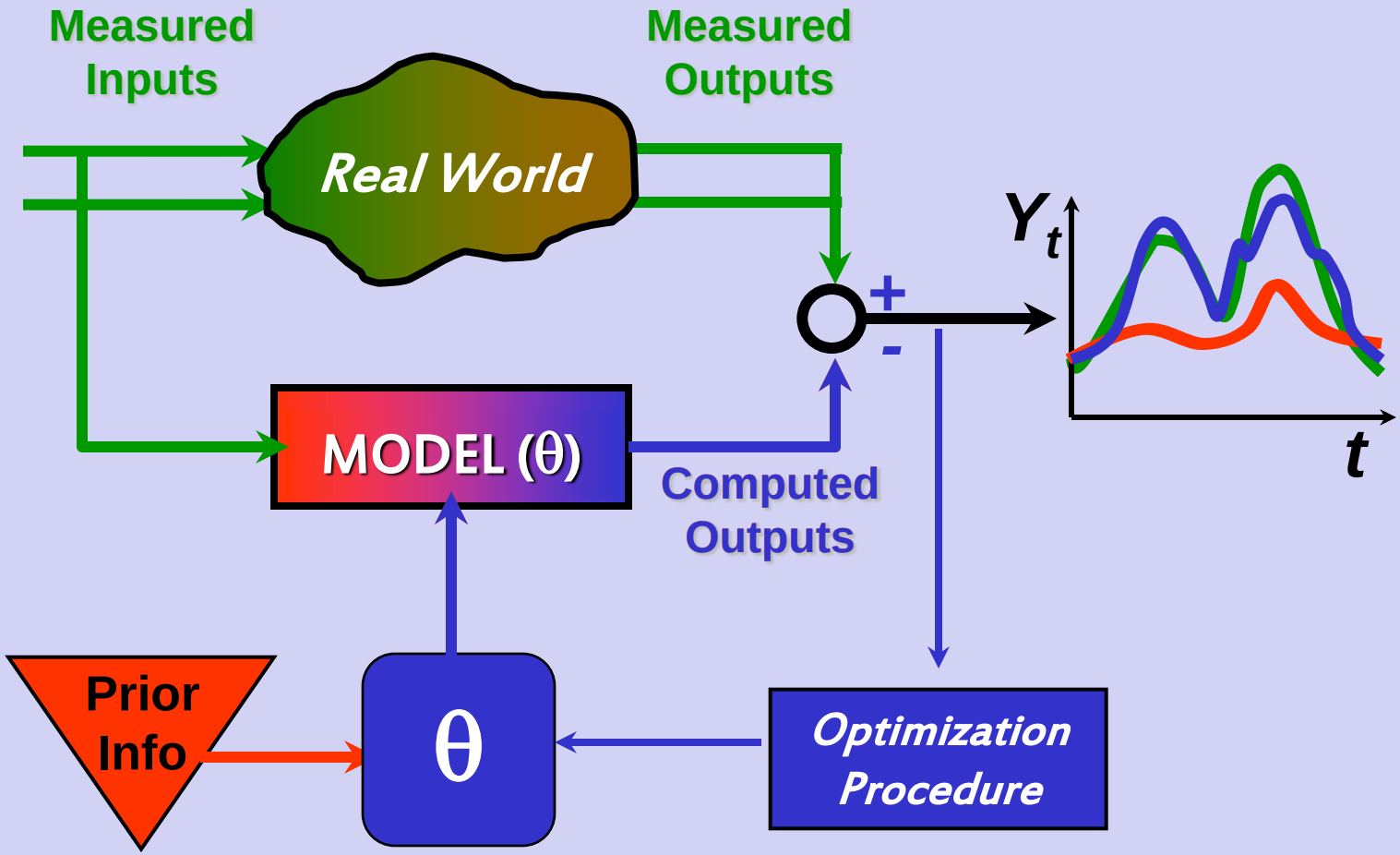
*U – Universal Set*

*B - Basin*

$M_i(\theta)$ *– Selected Model Structure*



# The Concept of Model Calibration




*"Calibration: constraining the model to be consistent with observations"*

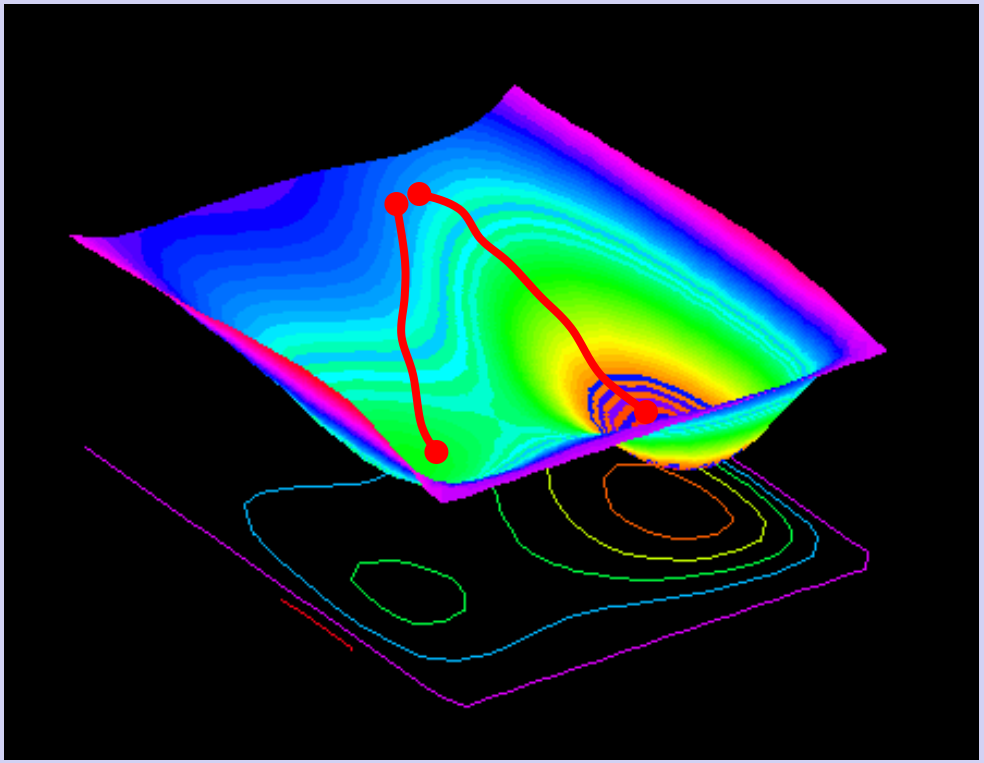
# The Automatic Calibration Approach

# Calibration components

*Objective Function*

*Search Algorithm*

*Sensitivity Analysis*



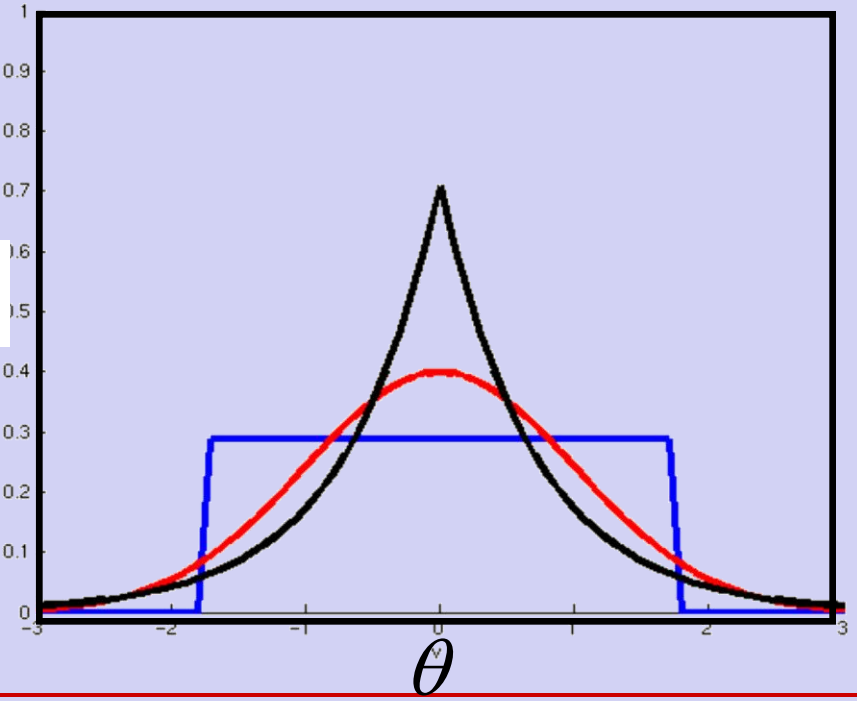
*Problems with identifiability*

# Calibration Criterion

## [General Exponential Power Density]

*(Posterior Parameter Probability Distribution Function)*

$$p(\theta_i \mid \mathbf{y}, \gamma) = \left[\frac{\omega(\gamma)}{\sigma}\right]^N \exp\left[-c(\gamma)\sum_{j=1}^{N}\left|\frac{e(\theta_i)_j}{\sigma}\right|^{2/(1+\gamma)}\right]$$

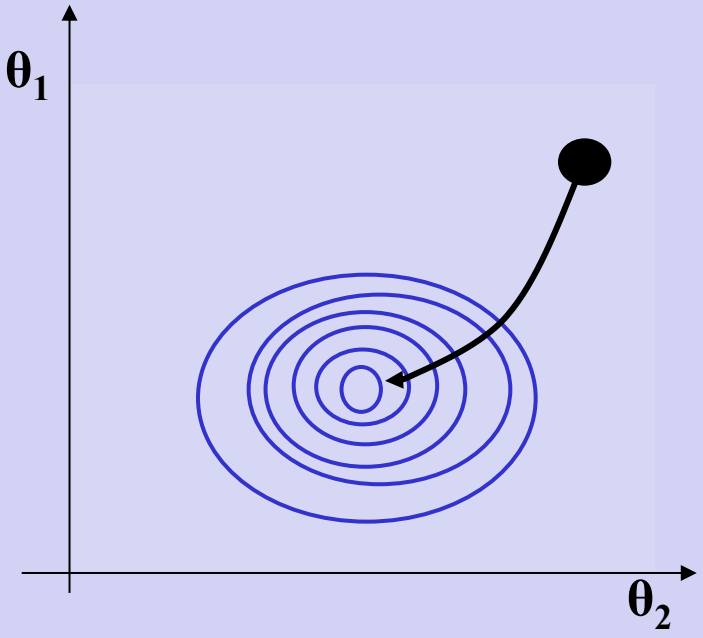



**Uniform** $\gamma \to (-1)$

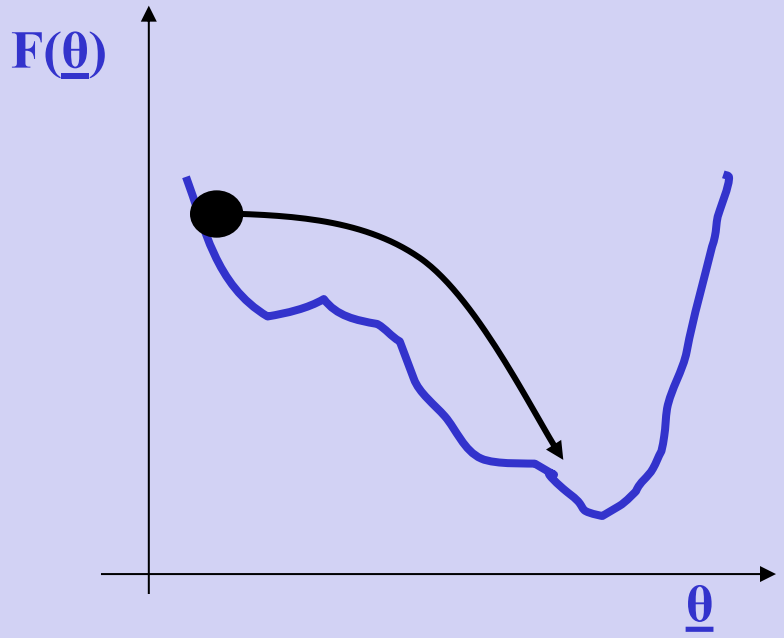
**Normal** $\gamma = 0$

**Exponential** $\gamma = 1$

# Objective function Parameter Space

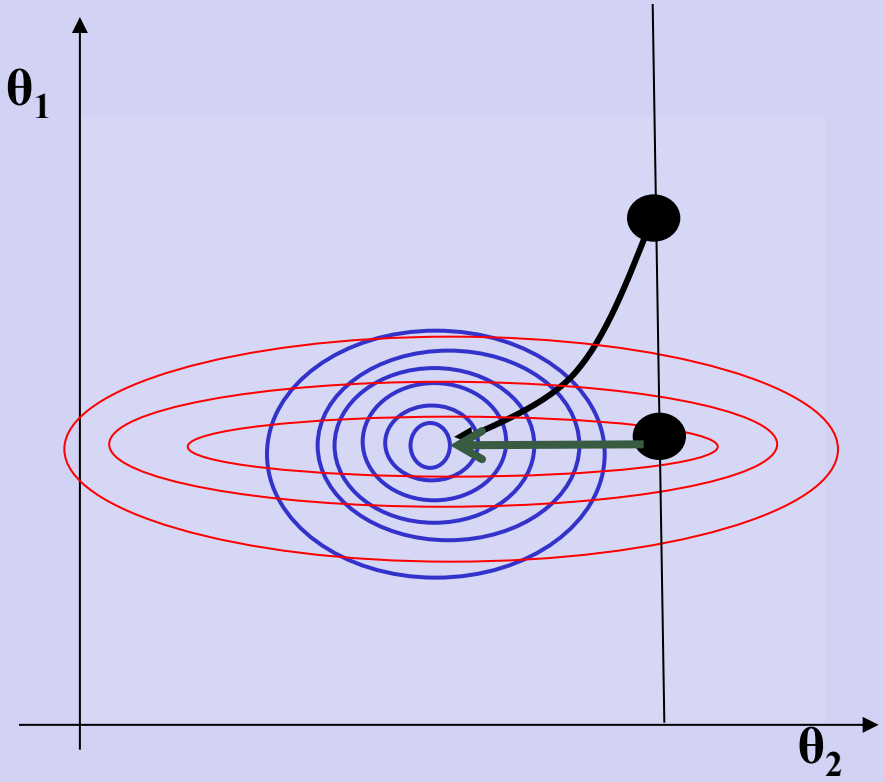



Parameter Space



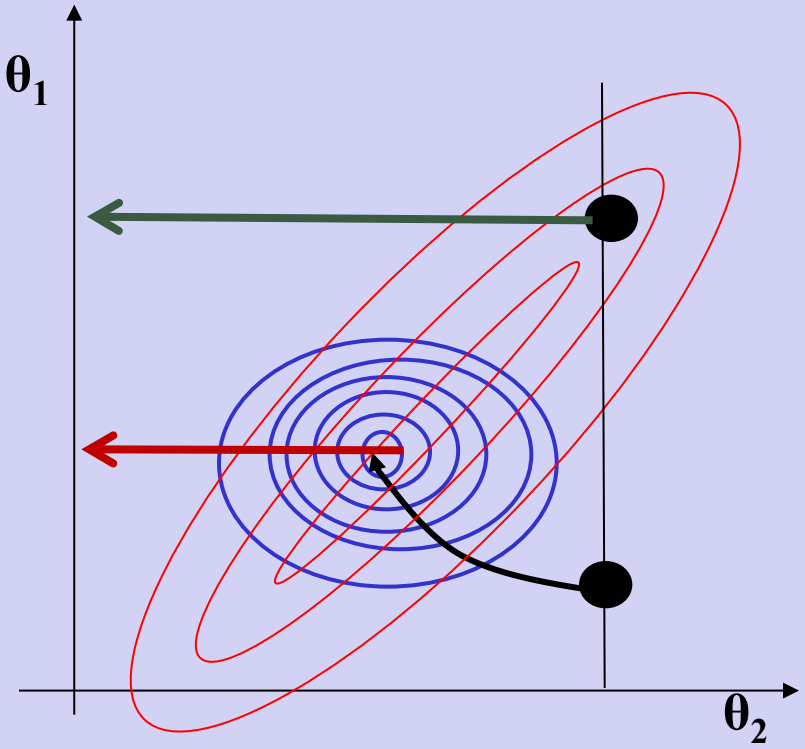

Objective Function Space

# Parameter Sensitivity



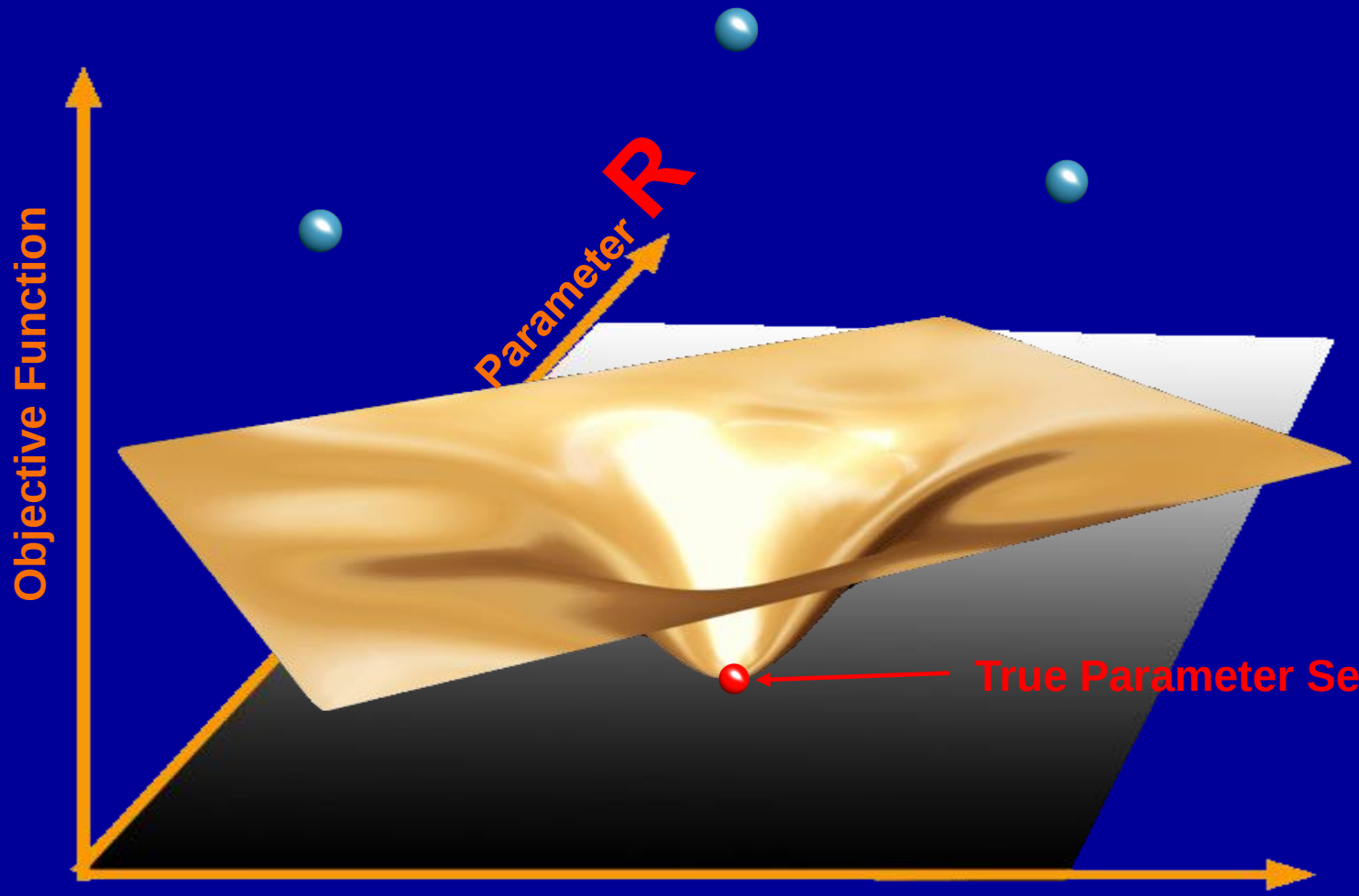

**Parmeter Space**

# Parameter Sensitivity



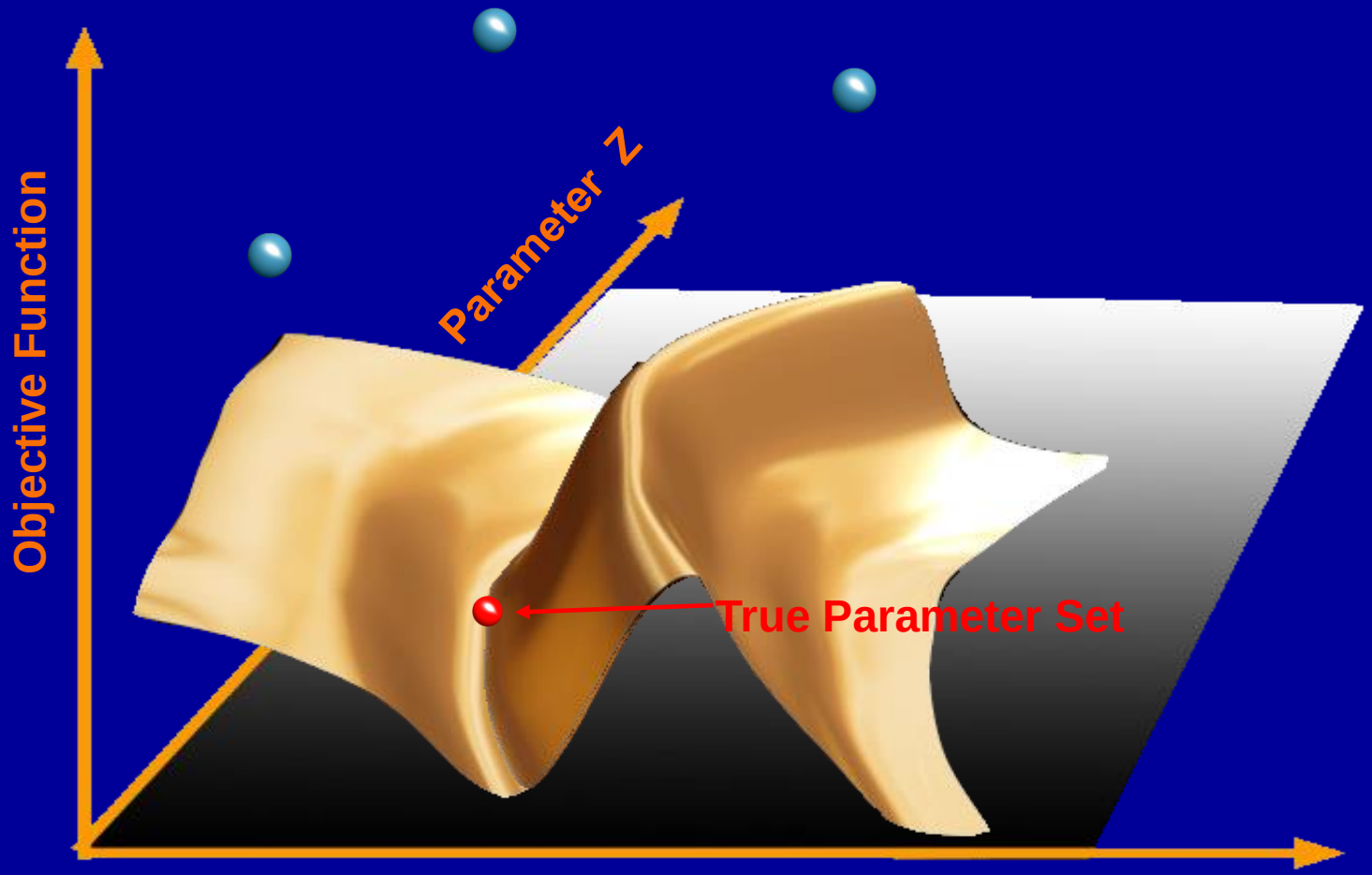

**Parameter Space**

# The Ideal case: Convex Optimization



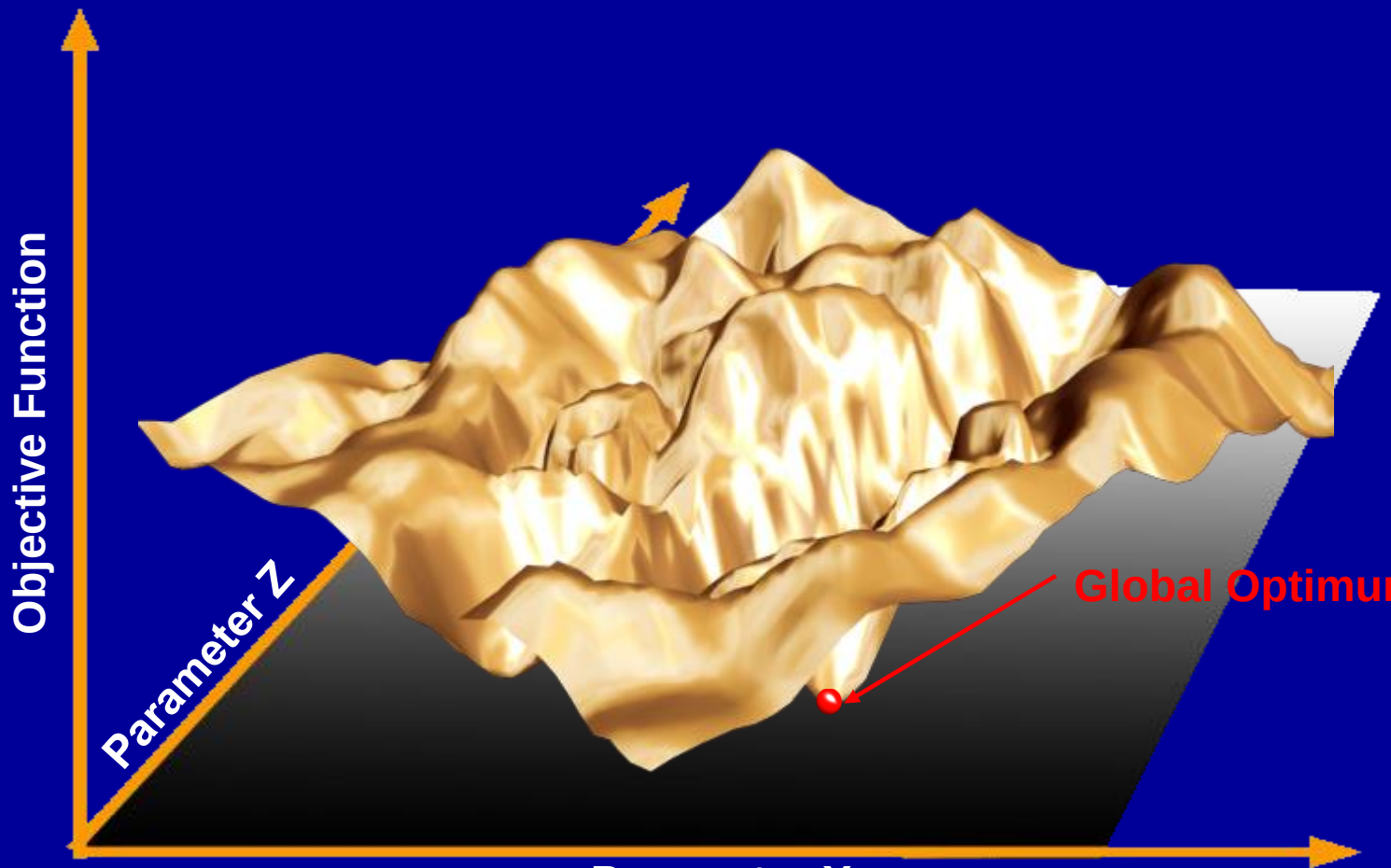

Created By G-H Park

# *Difficulties in Global Optimization*



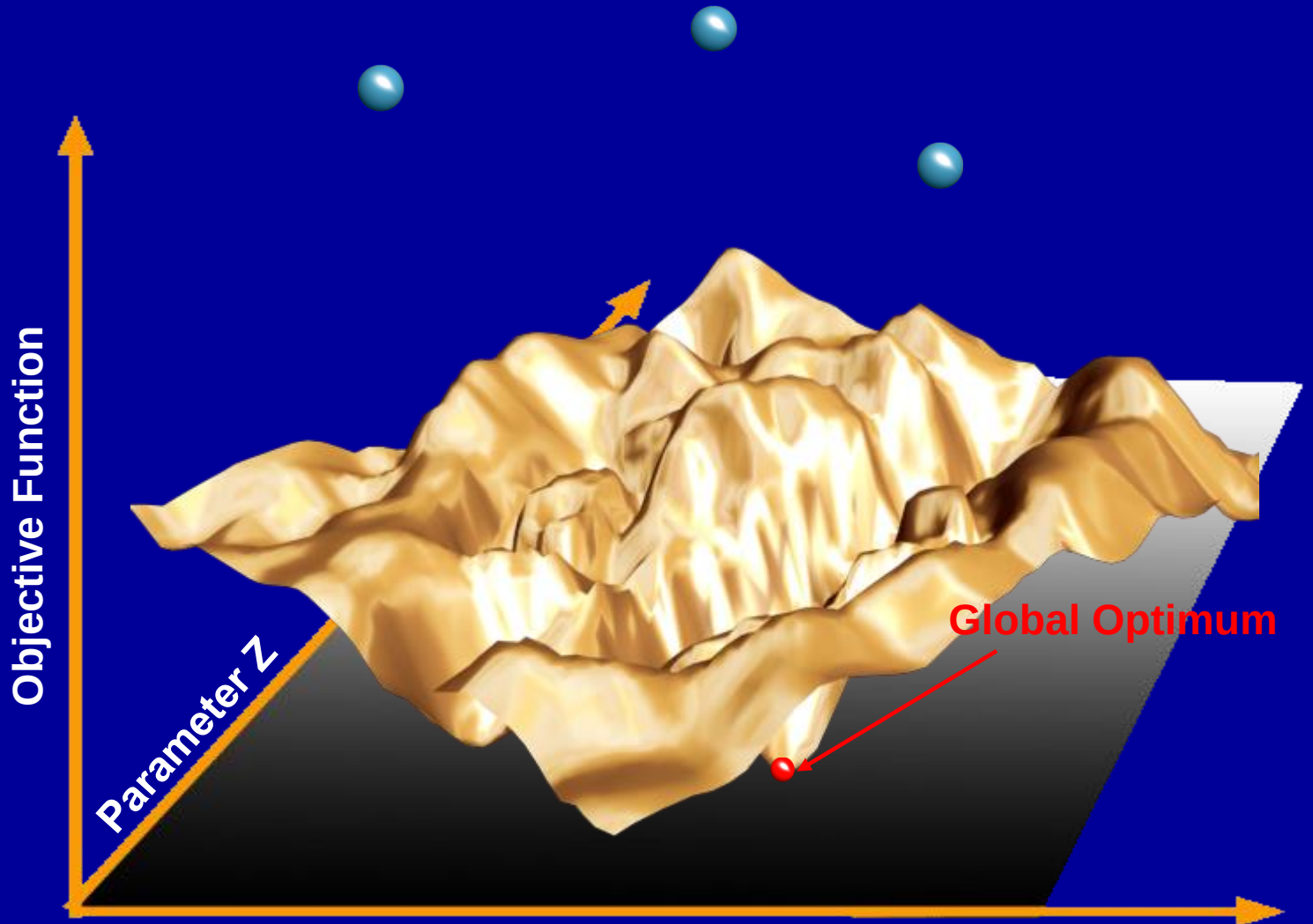

Created By G-H Park

# *Parameter Estimation (non-convex, multi-optima)*



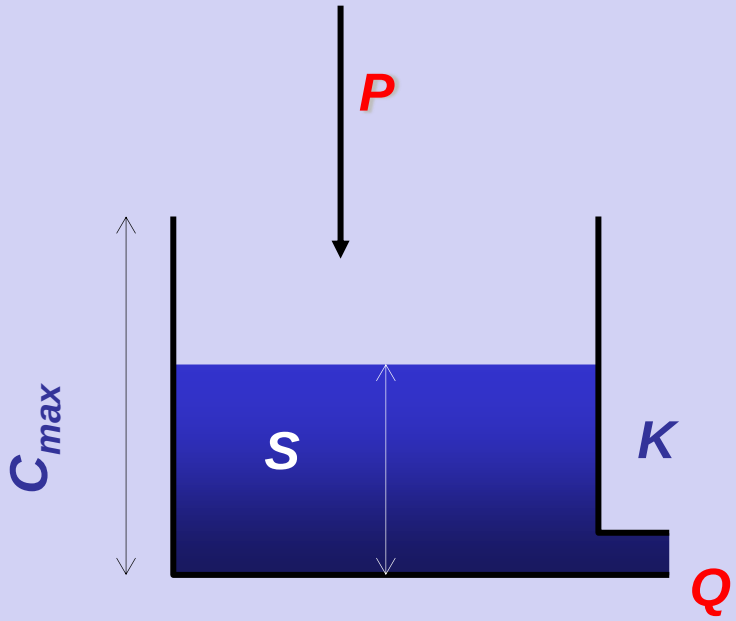

Created By G-H Park

# *Parameter Estimation (non-convex, multi-optima)*



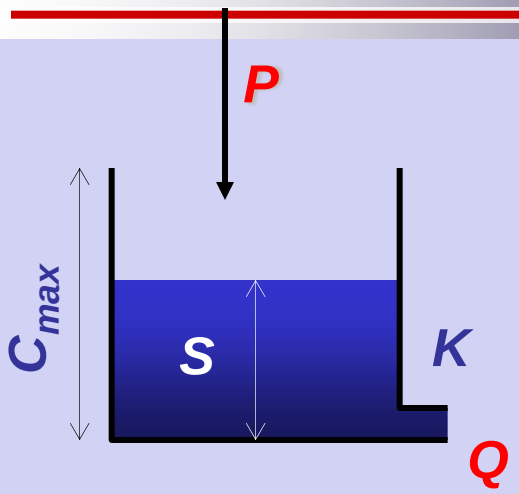

Created By G-H Park

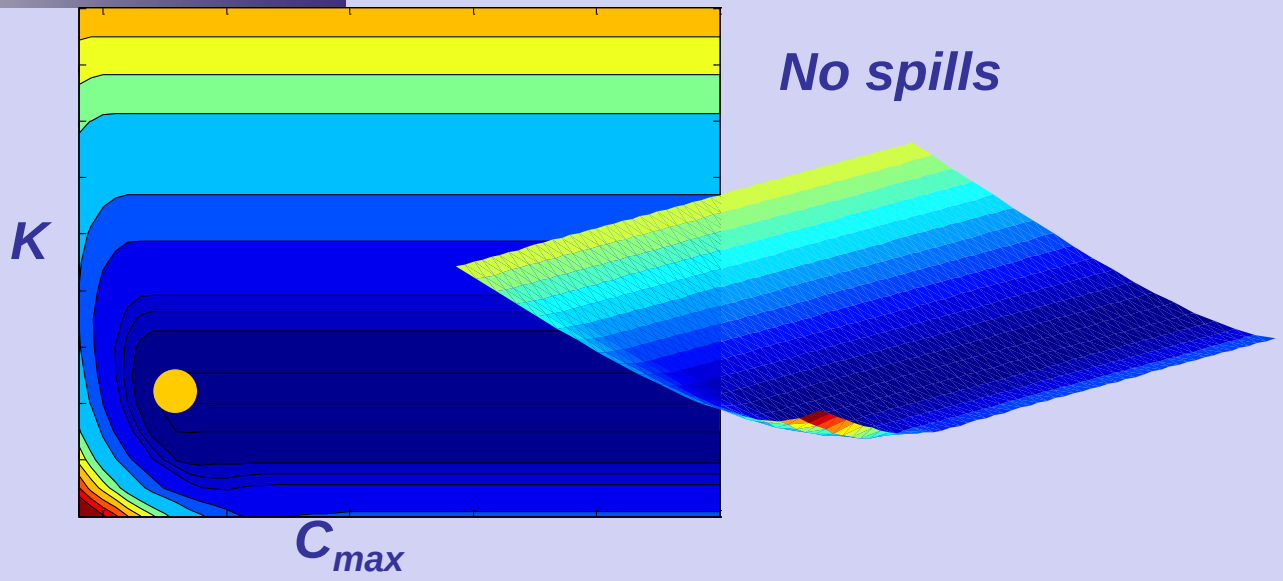
# Data information content

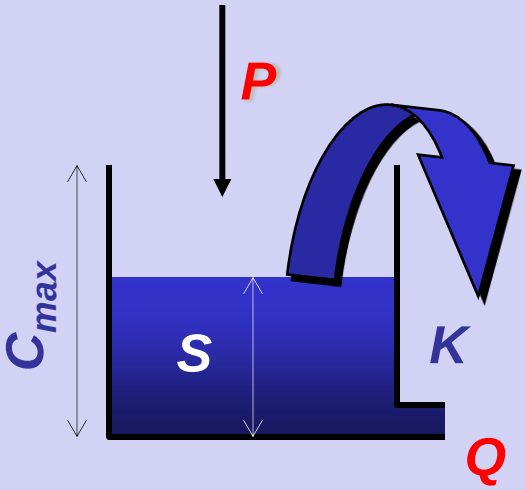


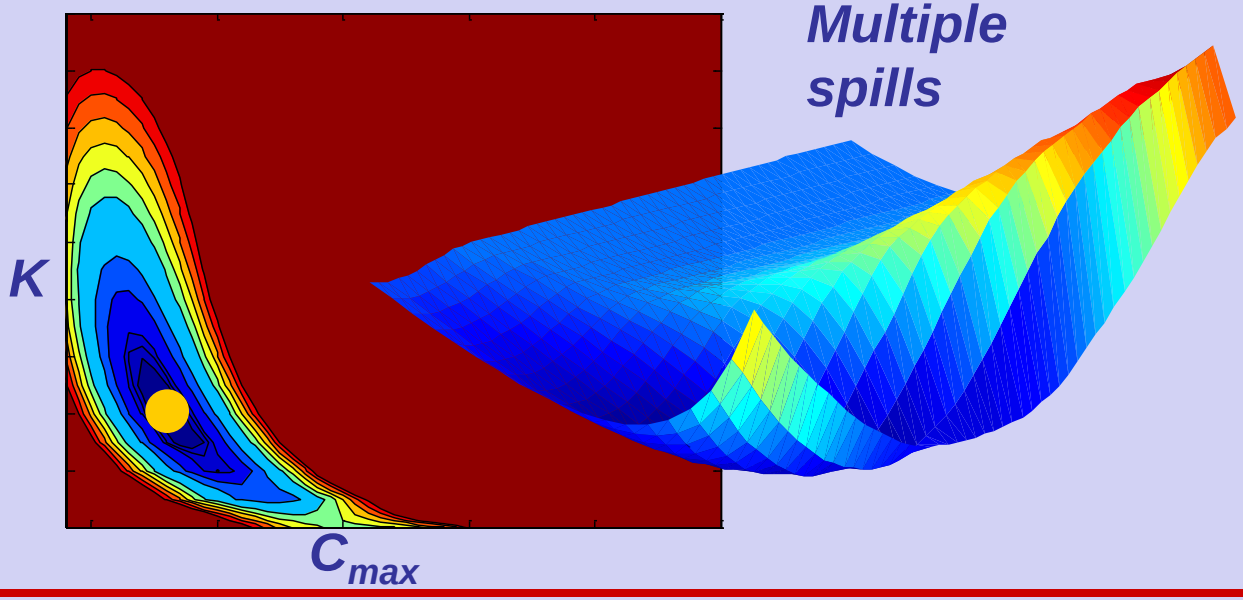

*"Bucket Model"*
*Simple two parameter Model*

# Data information content



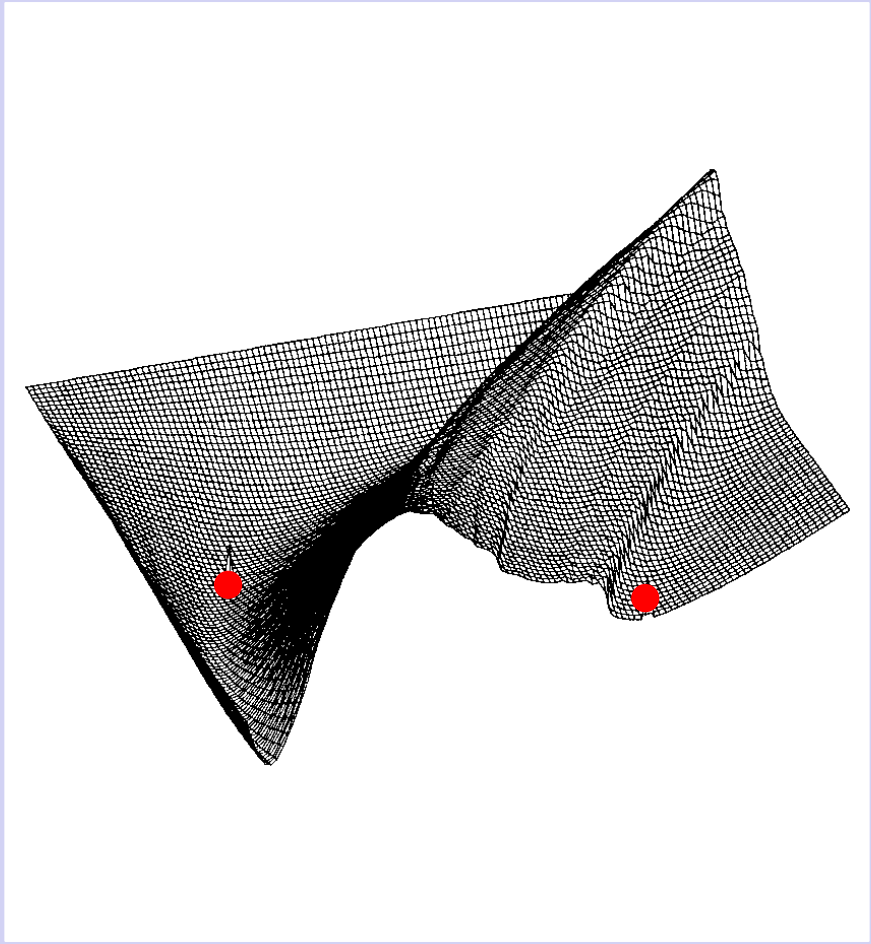



# Difficulties in Optimization

**1.- Regions of Attraction**

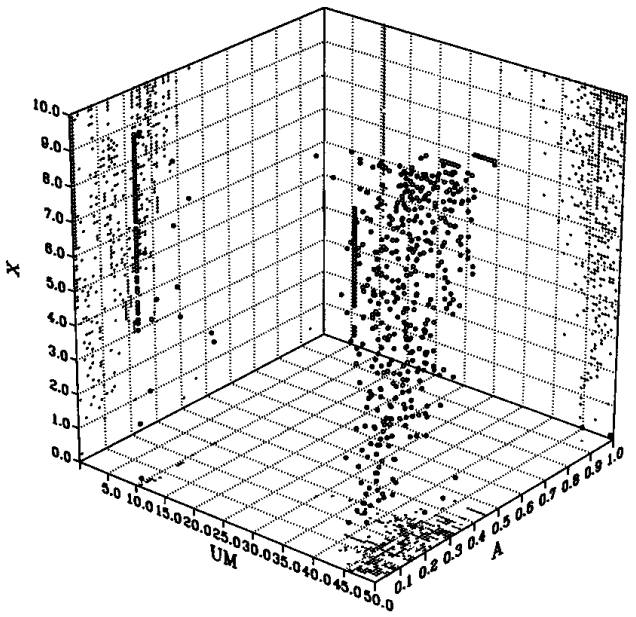
*More than one main convergence region*



Duan, Gupta, and Sorooshian, 1992, WRR

# Difficulties in Optimization

| | |
|---|---|
| **1.- Regions of Attraction** | *More than one main convergence region* |
| ***2.- Local Optima*** | *Many small "pits" in each region* |




Duan, Gupta, and Sorooshian, 1992, WRR

# Difficulties in Optimization

| | |
|---|---|
| **1.- Regions of Attraction** | *More than one main convergence region* |
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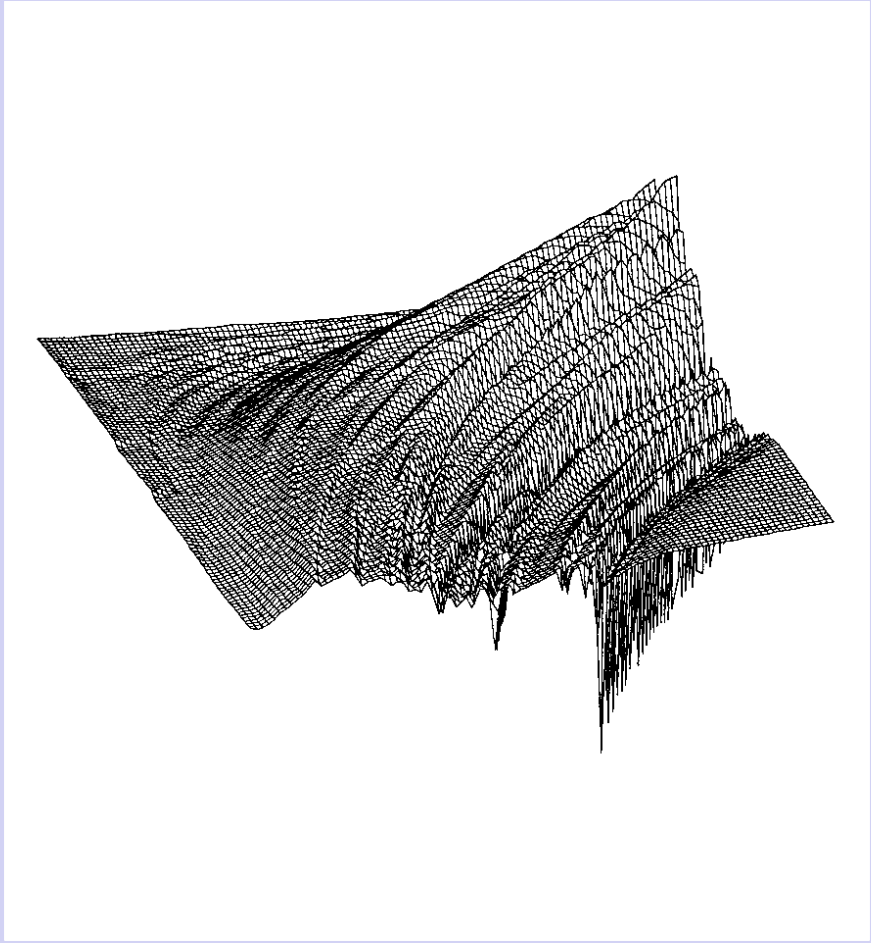
| ***3.- Roughness*** | *Rough surface with discontinuous derivatives* |



Duan, Gupta, and Sorooshian, 1992, WRR

# Difficulties in Optimization

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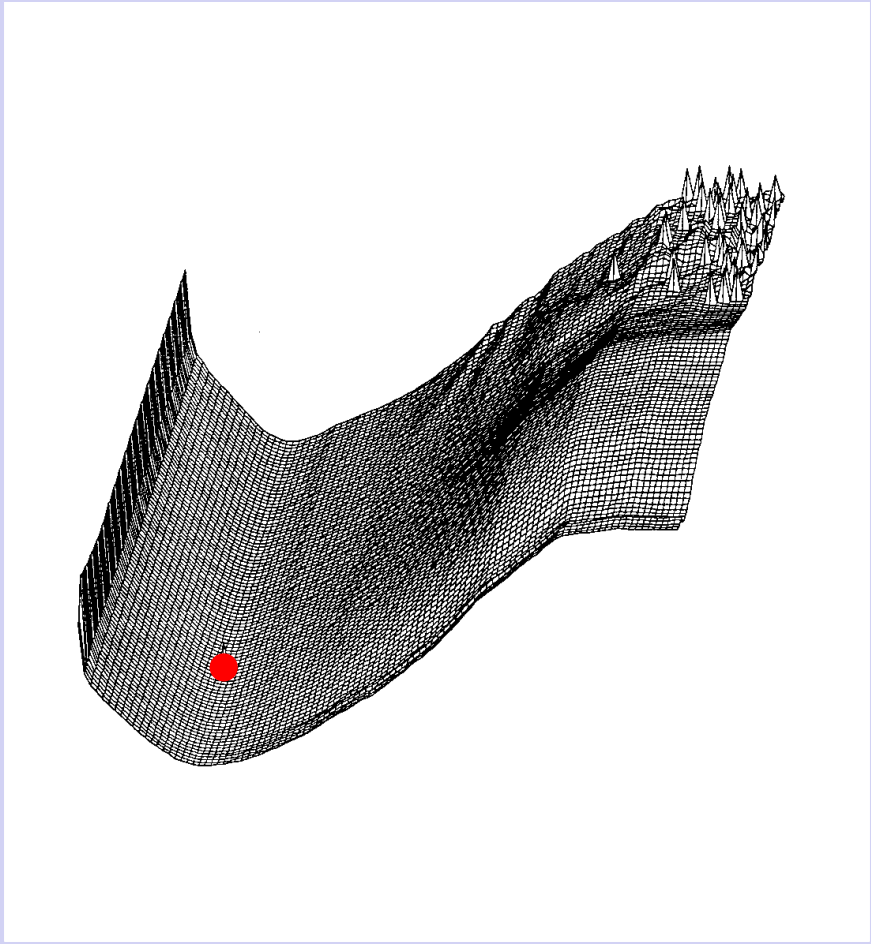
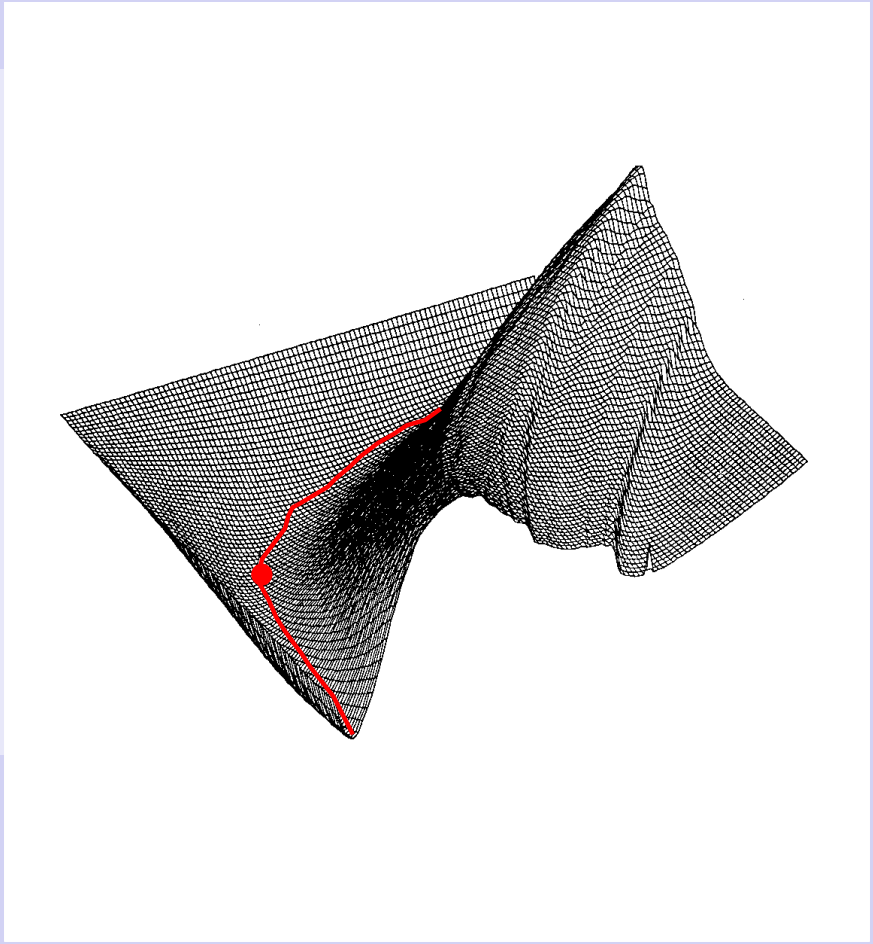
| ***3.- Roughness*** | *Rough surface with discontinuous derivatives* |
| ***4.- Flatness*** | *Flat near optimum with significantly different parameter sensitivities* |



Duan, Gupta, and Sorooshian, 1992, WRR

# Difficulties in Optimization

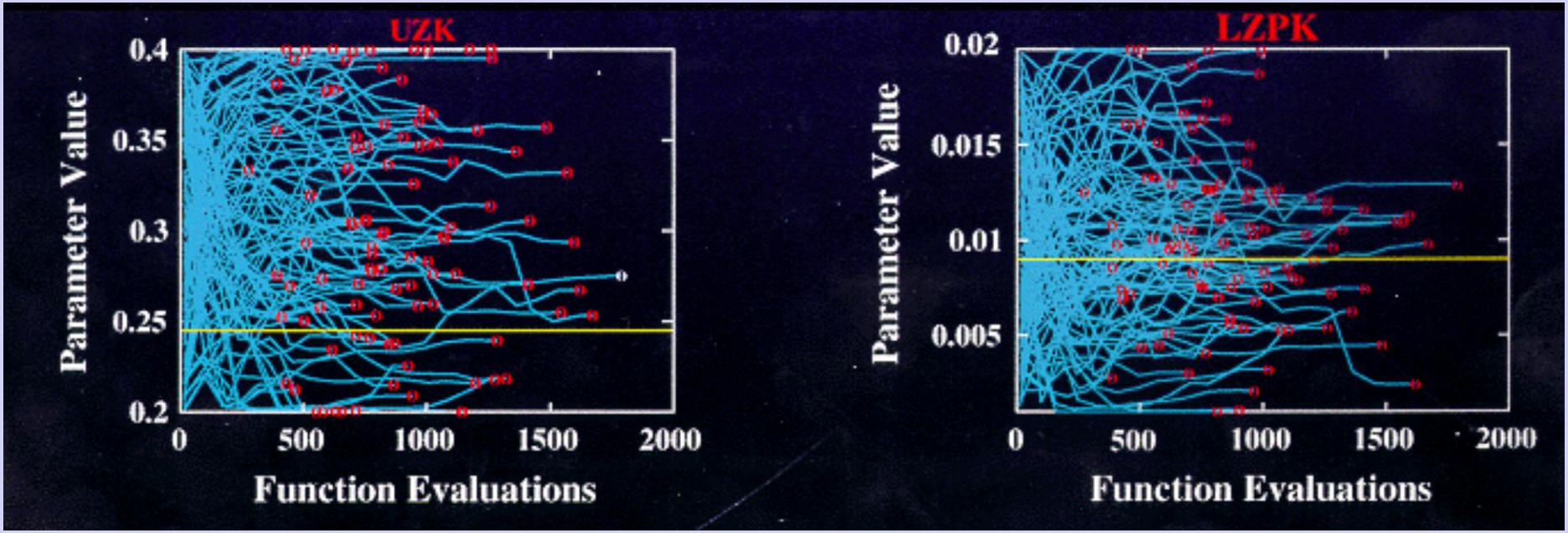
| | |
|---|---|
| **1.- Regions of Attraction** | *More than one main convergence region* |
| ***2.- Local Optima*** | *Many small "pits" in each region* |
| ***3.- Roughness*** | *Rough surface with discontinuous derivatives* |
| ***4.- Flatness*** | *Flat near optimum with significantly different parameter sensitivities* |
| ***5.- Shape*** | *Long and curved ridges* |



Duan, Gupta, and Sorooshian, 1992, WRR

# Optimization Strategy – Local Direct Search

***Calibration of the Sacramento Model***
***Downhill Simplex Method,*** *Nelder & Mead, 1965*



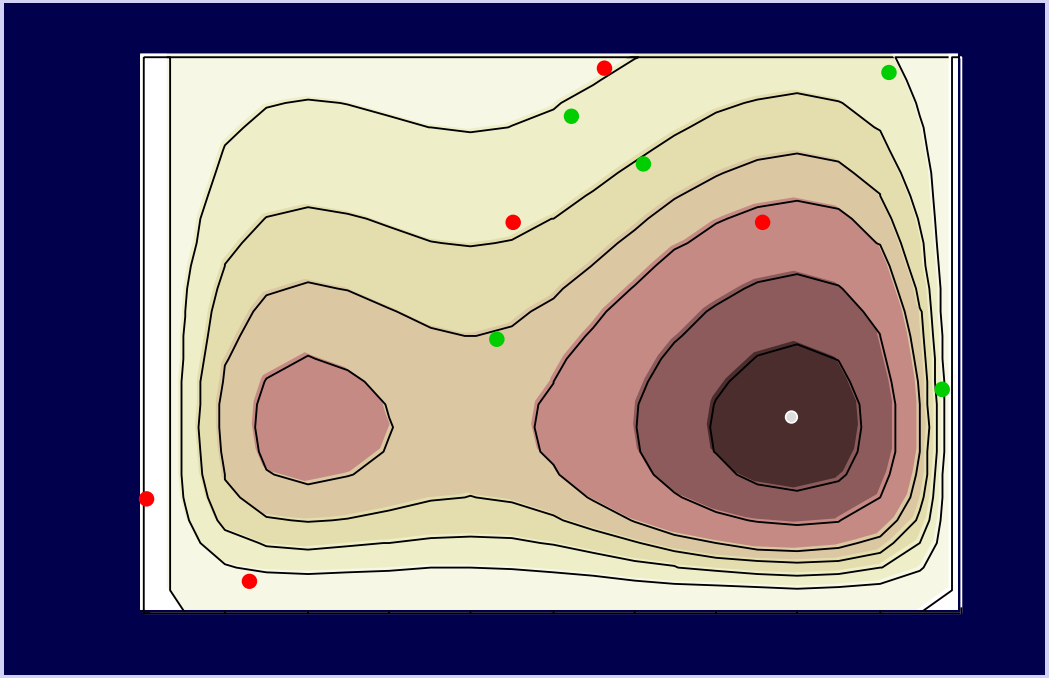

Duan, Gupta, and Sorooshian, 1992, WRR

# *The* SCE-UA *Algorithm …*
# *(1992)*

Duan, Gupta, and Sorooshian, 1992, WRR

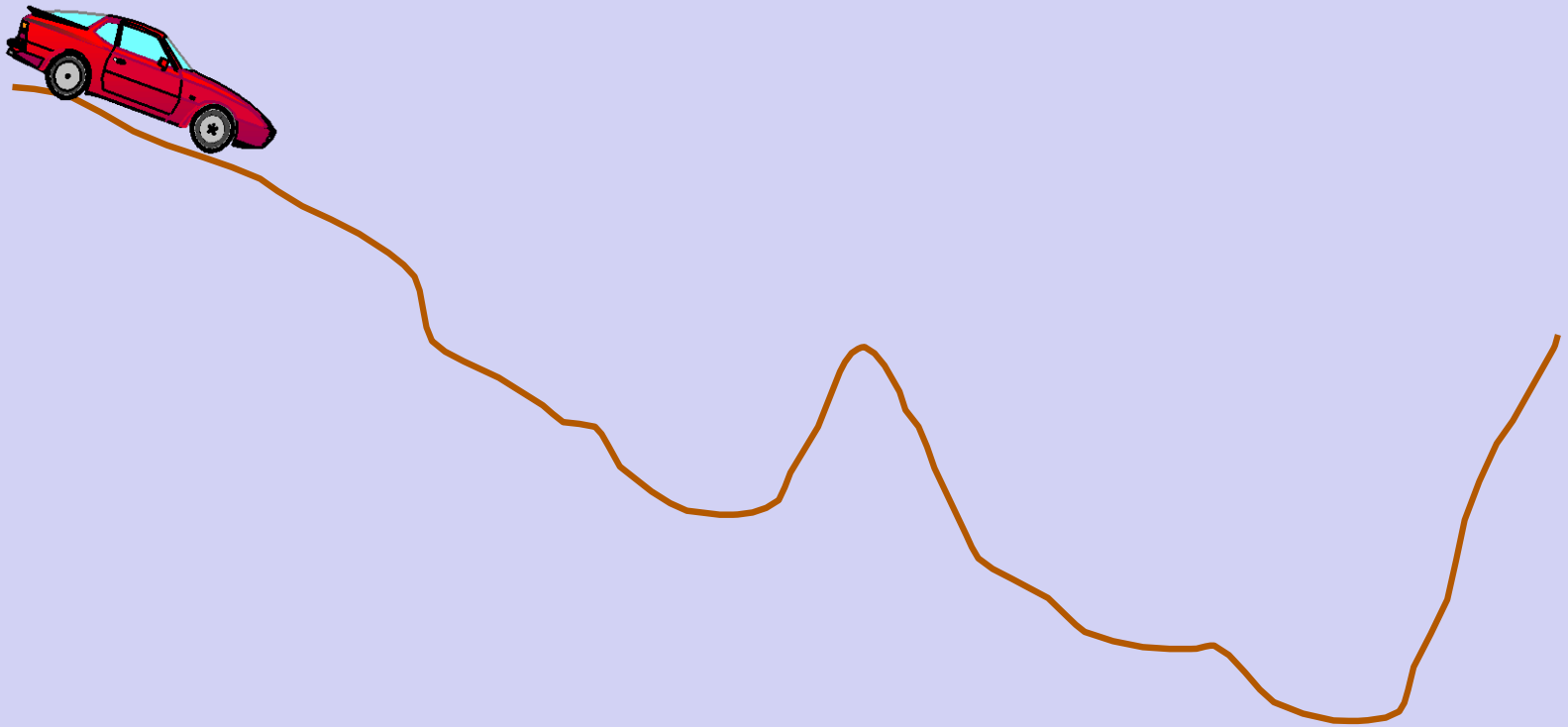
# The Shuffled Complex Evolution Algorithm

## *The* SCE-UA *Algorithm …*

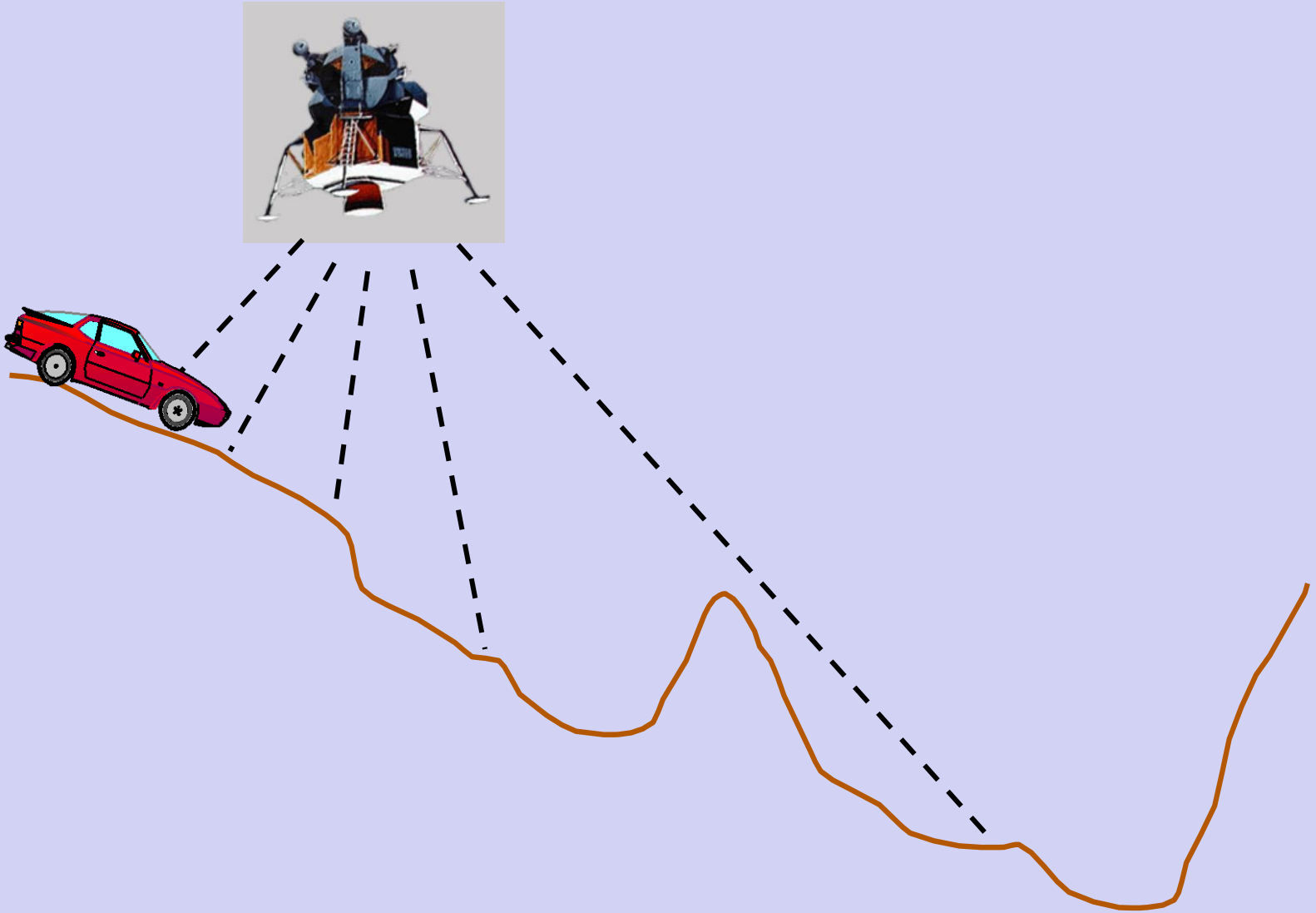


Duan, Sorooshian, and Gupta 1992, WRR

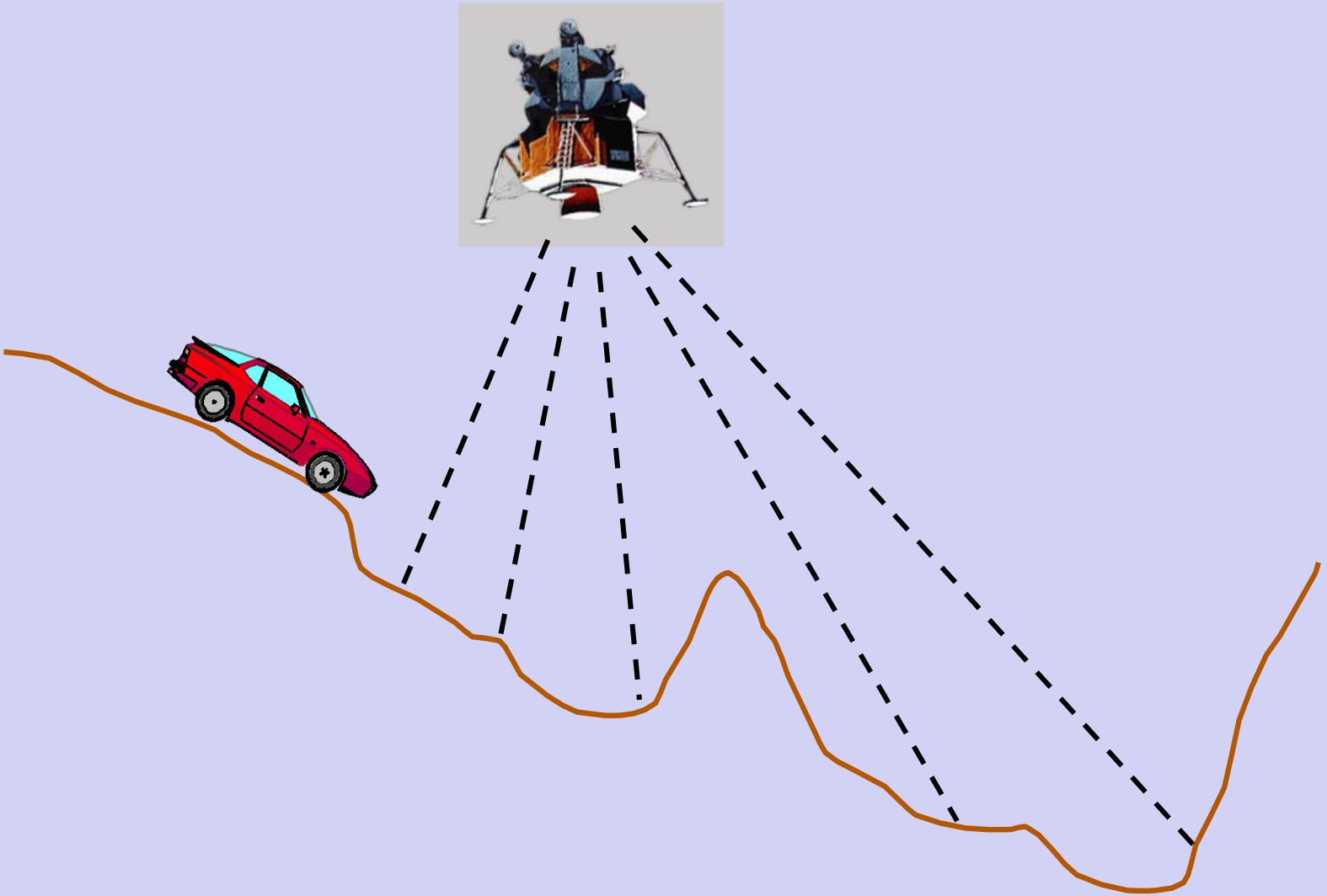
# The Concept Behind SCE Method



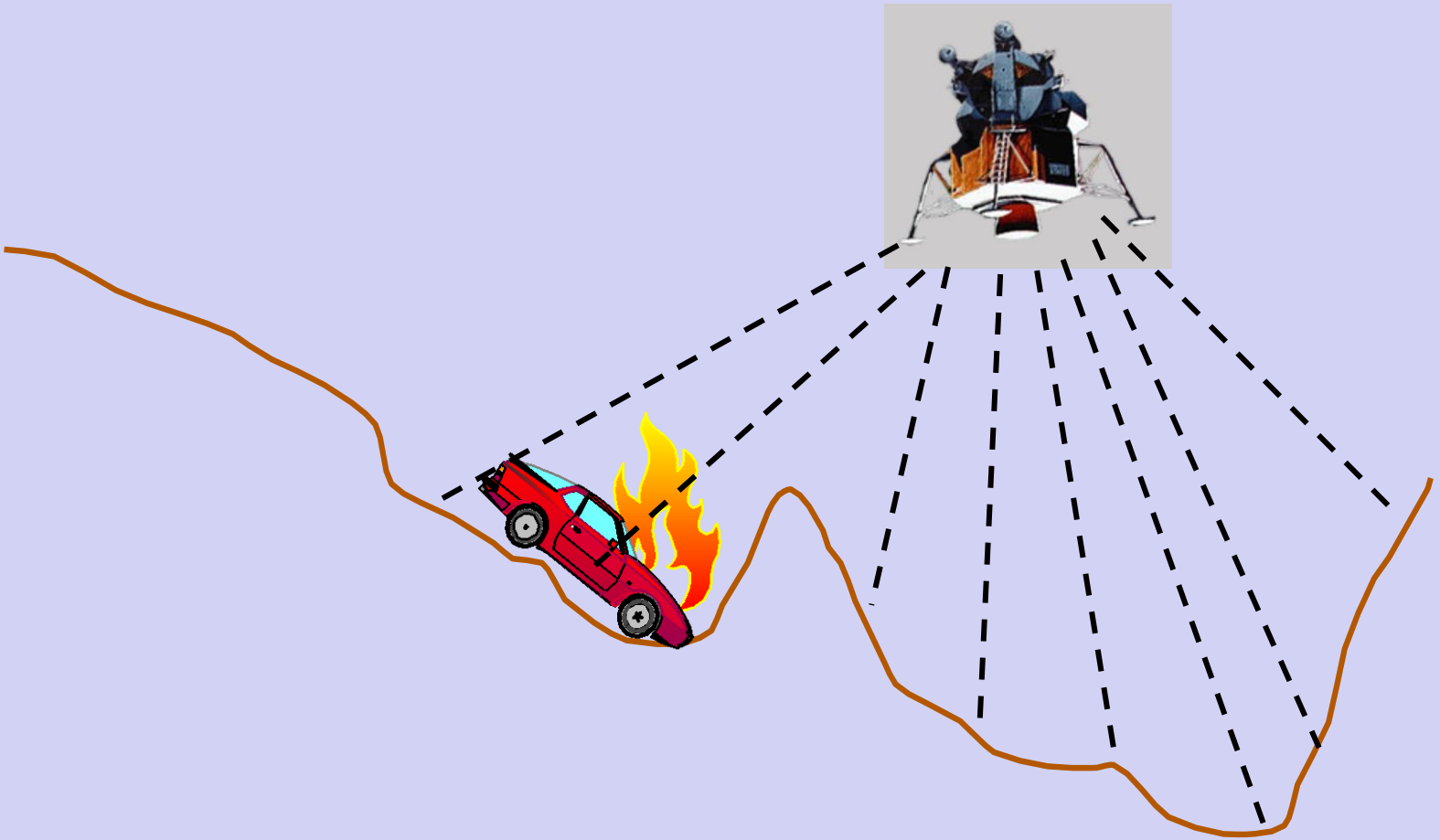
# The Concept Behind SCE Method



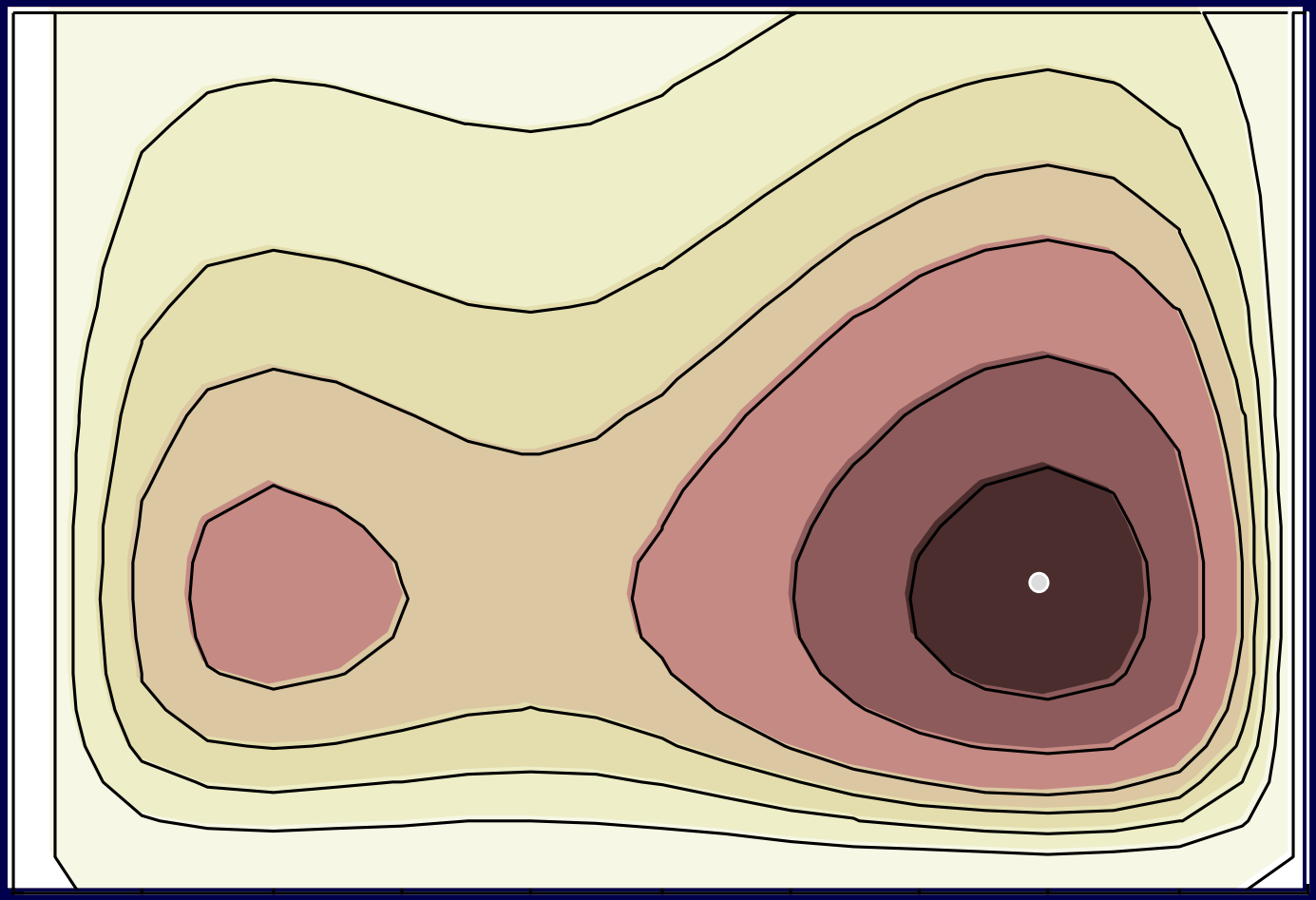
# The Concept Behind SCE Method



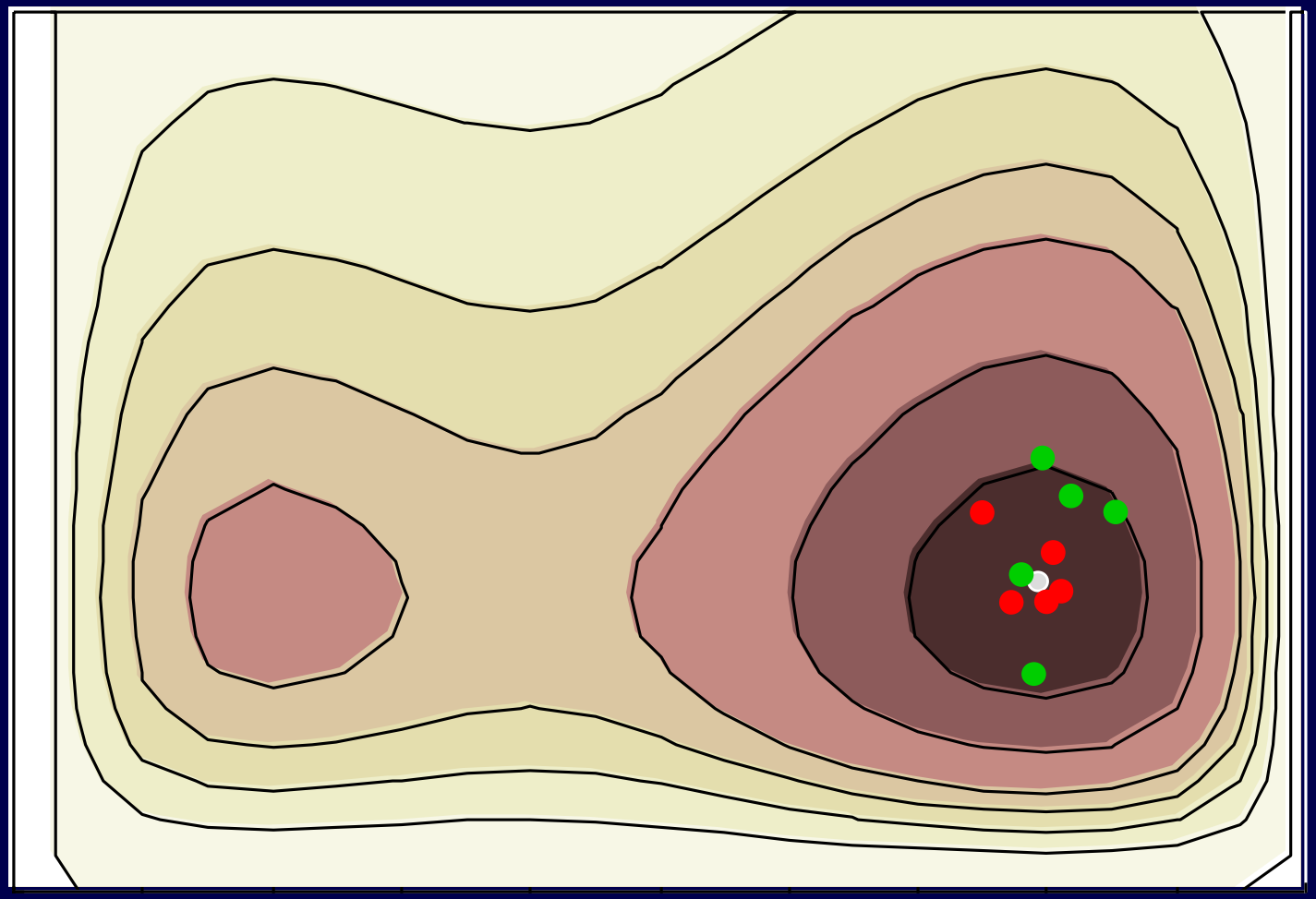
# The Concept Behind SCE Method



# SCE Method – How it works …



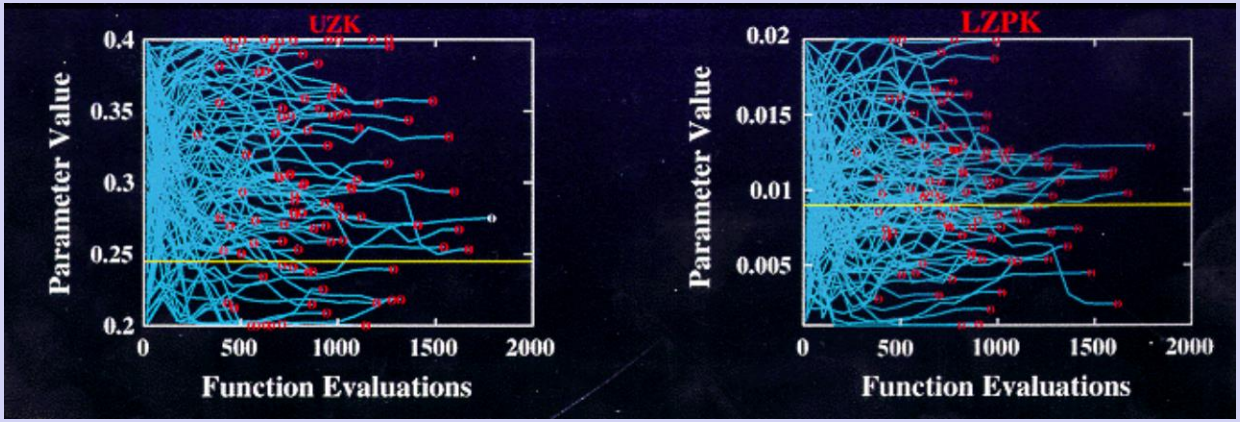
# Shuffled Complex Evolution (SCE-UA)



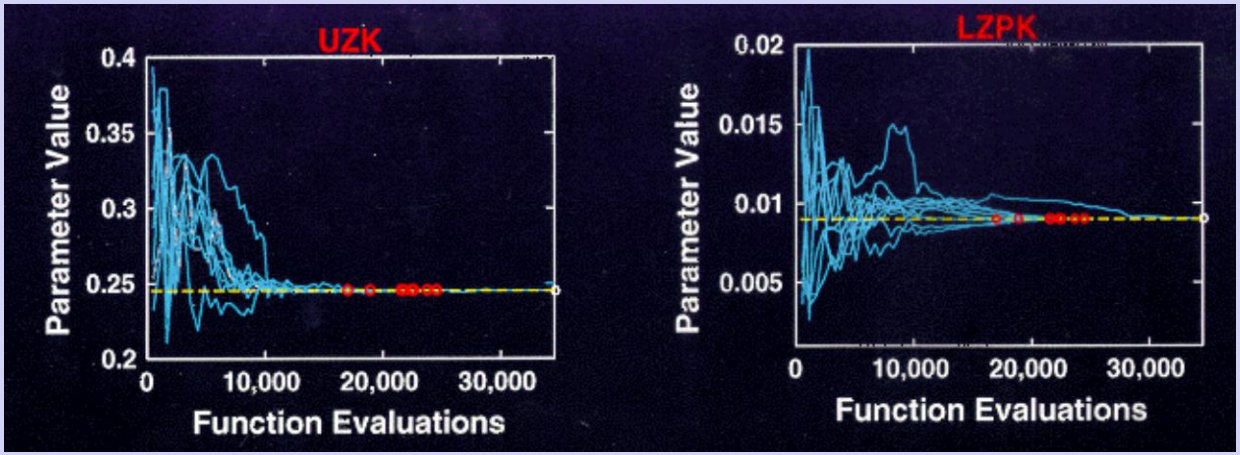
# Global Optimization – The SCE-UA Algorithm

*Duan, Gupta & Sorooshian, 1992, WRR*

***Simplex Method***



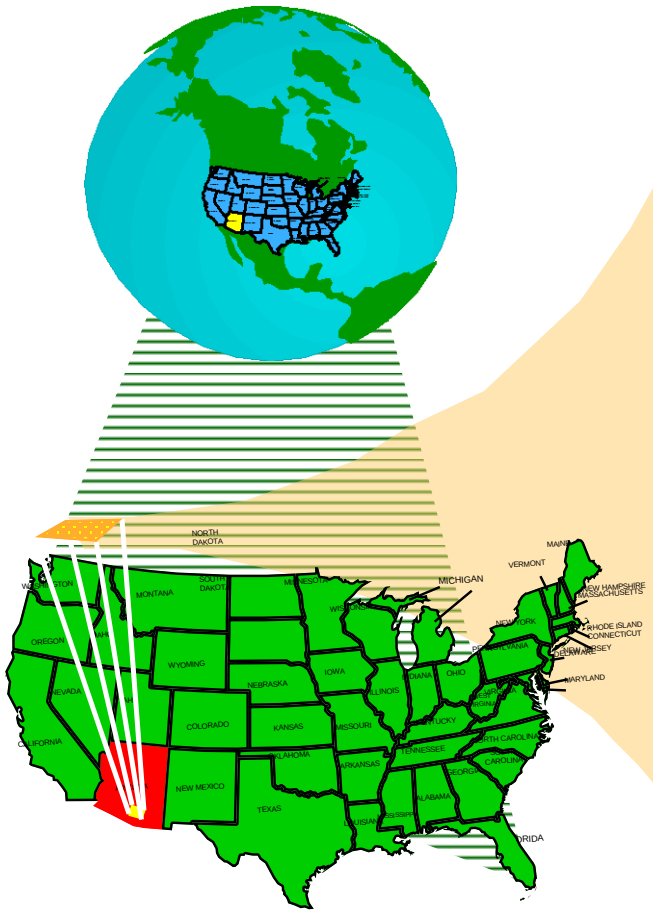

***Shuffled Complex Evolution (SCE-UA)***

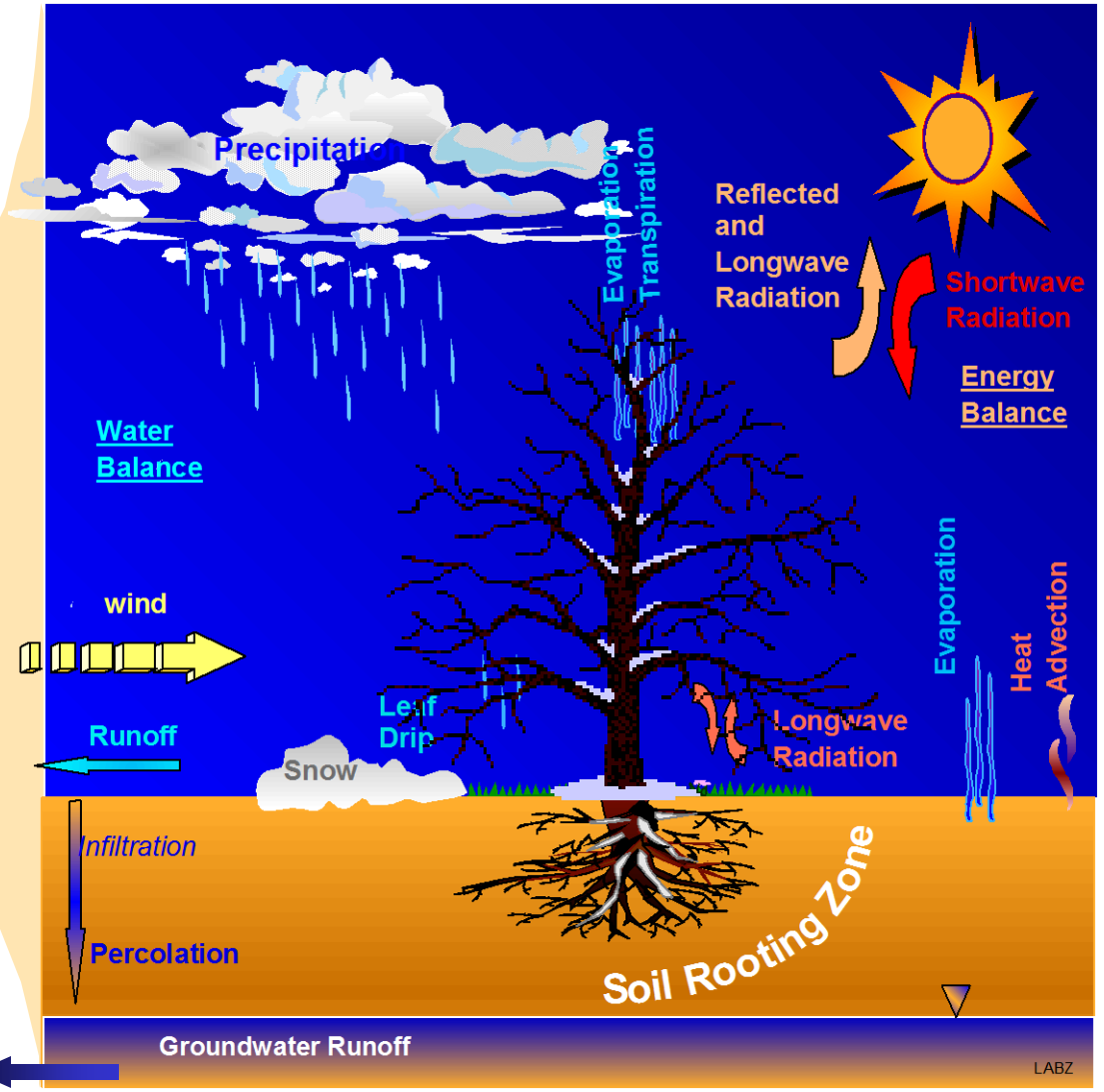


# Advances in Parameter Estimation

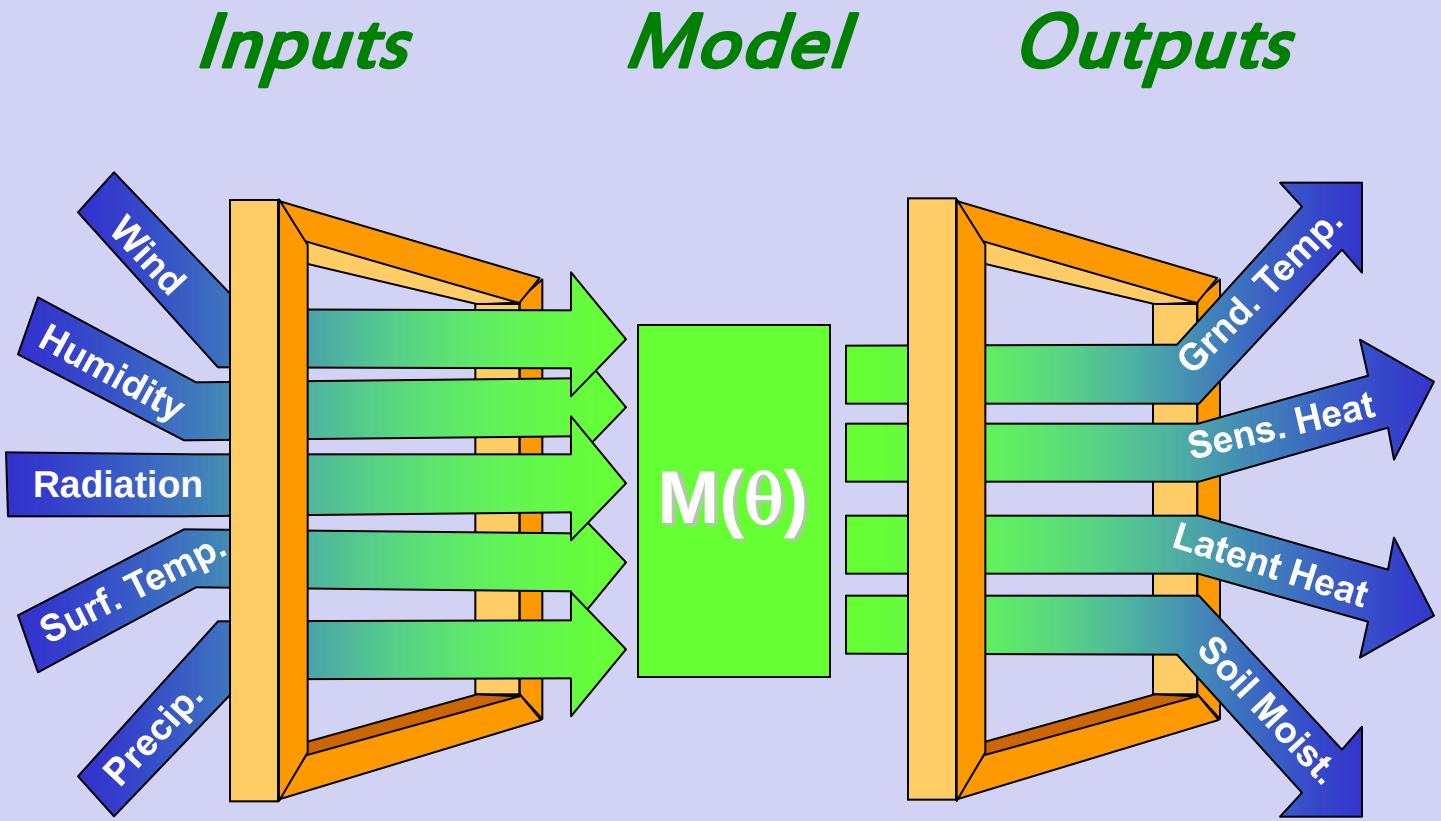
## Evolving Directions

# Land-Surface Model

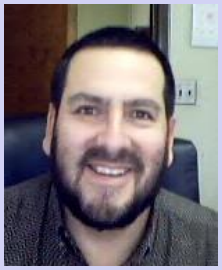


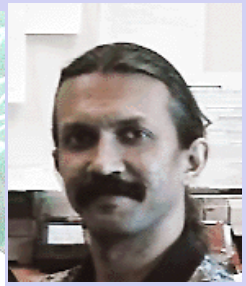
# Multi-Objective Approaches



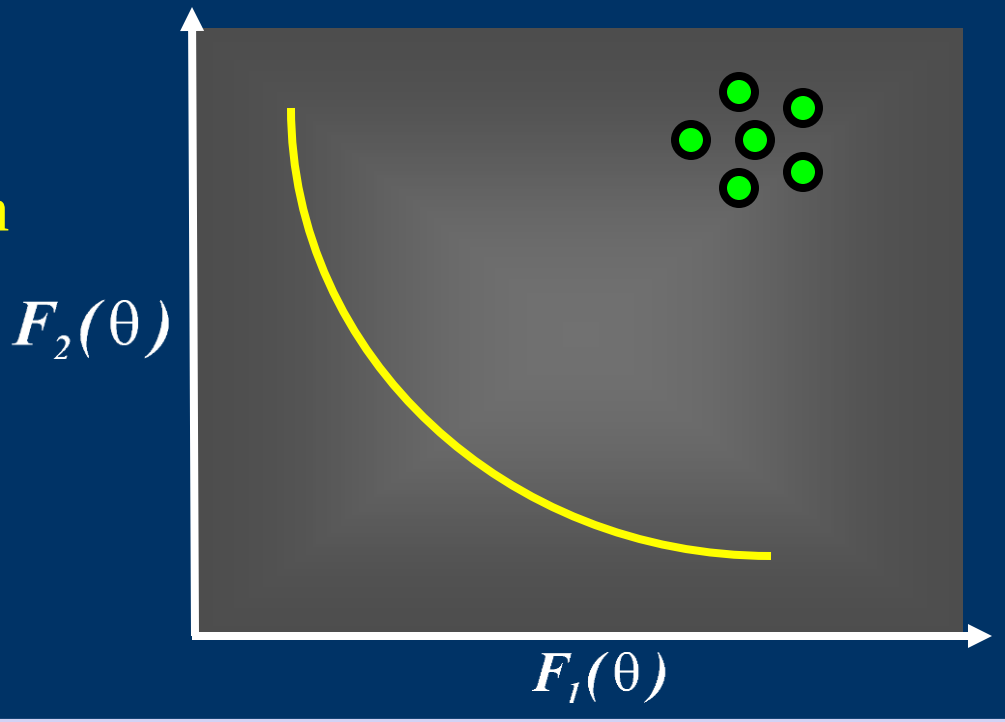
# Multi-Objective Optimization Problem



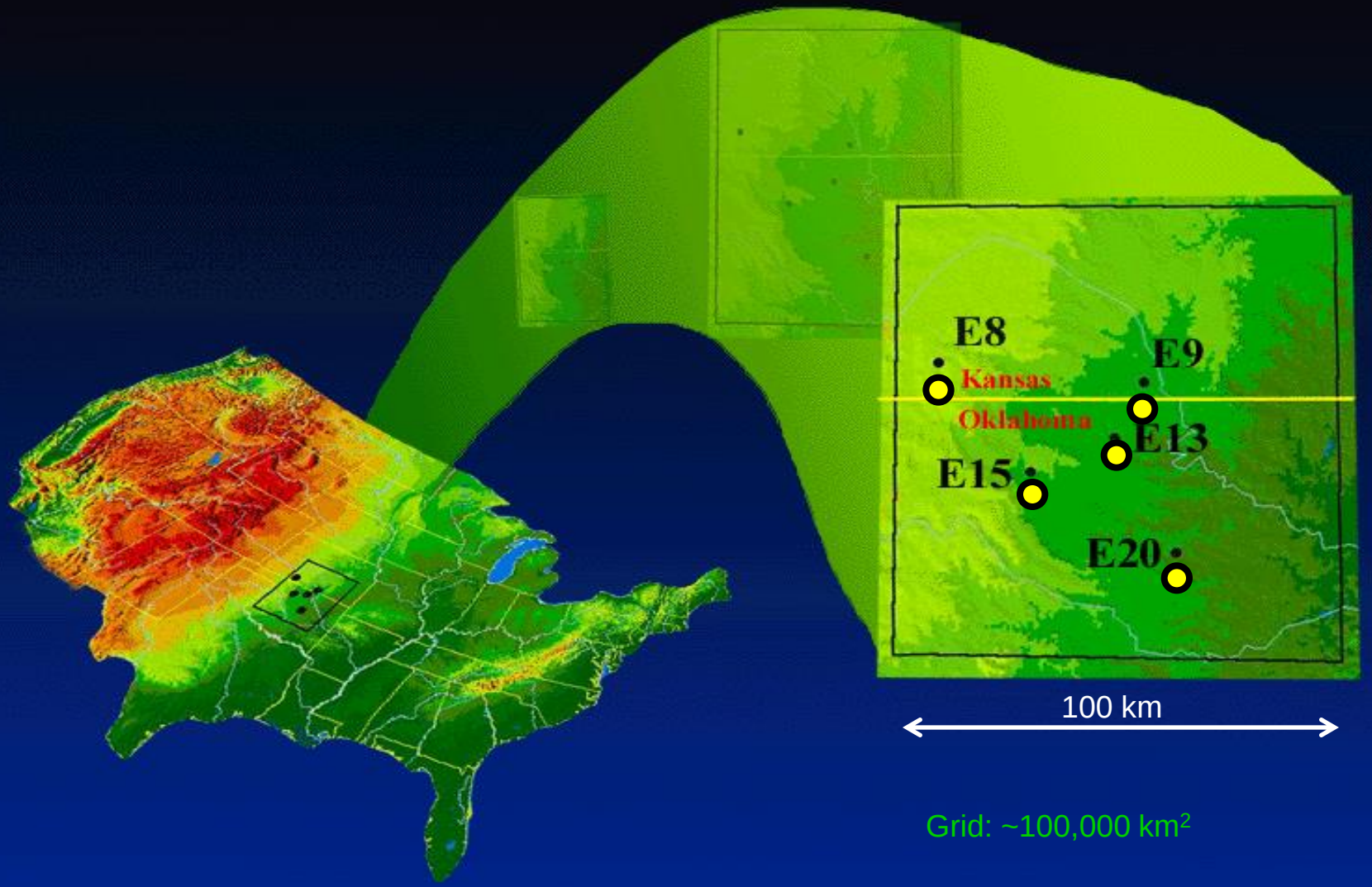
$$\text{Minimize}_{\text{wrt } \theta \subset \Omega} \quad F(\theta) = \{ F_1(\theta), \ldots, F_n(\theta) \}$$



- ✓ Simultaneously finds several Pareto Solutions in a Single Optimization



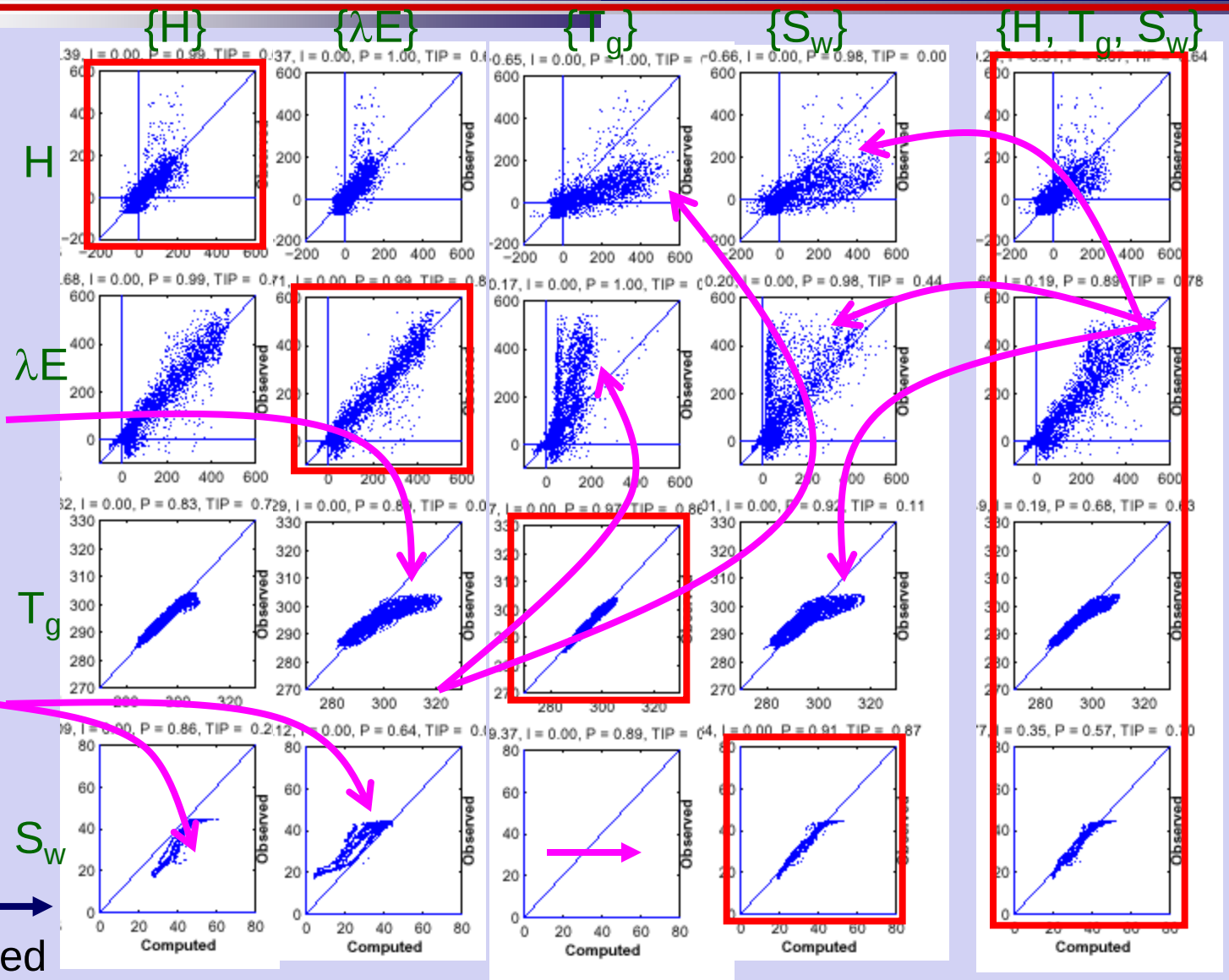
# ARM-CART SGP Site



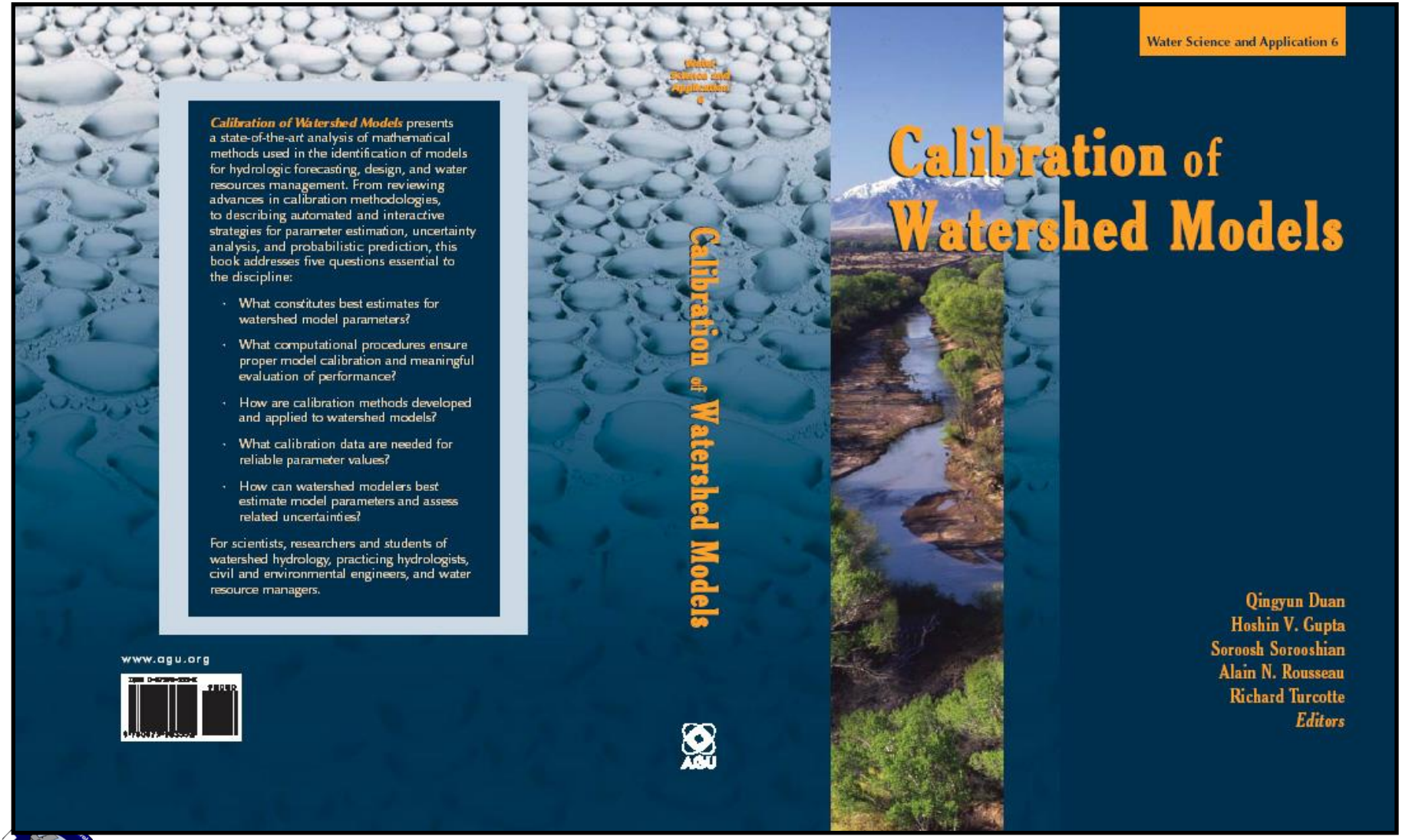

Grid: ~100,000 km$^2$

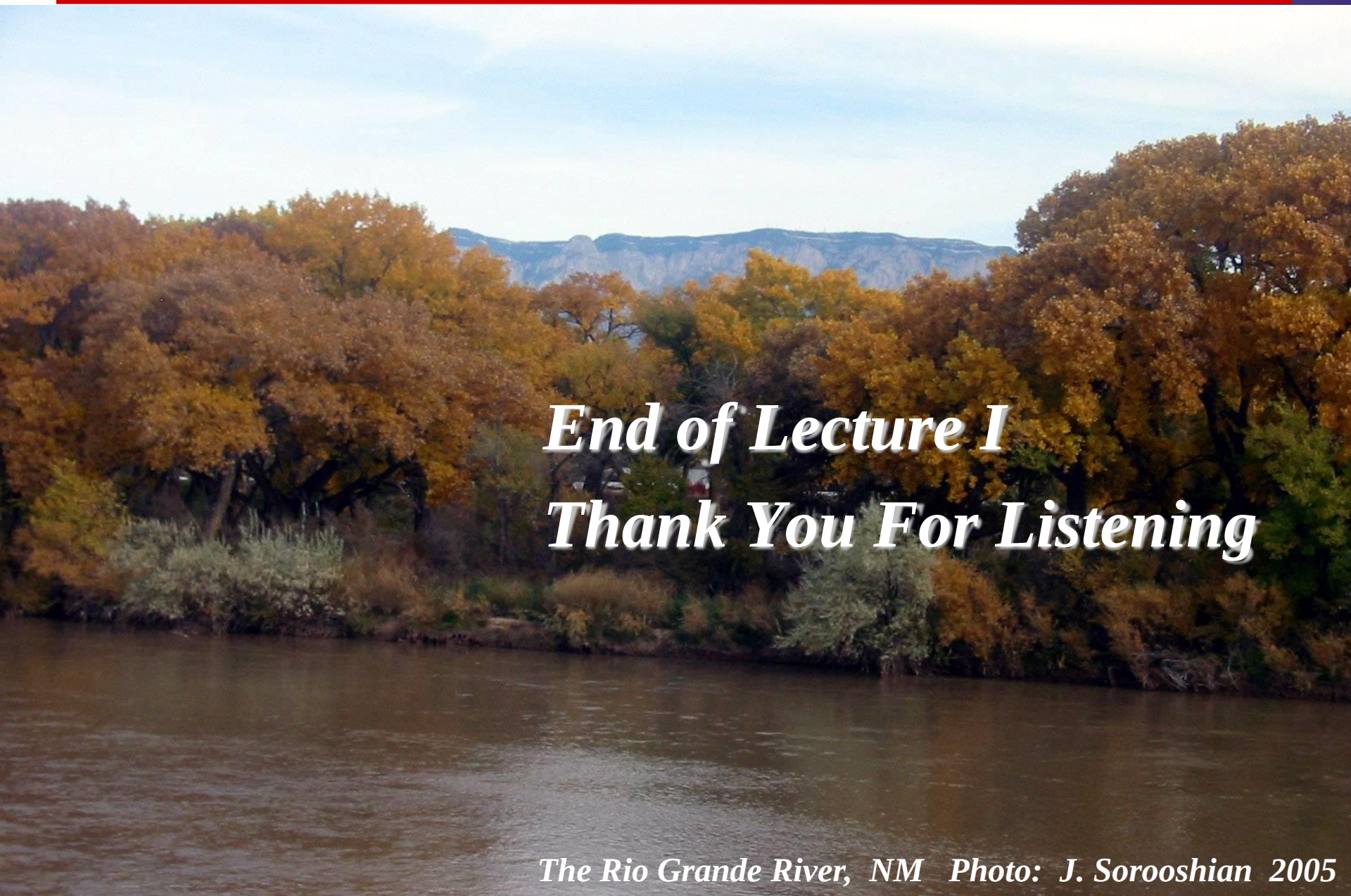
*Luis A. Bastidas Z.* *(lucho@hwr.arizona.edu)*

# Single- & Multi-Flux Calibrations



# AGU Monograph – Now Available

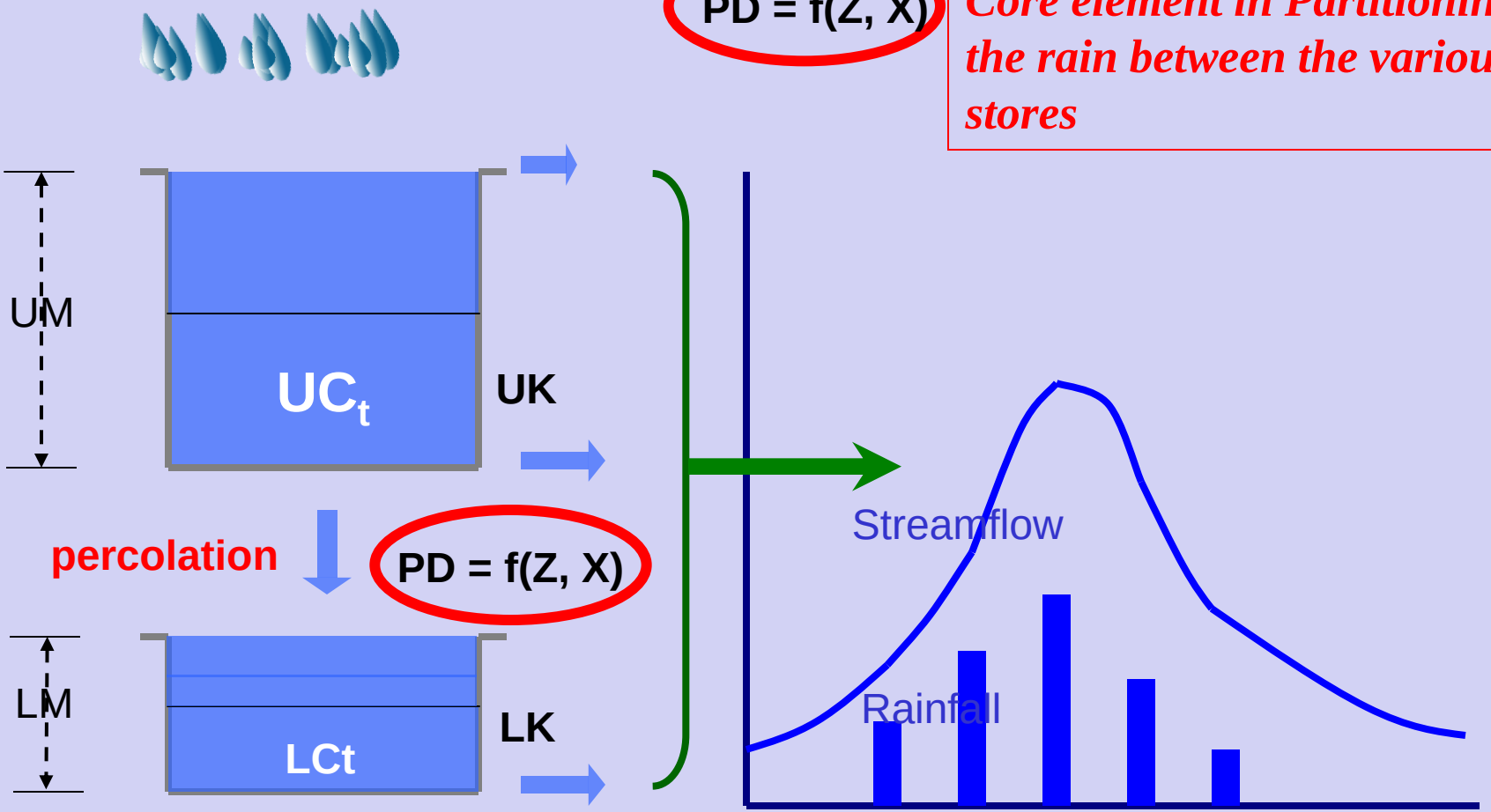




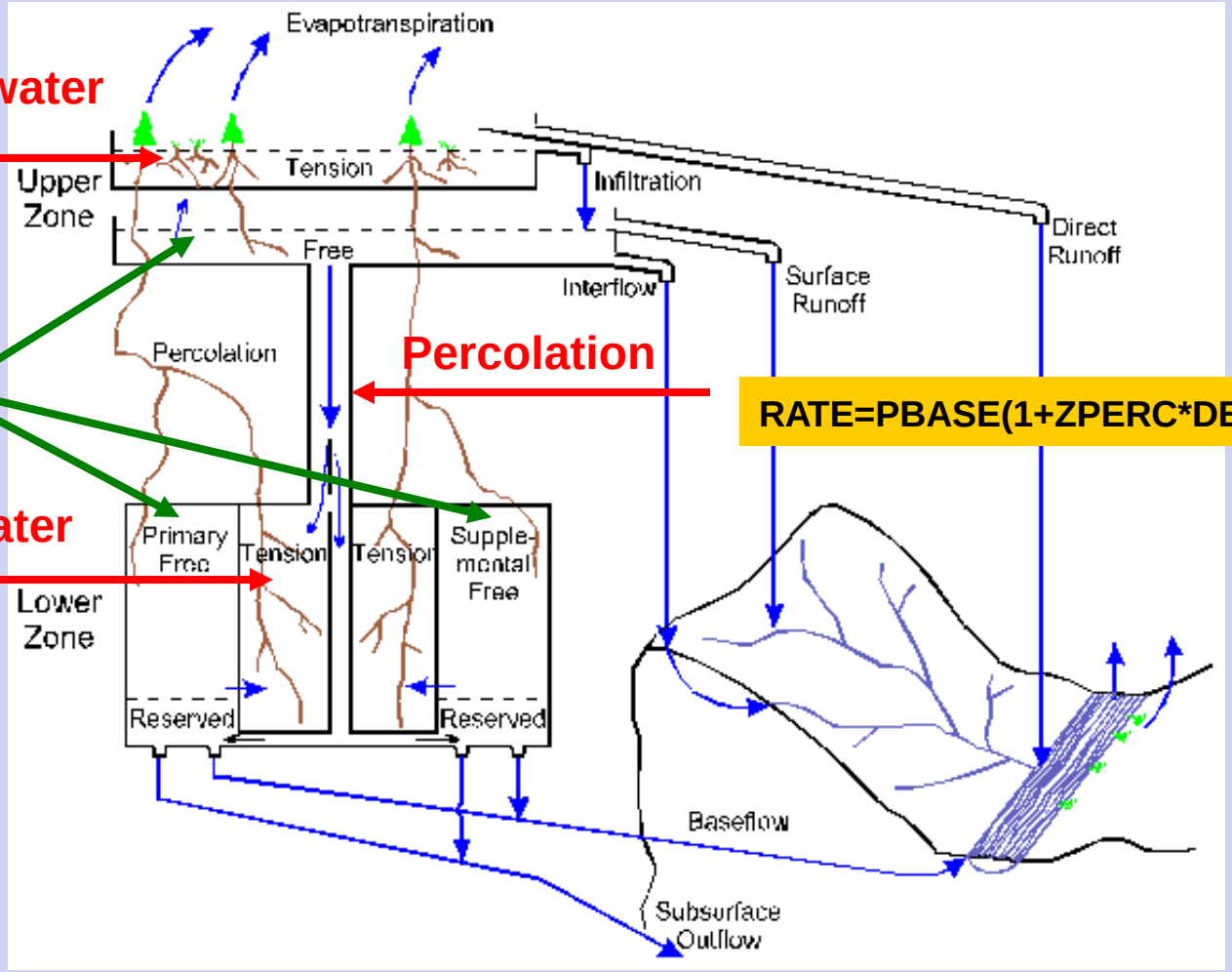

*The Rio Grande River, NM Photo: J. Sorooshian 2005*

# Backup Material

# A look into the "heart" of R-R Models



# *NWS Soil Moisture Accounting Model:* SMA-NWSRFS



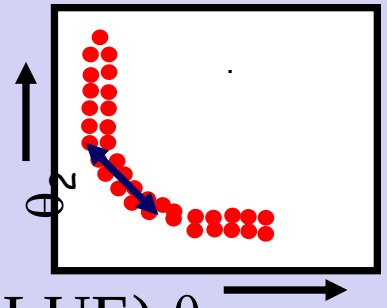

**Nonlinear structure with large number of parameters**

# Parameter Uncertainty Methods

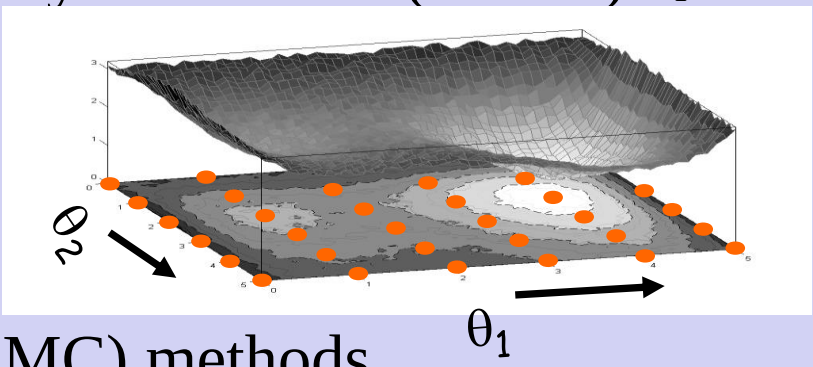
(1) First-order approximations near global optimum (Kuczera etal)

**Limitations**

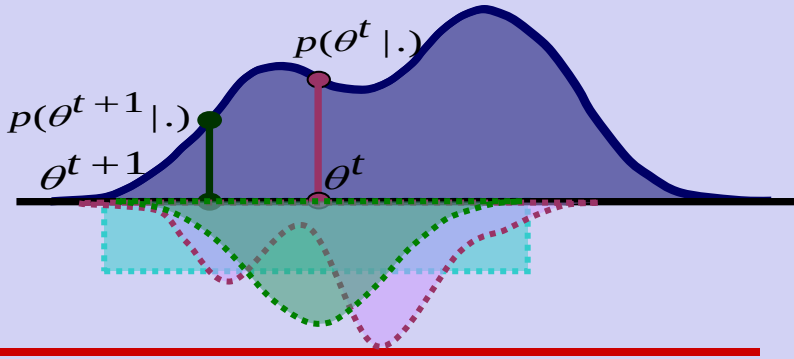
- **Assumes Model is Linear**
- **Assumes Posterior Dist. Guassian**



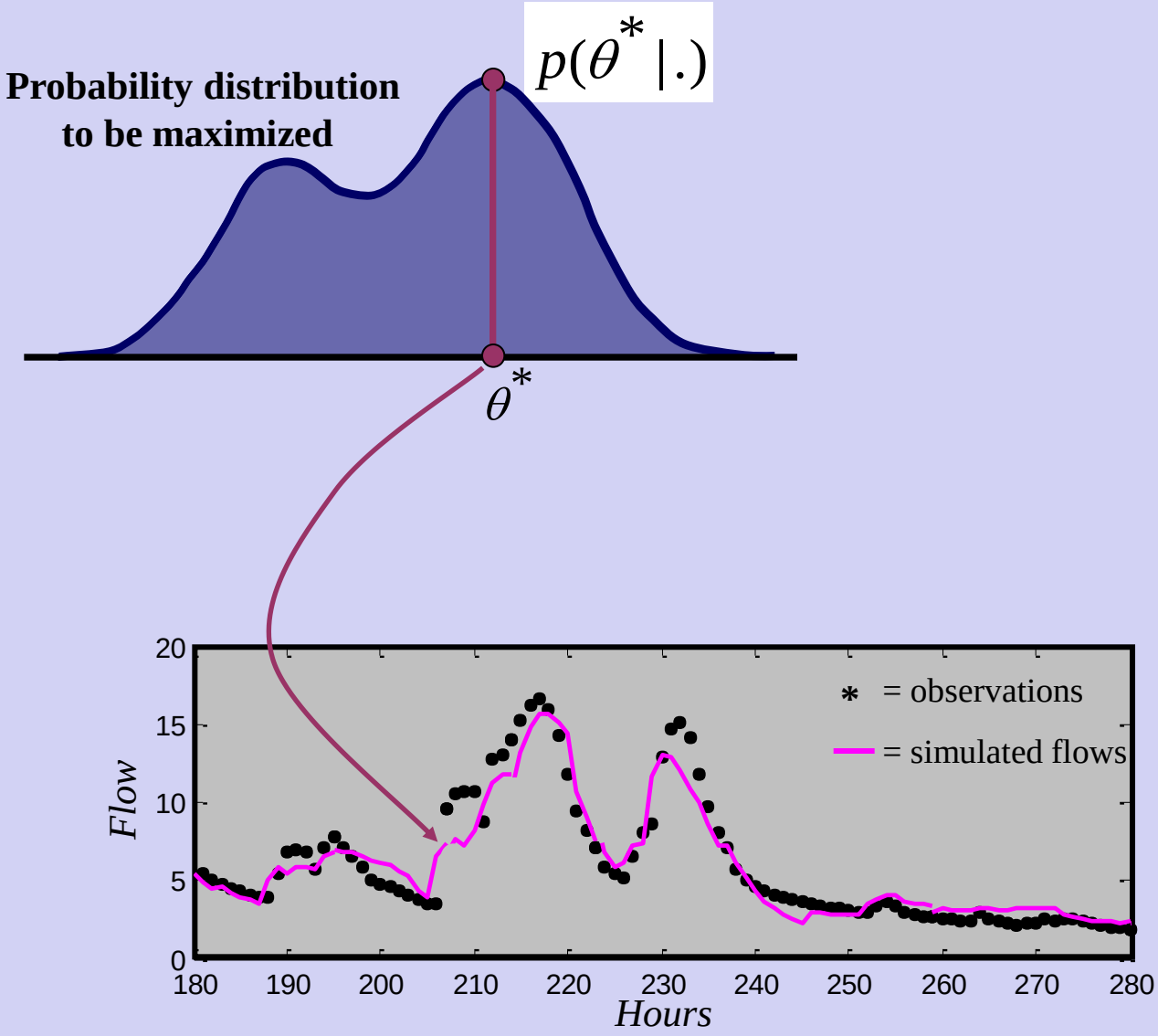

(2) Generalized Likelihood Uncertainty Estimation (GLUE) method (Beven and co-workers)



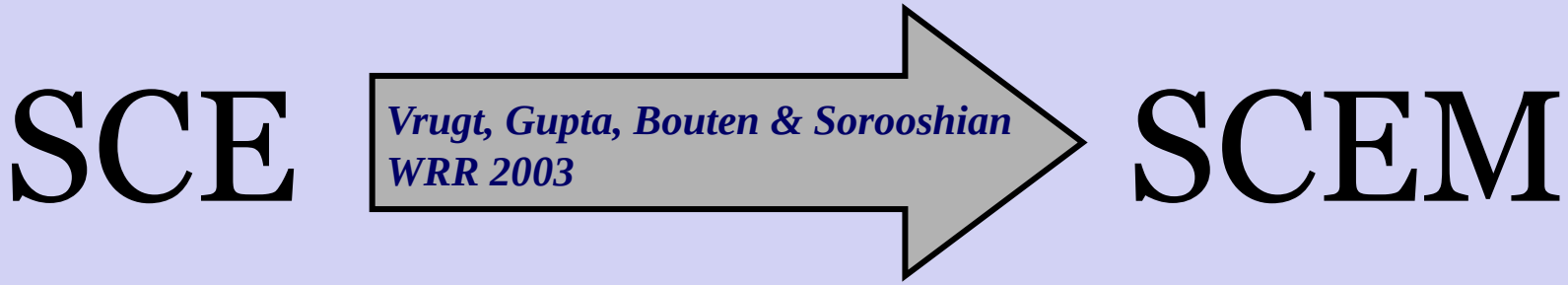

(3) Markov Chain Monte Carlo (MCMC) methods (Vrugt and others)



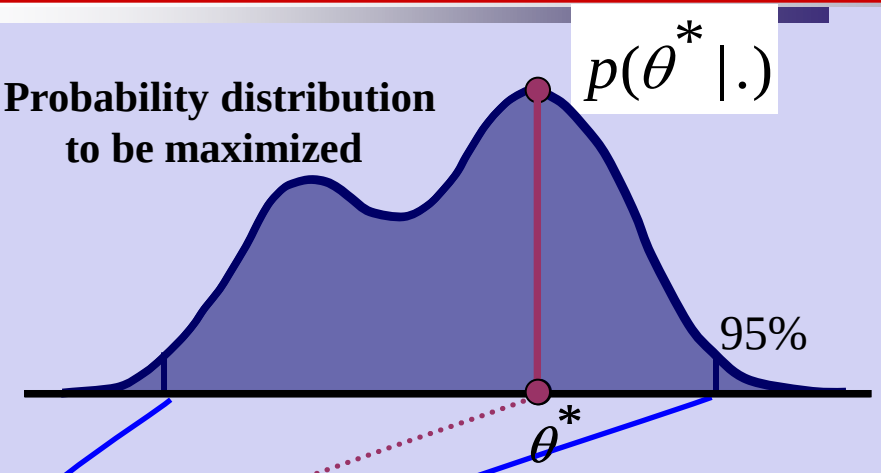
# SCE-UA *only solves for Mode of Distribution*

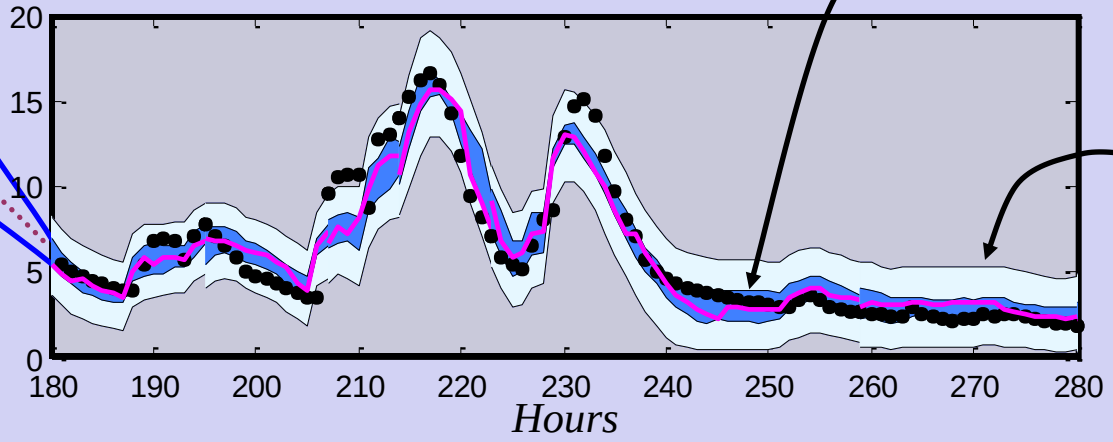


# *Shuffled Complex Evolution Metropolis*



# Need estimates of the prediction uncertainty

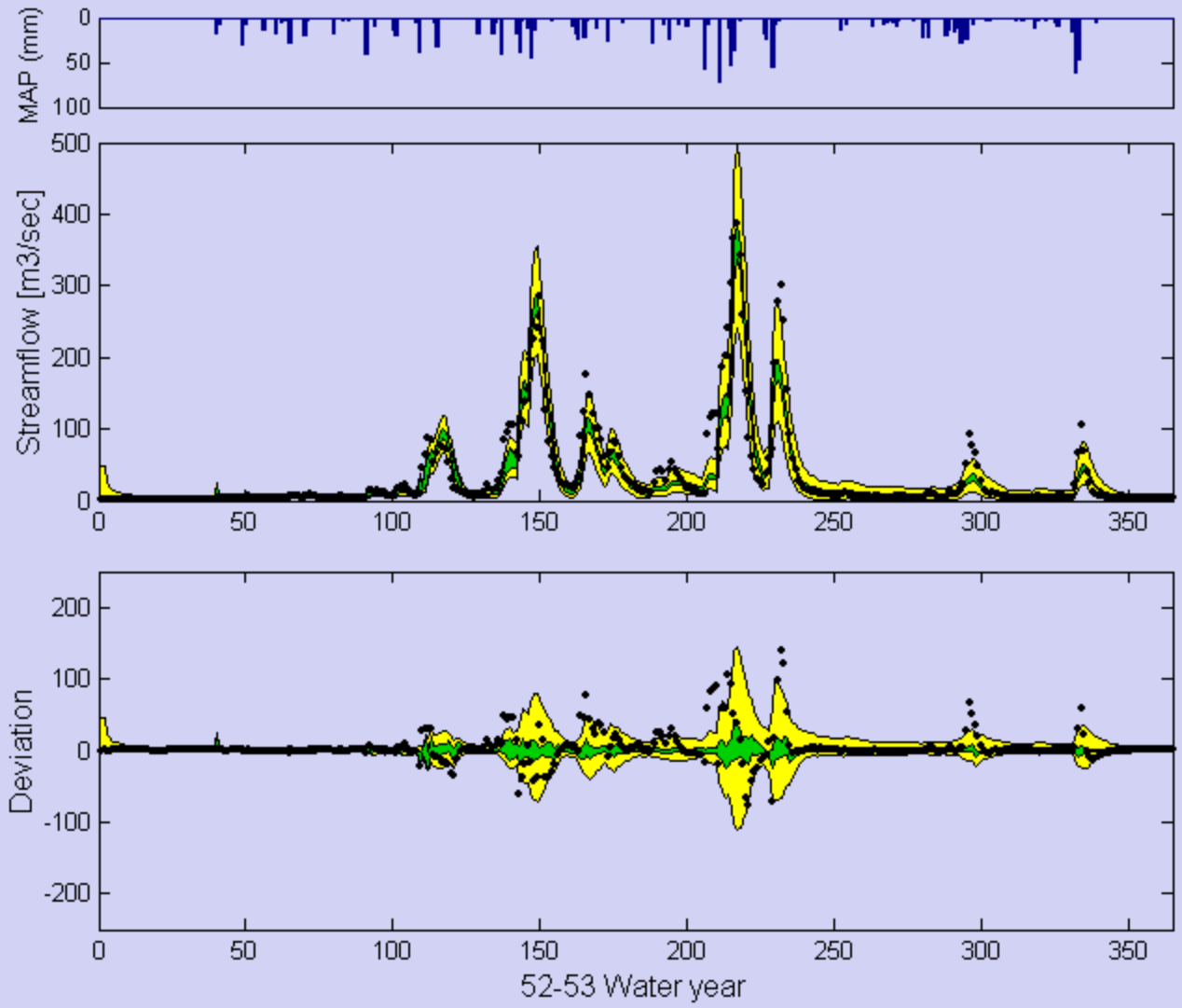


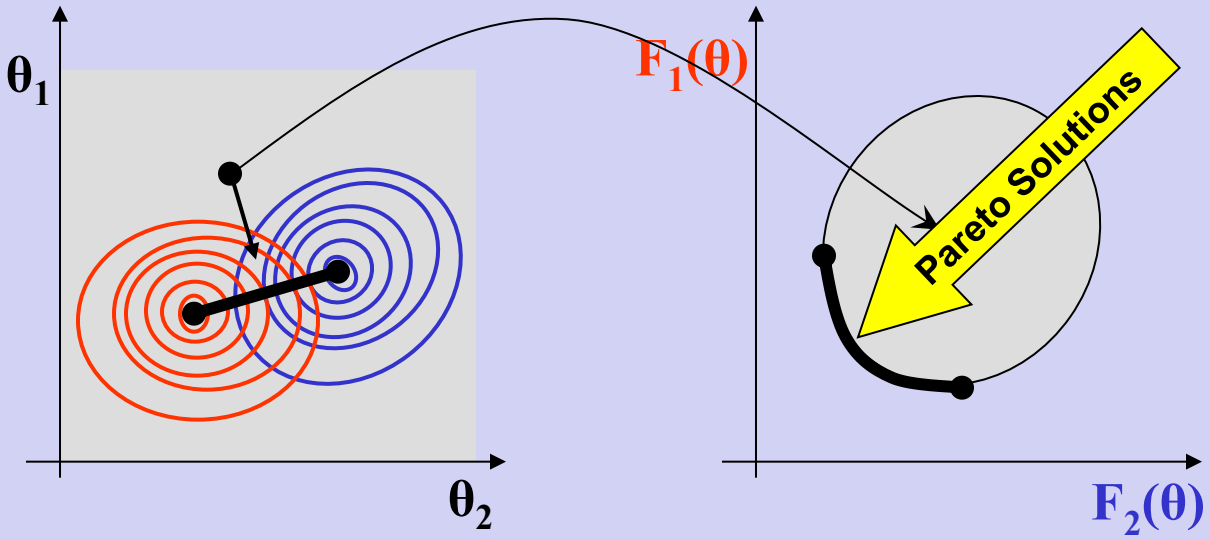

**Uncertainty associated with parameters**

**Total Uncertainty including structural errors**

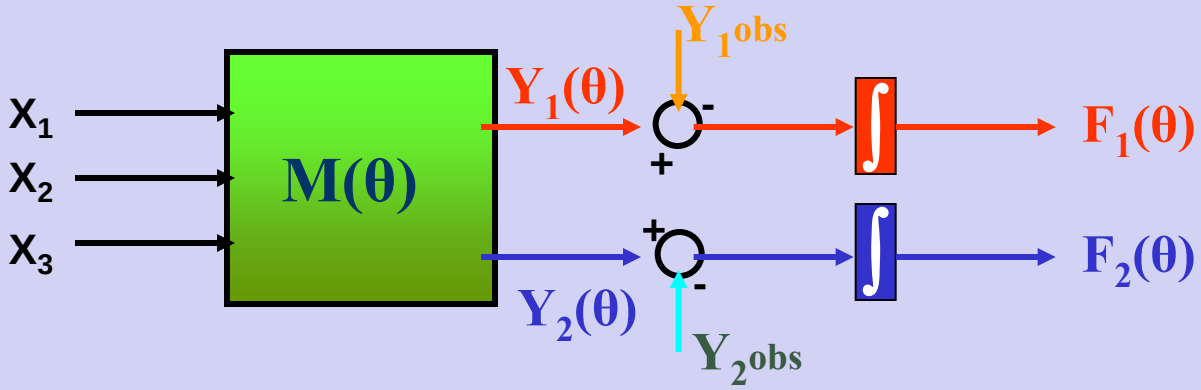
# Flow Ranges instead of point estimates

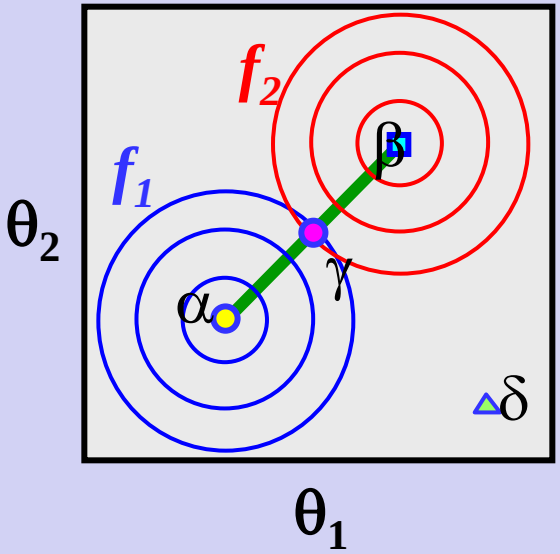


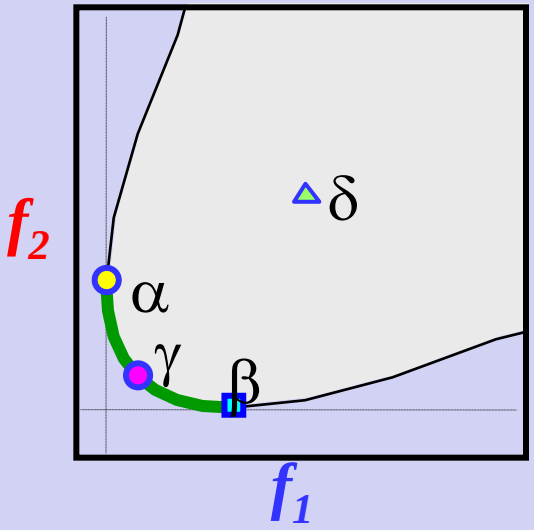
# Multi-Criteria Calibration Concept



# Multi-Criteria Calibration Approach




*Gupta, Sorooshian, Yapo, WRR, 1998*

# "Semi-distributed" Hydrologic Models