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Numerical Simulation of Integrated Terrestrial Processes over the East River (Dongjiang) in South China

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Groups:

Hong Kong Observatory, Water Supplies Department

Pearl River Water Resources Commission in Guangzhou

Xinfengjiang Reservoir Authority in Heyuan

Research Cooperators:

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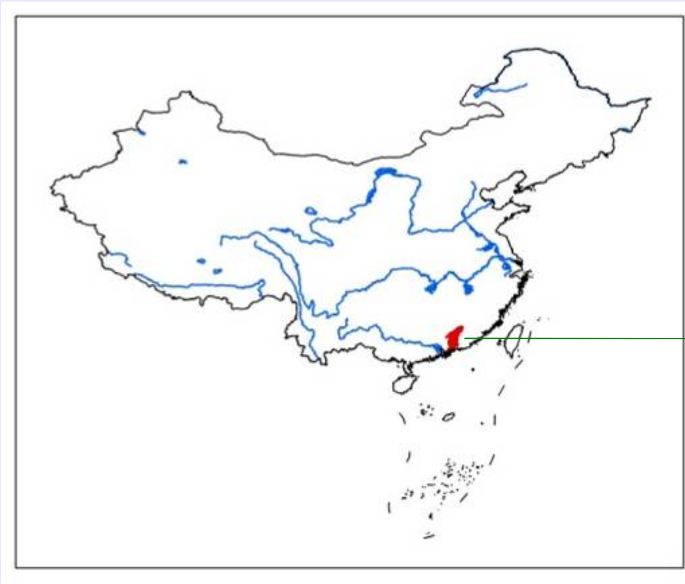
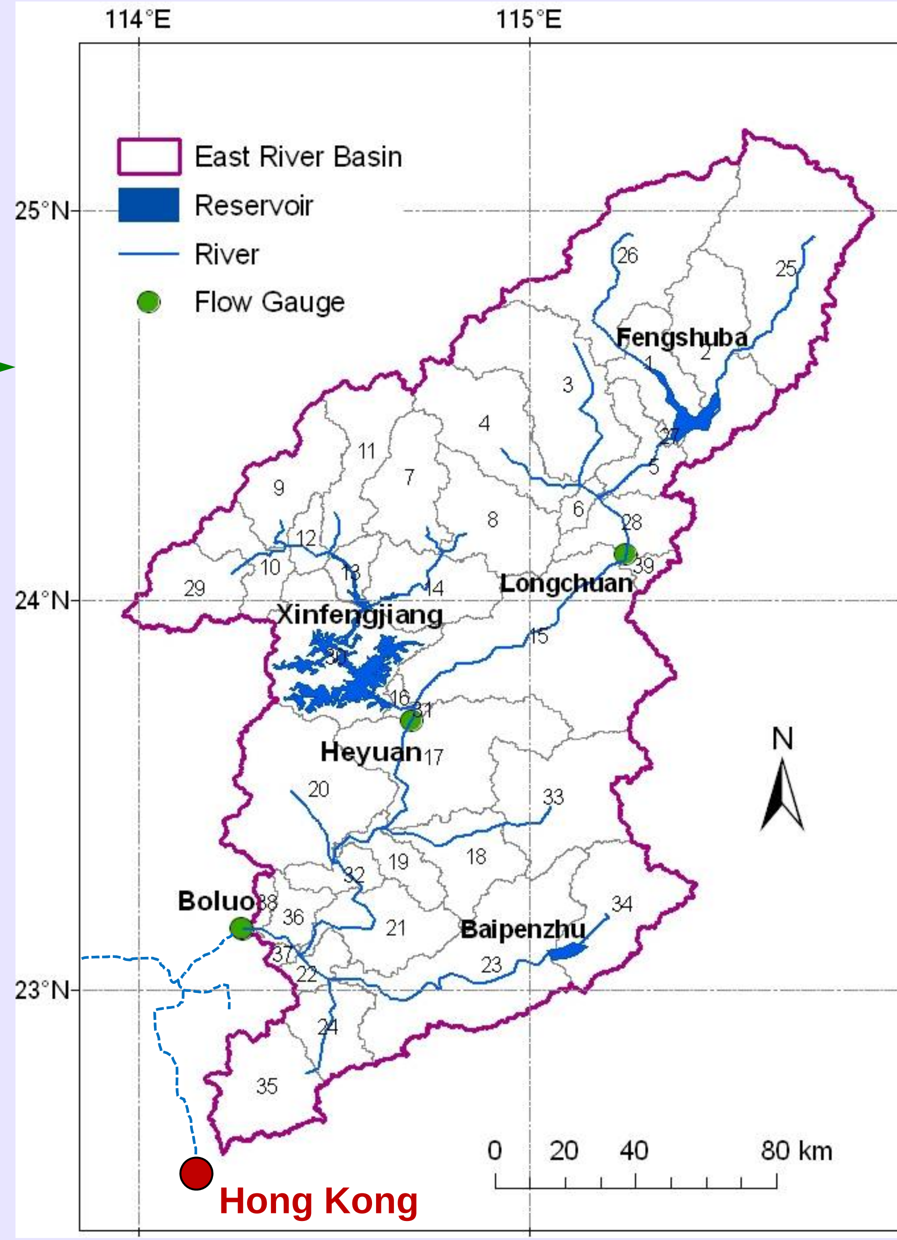
Study area



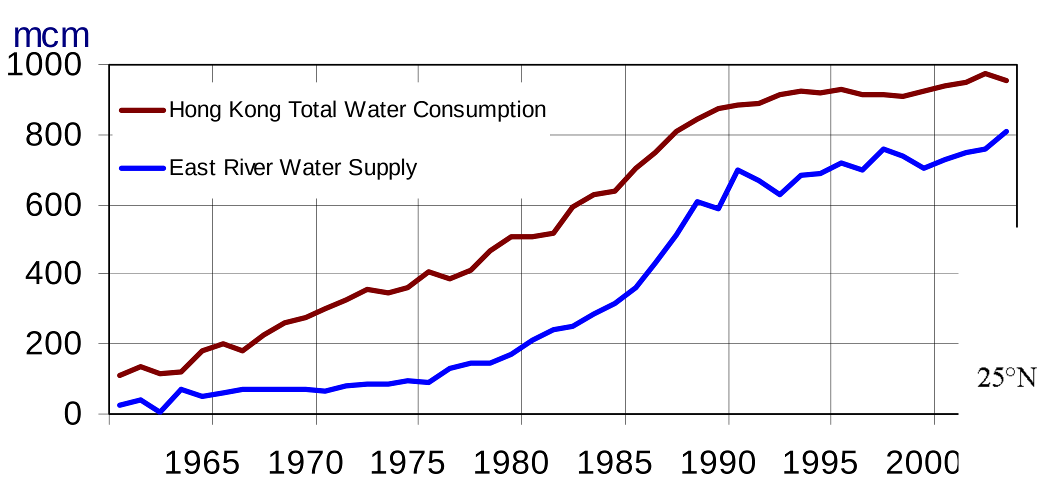
The East River (Dongjiang) Basin



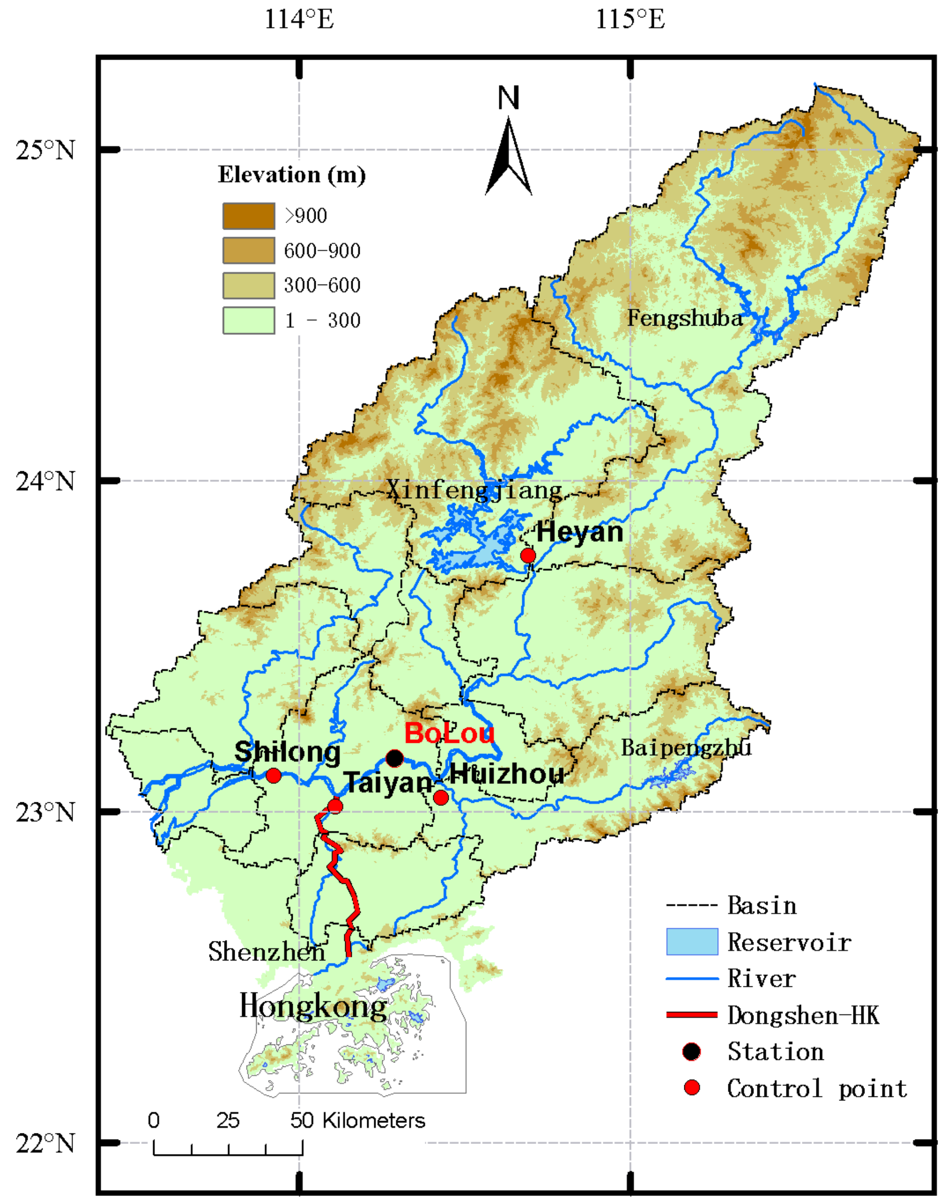
- Drainage area: 25,325 km^2
- Mainstem length: 562 km
- Total reservoir storage capacity: 18.2×10^9 m^3
- XFJR is the biggest reservoir in the basin
- Water supply for:

  Hong Kong, Shenzhen, Heyuan, Huizhou, Dongguan, Guangzhou

- 80% of fresh water supply in Hong Kong is from the East River

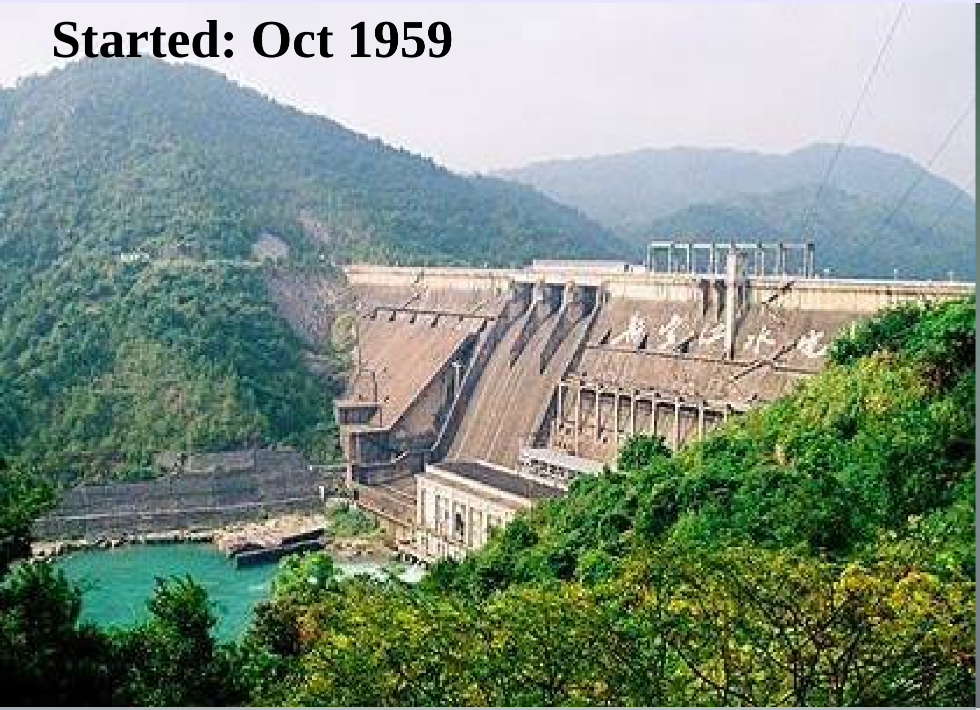


The East River water and the water supply in Hong Kong



Xinfengjiang Reservoir (XFJR)

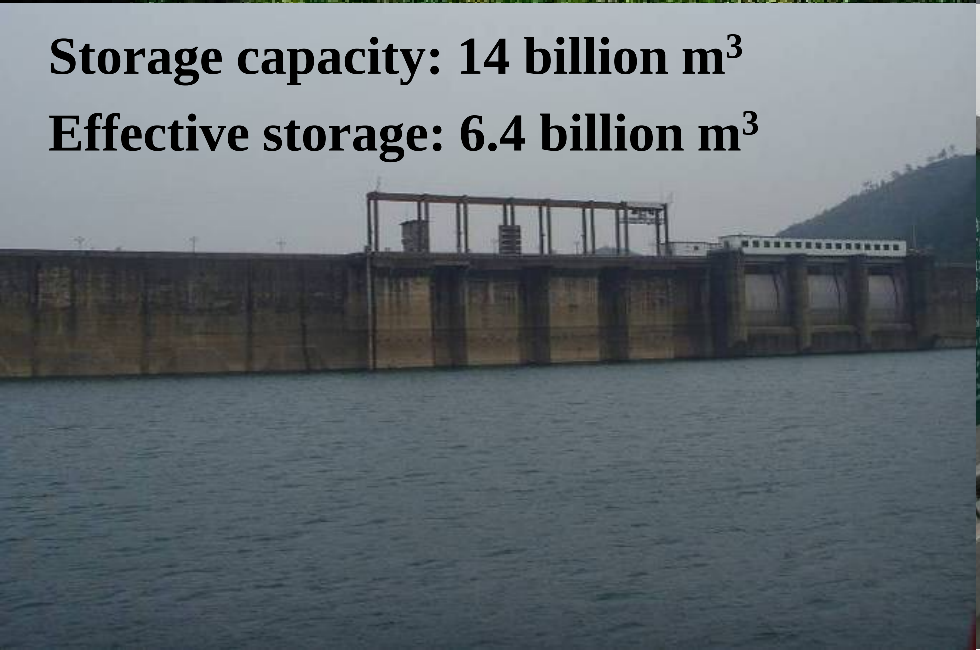
Started: Oct 1959



Area: 5,734 km^2

Storage capacity: 14 billion m^3

Effective storage: 6.4 billion m^3



Field Trip: Oct 14, 2007

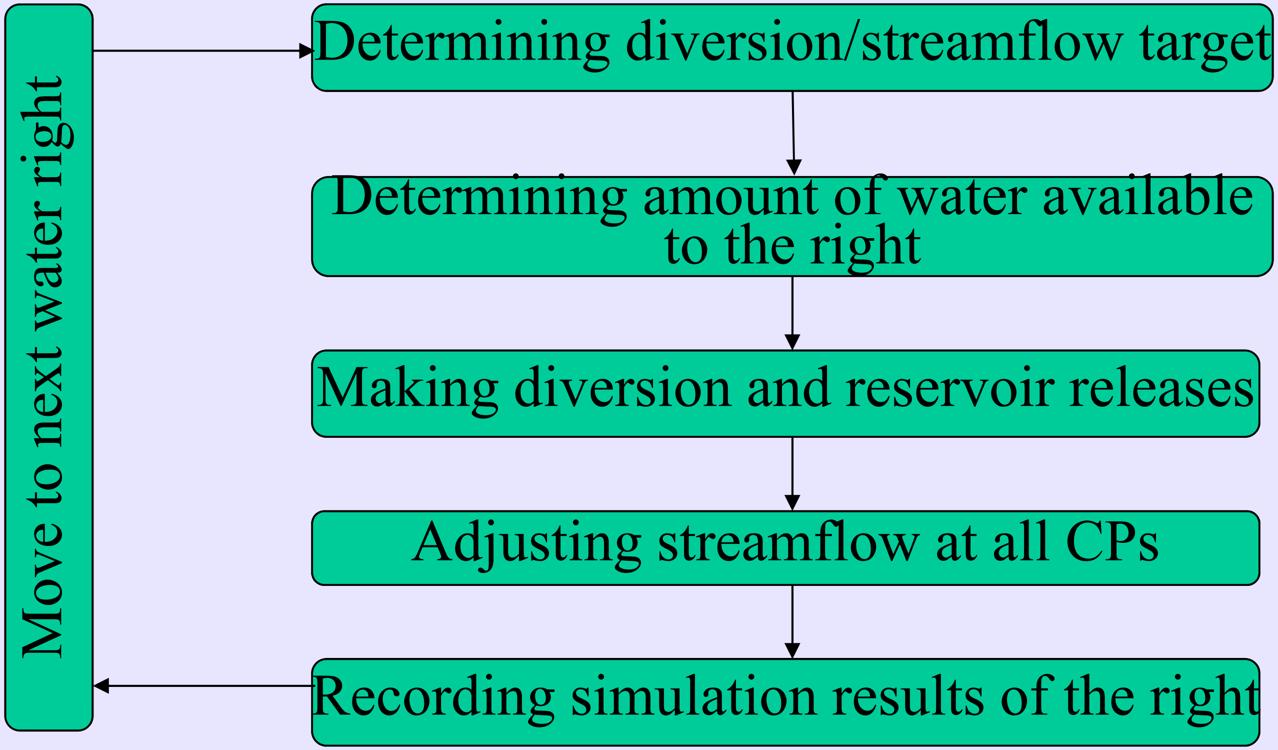
Water Resources in the East River

WRAP

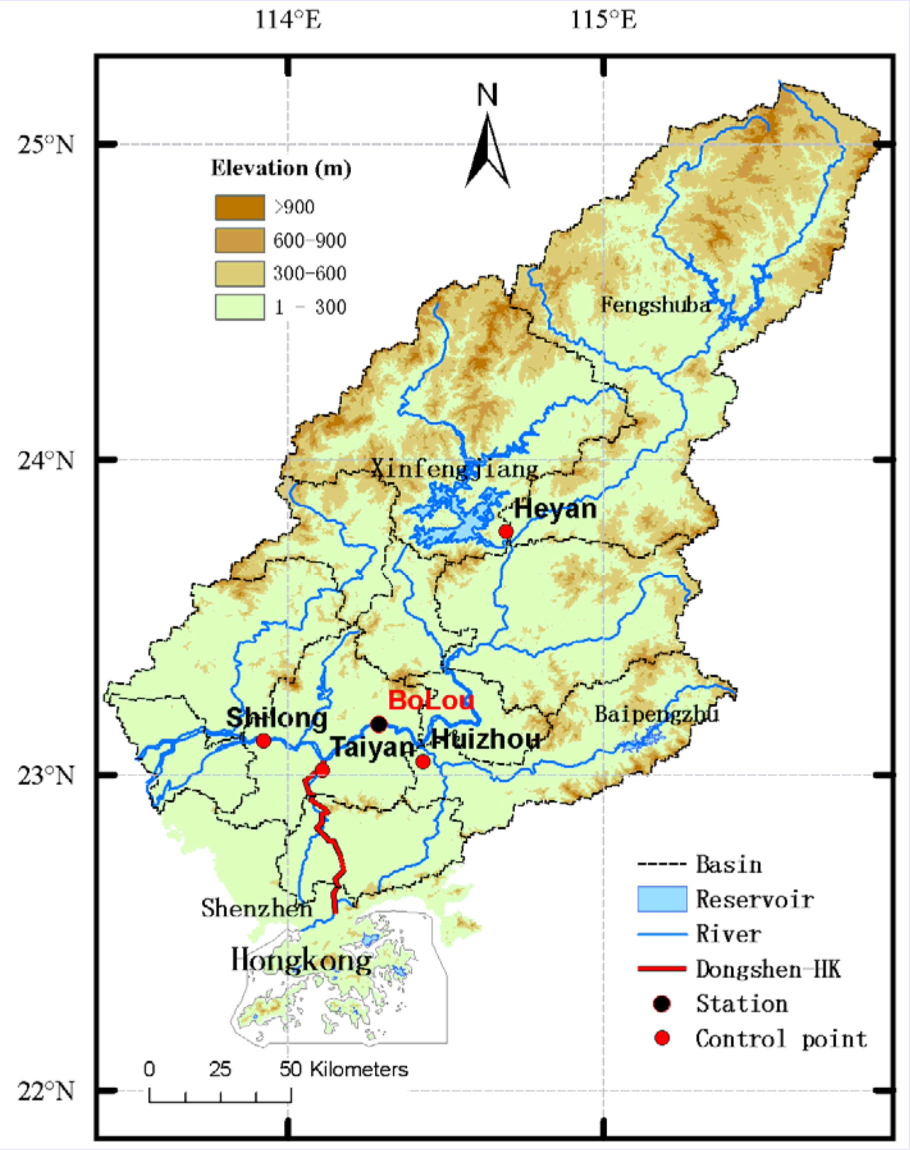
- Developed by **Prof. Ralph A. Wurbs** and his students in Texas A&M University, USA, in the late 1980s
- **Priority-based simulation system**
  - Available streamflow is allocated to each water right in turn in ranked priority order
  - The most senior water right (with the highest priority) can get water required first
- **Modeling and analysis of river/reservoir system operations under the effects of**
  - Water supply diversions
  - Basic streamflow requirements (for environmental and navigation purpose)

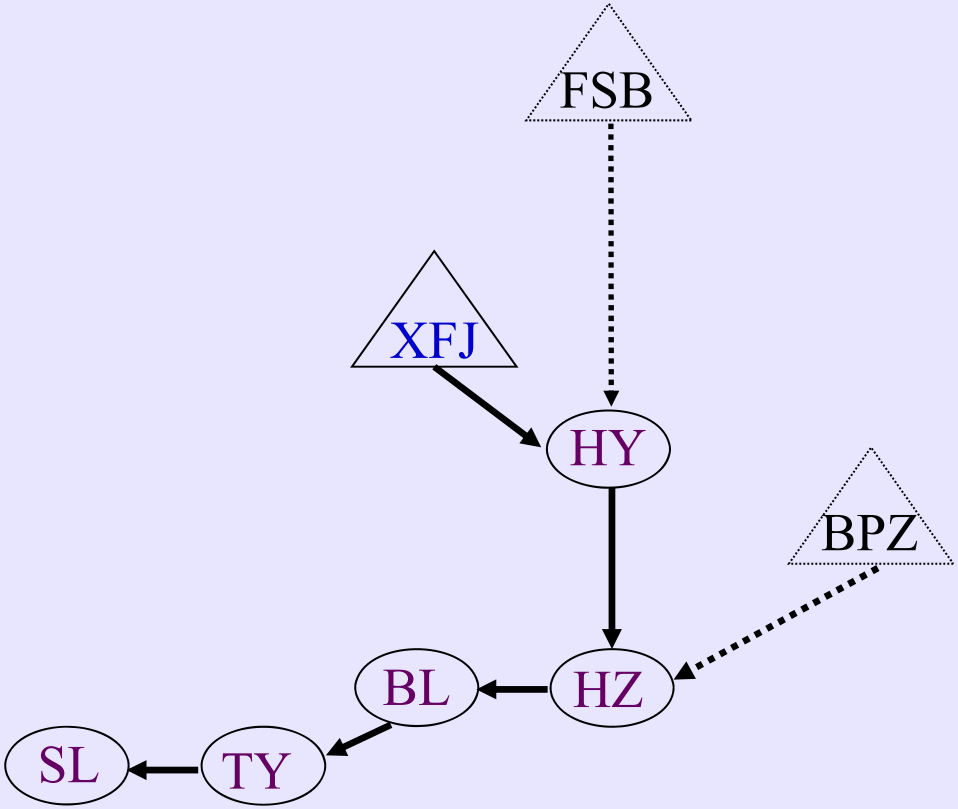
WRAP Main Structure

1. Ranking water rights in priority order
2. Reading natural streamflow and evaporation rate
3. Carrying out simulation for each water right as follows:



Control Points of the East River Basin





Xinfengjiang Reservoir

- Only Xinfengjiang Reservoir is included
- The reservoir contains 76% of total reservoir storage capacity in the East River basin
- Total capacity: 13.89 billion m^3
  - Conservative capacity: 6.49 billion m^3
  - Inactive capacity: 4.31 billion m^3
  - Flood control capacity: 3.09 billion m^3

Water Right Priority Order

Water availability for each water user is affected by the water right priority

Two different priority orders:

- City Direction Priority Order
- D-I-A Priority Order

City Direction Priority Order

- the priority is assigned to the cities and regions according to their location (upstream to downstream) and their importance, i.e.

  HK > SZ > HY > HZ > DG > GZ

- for each city, its priority is assigned according to the types of water usage, i.e.

  Domestic > Industrial > Agricultural > Streamflow Requirement

- the salinity suppression requirement at SL, BL and the minimal instream flow requirement in HY should be satisfied first before any water diversion

D-I-A Priority Order

- for each city, priority is assigned according to the types of water usage, i.e.

  Domestic > Industrial > Agricultural > Streamflow Requirement

- the priority is assigned to the cities according to their location (upstream to downstream) and the GDP i.e.

  HK > SZ > HY > HZ > DG > GZ

- the salinity suppression requirement at SL, BL and the minimal instream flow requirement in HY should be satisfied first before any right water diversion

Main Settings in Simulations

Main Parameters	**Settings**
Length of simulation period in month	12 months (the 1963 water year)
Starting month of each cycle	Starting at **October** for each simulation
Reservoir initial storage	Different storages for each simulation

Mean *Rv*(%) of each water right with different initial reservoir storage at the beginning of Oct (CC (conservative capacity))

DESCENDING PRIORITY ORDER	City	10%CC	50%CC	70%CC	90%CC
	HK(D)	100.00	100.00	100.00	100.00
	HK(O)	93.78	100.00	100.00	100.00
	SZ(D)	80.07	100.00	100.00	100.00
	SZ(I)	66.67	100.00	100.00	100.00
	SZ(A)	77.90	100.00	100.00	100.00
	HY(D)	66.67	100.00	100.00	100.00
	HY(I)	66.67	100.00	100.00	100.00
	HY(A)	41.70	66.58	85.44	100.00
	HZ(D)	66.67	91.67	100.00	100.00
	HZ(I)	60.39	85.39	100.00	100.00
	HZ(A)	36.08	61.08	94.78	100.00
	DG(D)	57.11	82.11	96.41	100.00
	DG(I)	50.00	75.00	87.43	100.00
	DG(A)	52.20	63.80	74.30	100.00
	GZ(D)	50.00	75.00	83.33	100.00
	GZ(I)	50.00	75.00	83.33	100.00
	GZ(A)	52.20	63.80	74.30	100.00

Mean R_v(%) of each water right with different initial reservoir storage at the beginning of Oct (CC (conservative capacity))

D-I-A	10%CC	50%CC	70%CC	90%CC
HK(D)	100.0	100.00	100.00	100.00
HK(O)	93.78	100.00	100.00	100.00
SZ(D)	80.07	100.00	100.00	100.00
HY(D)	66.67	100.00	100.00	100.00
HZ(D)	66.67	100.00	100.00	100.00
DG(D)	66.67	100.00	100.00	100.00
GZ(D)	66.67	91.67	100.00	100.00
SZ(I)	62.26	91.67	100.00	100.00
HY(I)	58.33	84.35	100.00	100.00
HZ(I)	58.33	83.33	100.00	100.00
DG(I)	58.33	83.33	100.00	100.00
GZ(I)	58.33	83.33	100.00	100.00
SZ(A)	70.90	82.50	100.00	100.00
HY(A)	35.51	55.71	79.55	100.00
HZ(A)	28.70	53.70	80.00	100.00
DG(A)	52.20	63.80	74.30	100.00
GZ(A)	52.20	63.80	74.30	100.00

Hydrologic Processes

Introduction of SWAT (Soil & Water Assessment Tool)

- **Development**

  Developed in the USDA-ARS in the 1990s

- **Objective**

  Predict the impact of climate change and land management practices on water, sediment and agricultural chemical yields.

- **Application**

  Contributed by several federal agencies (USA EPA, NRCS, etc.)

- **Components**

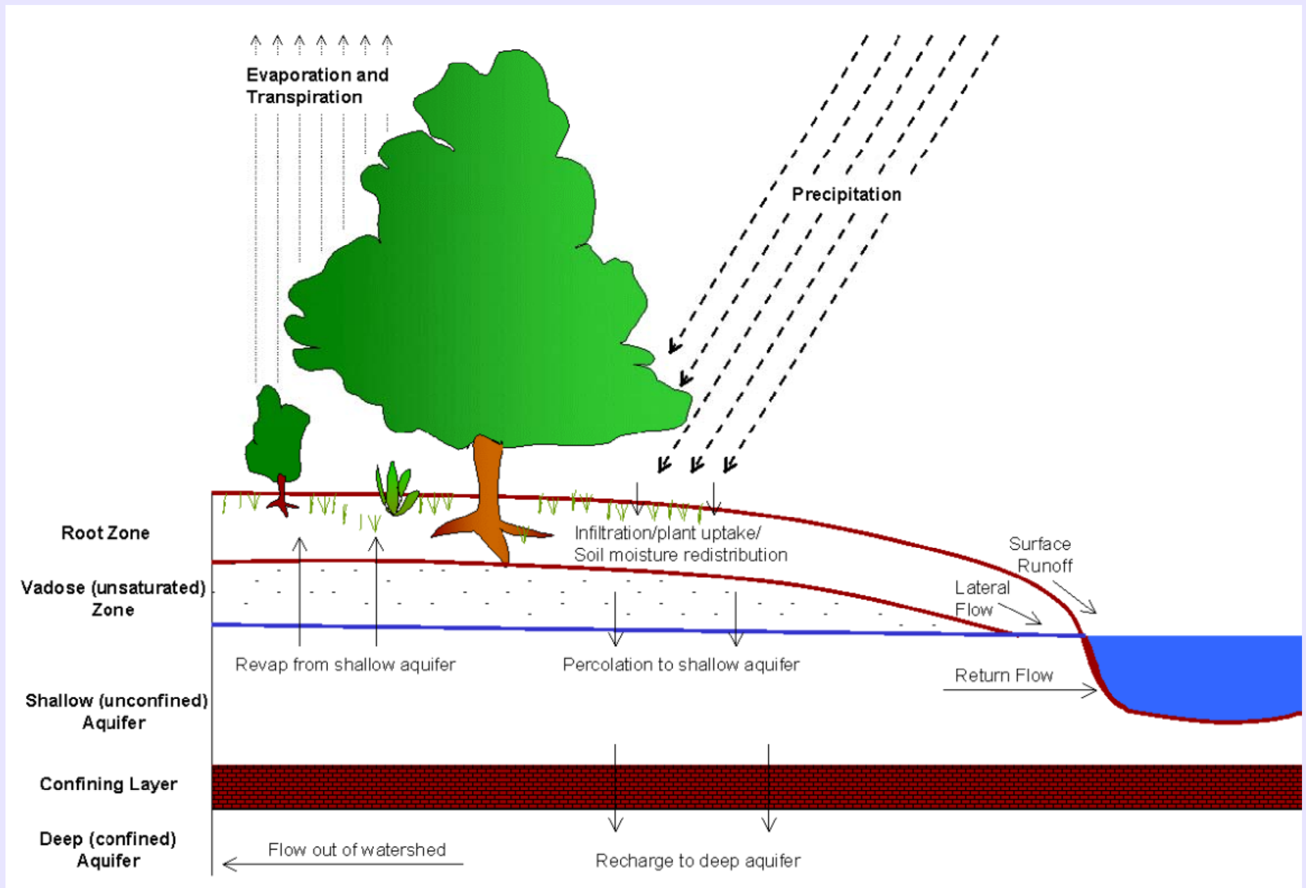
  - **Weather**
  - **Hydrology**
    - Runoff
    - Base Flow
    - Evaporation
  - **Soil erosion**
    - Sediment
  - **Pollutant transportation**
    - Nutrients
    - Pesticides
    - Crop Growth
    - Land Management

Hydrologic cycle in SWAT (Soil and Water Assessment Tool)

$$SW_t = SW_o + \sum_{i=1}^{t} (R_{day,i} - Q_{surf,i} - E_{act,i} - W_{seep,i} - Q_{lat,i}) \quad \text{(mm/d)}$$

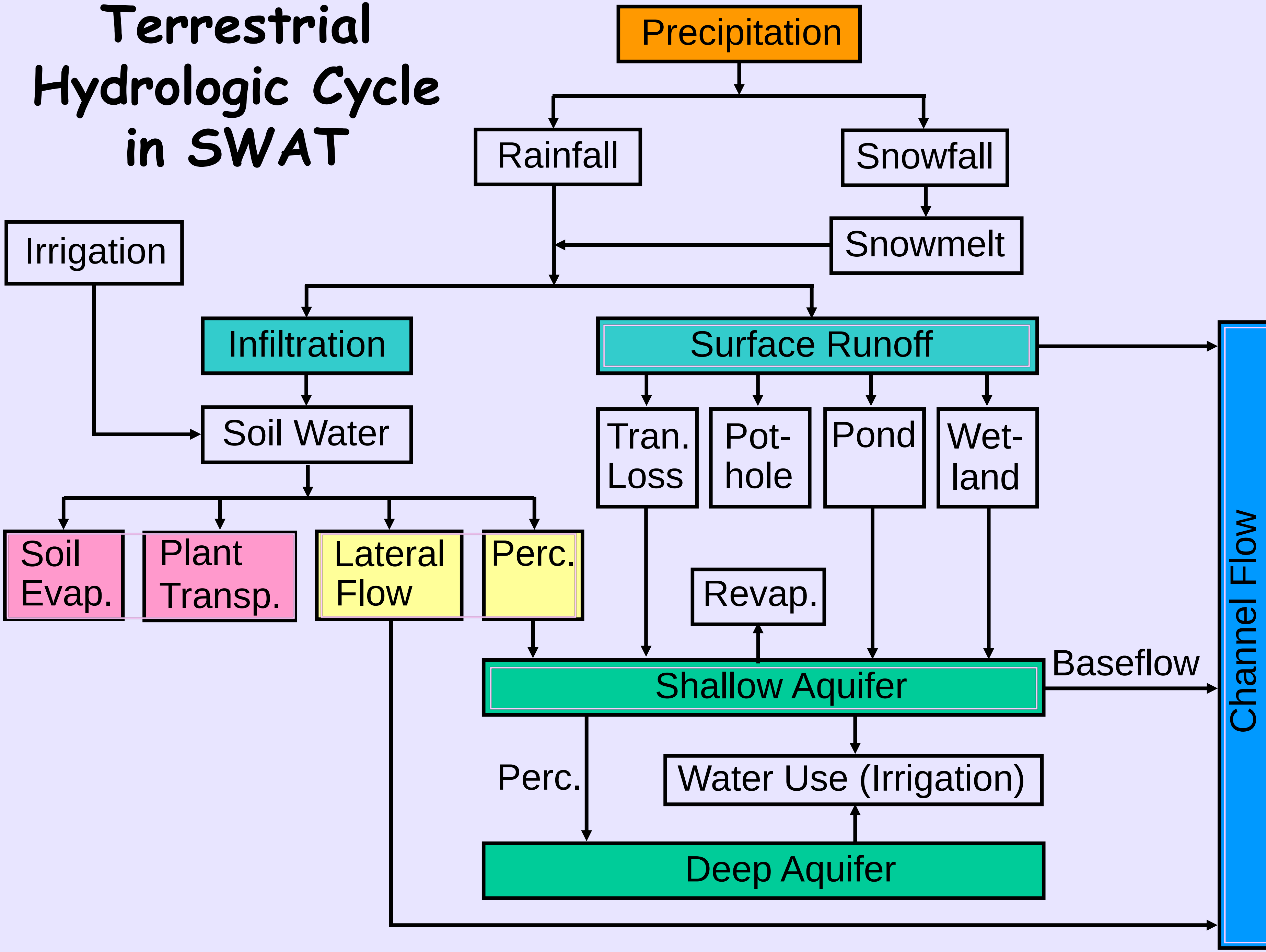
Soil profile

Groundwater



(Neitsch *et al.* 2005)

Terrestrial Hydrologic Cycle in SWAT



Main Inputs to SWAT

- **DEM data** (Topographic features)
- **Soil data**
  - **Soil Texture** (Percentage of silt, clay, and sand)
  - **Characteristics** (Soil depth, Bulk density, K_{sat}, etc.)
- **Land Use data**
- **Weather data**
  - **Precipitation**
  - **Air Temperature**
  - \+
  - **Wind Speed**
  - **Solar Radiation**
  - **Relative Humidity**
- **Crop Growth**
  - **Planting/Harvesting date**
  - **PHU (Potential Heat Unit) for the maturity of crop**
- **Land Management**
  - **Tillage**
  - **Irrigation**
  - **Fertilization**
  - **Pesticide**
  - **Harvest / Kill Operation**

Major Outputs

- **Hydrologic Output**
  - Runoff
    - Surface runoff
    - Lateral flow
    - Base flow
  - Sediment
  - Evaporation
  - Soil water
- **Water Quality Output**
  - Nitrogen
    - Organic N
    - NO_x-N
  - Phosphorus
    - Organic P
    - Mineral P
  - BOD
  - DO

HRUs Distribution

- Subbasin can be divided into hydrologic response units (HRUs) , Each HRU possesses unique landuse / soil attributes / management.

  Based on Land Use & Soil Type

- How to distribute HRUs for a subbasin

A	B	C
B	C	C
B	A	A

Land Use

+

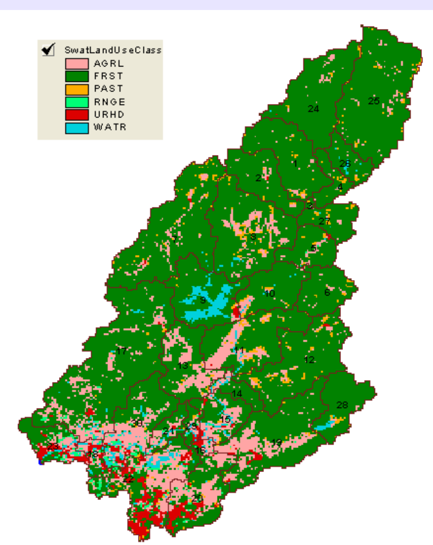
1	2	1
2	2	1
1	3	3

Soil Type

→

A1	B2	C1
B2	C2	C1
B1	A3	A3

Land Use / Soil Type



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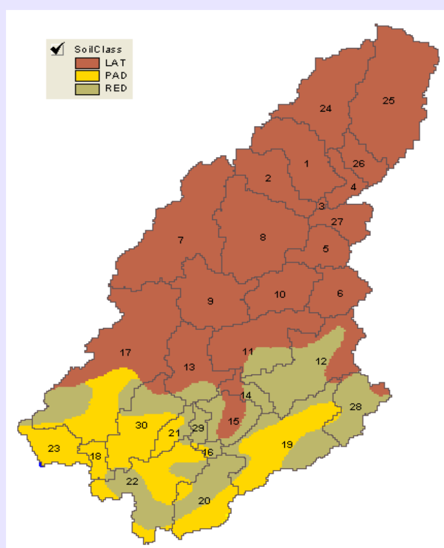

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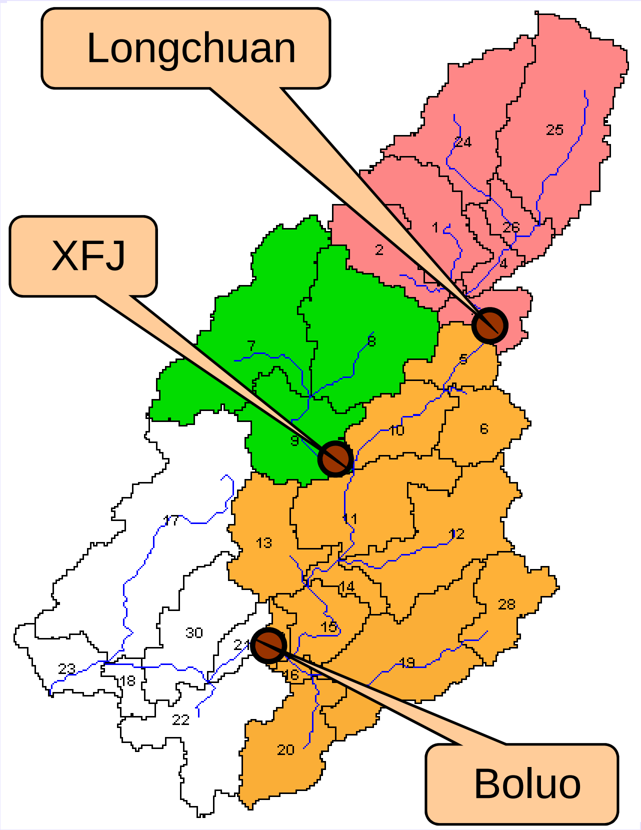
Sub #	Land Use	Soil Type	Hydr. Group	HRU #	CN2
1	FRST	LAT	C	1	77
2	FRST	LAT	C	2	77
...	...	...	...	...	...
30	URHD	PAD	D	102	87
	...	...	...	...	...
	AGRL	RED	B	109	77

Calibration

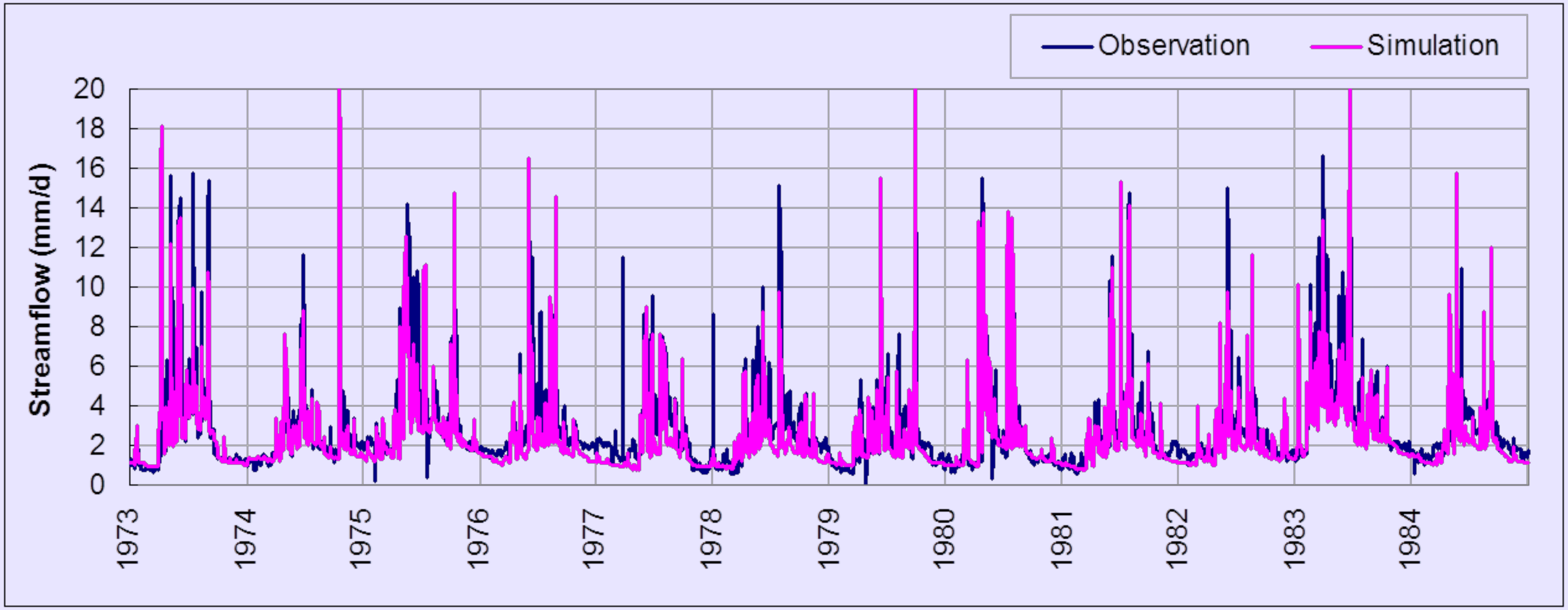


Drainage area controlled by	Observation Daily	Calibration	Validation
Longchuan	1952 – 1984 **33yr**	1952 – 1972 **21yr**	1973 – 1984 **12yr**
XFJ	1965 – 1984 **20yr**	1965 – 1984 **20yr**	
Boluo	1954 – 1984 **31yr**	1954 – 1972 **19yr**	1973 – 1984 **12yr**

Parameter	Description	Range	Calibrated Value		
			Longchuan	XFJ	Boluo
α_{gw}	Base flow recession constant	0 – 1	0.003	0.0054	0.0054
esco	Soil evaporation compensation factor	0.001 – 1	0.999	0.999	0.999
epco	Plant uptake compensation factor	0.001 – 1	0.001	0.001	0.001
gw_revap	Groundwater “revap” coefficient	0.02 – 0.2	0.05	0.02	0.2
rchrg_dp	Deep aquifer percolation fraction	0 – 1	0.1	0.016	0.5

Validation

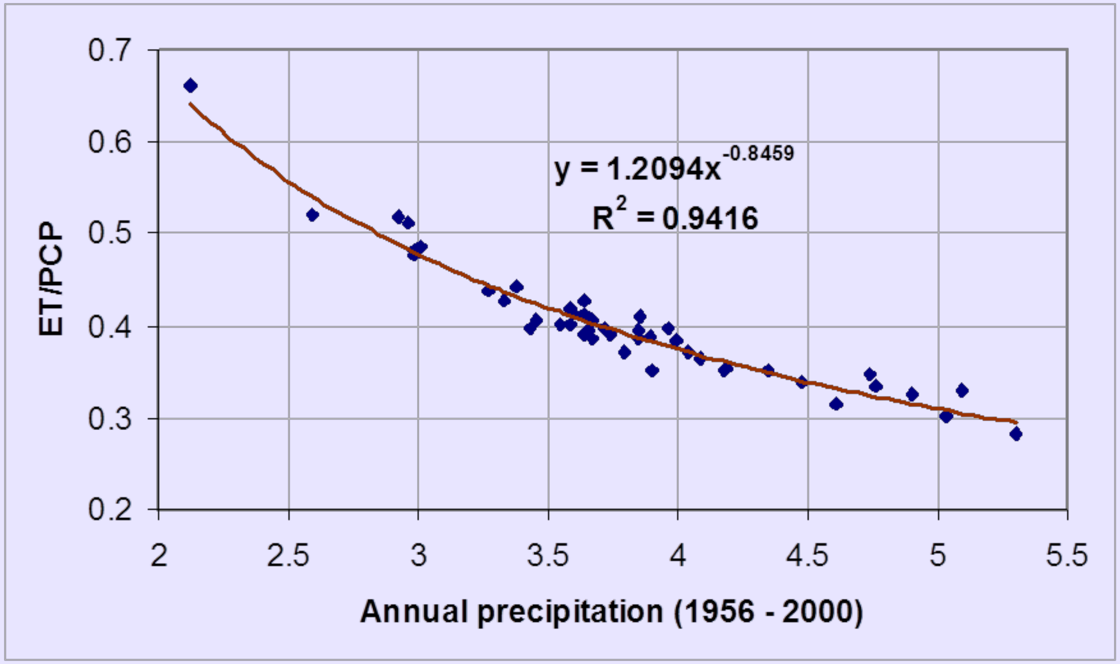
Daily streamflow at Boluo (Validation period)



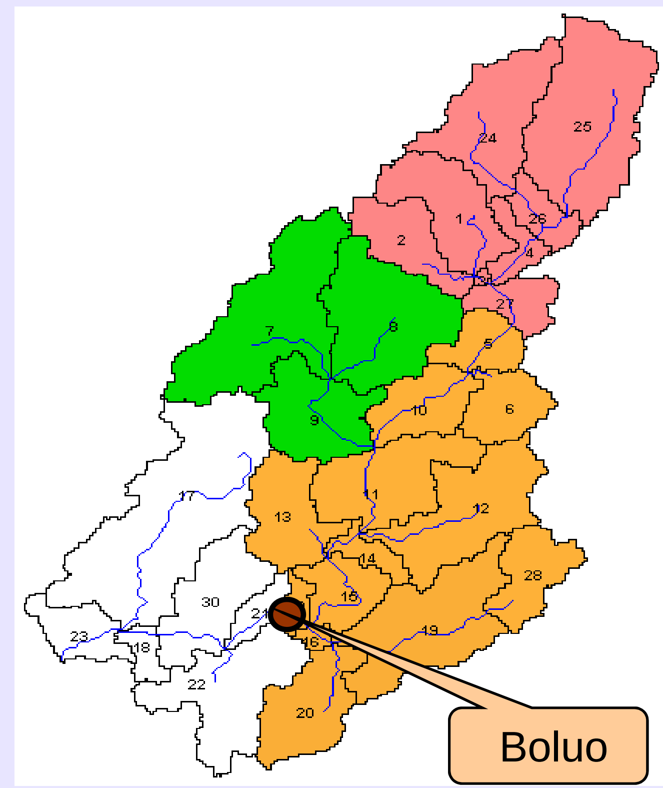
Evaluation

	Relative Bias	Correlation Coefficient
Daily flow	– 0.16	0.87

Water balance - over watershed



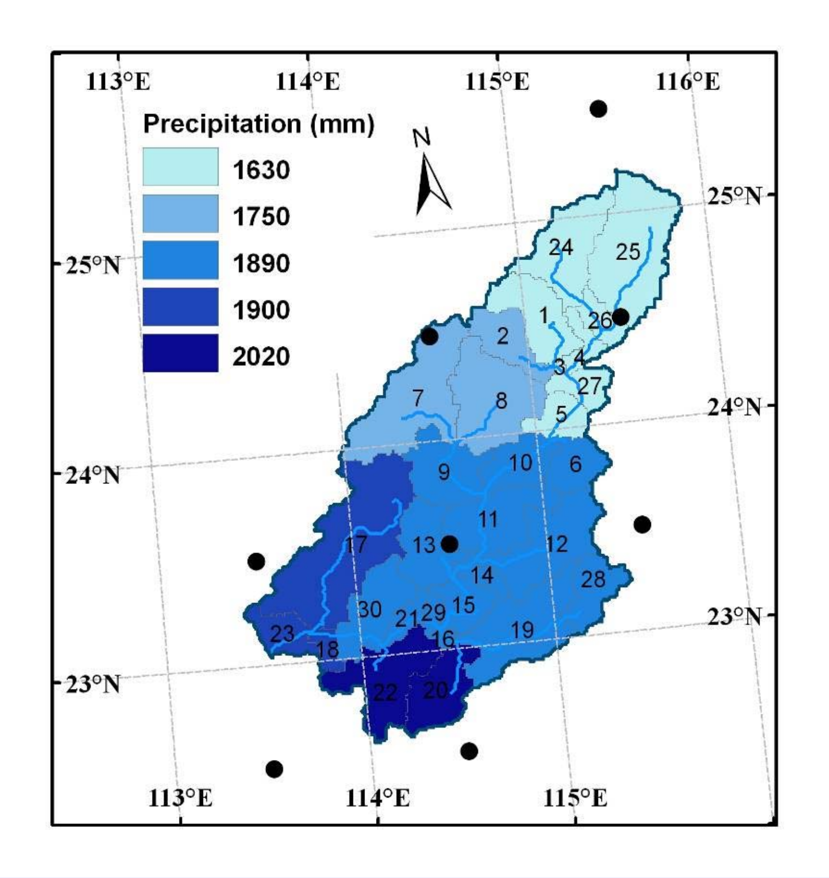
Annual Mean Item	Value (mm/d)
PCP	3.798
ET	1.484
Flow	2.155
ET/PCP	40.1%
SF/PCP	56.7%



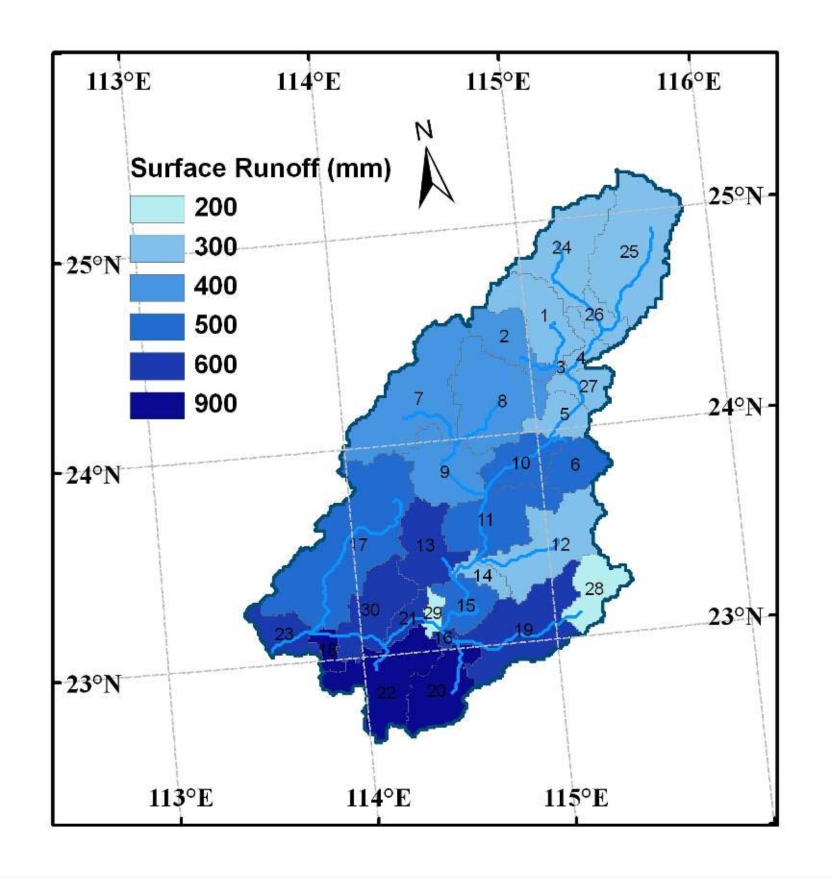
Spatial distribution of hydrologic components

Annual average (1951 – 2000)

Precipitation (mm/yr)



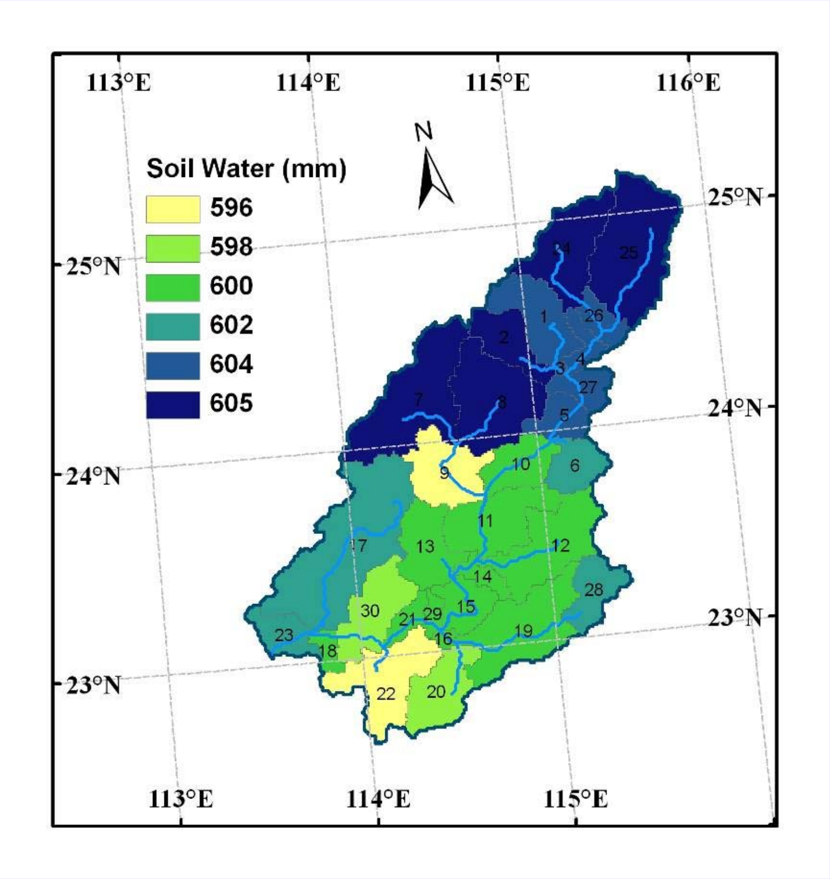
Surface Runoff (mm/yr)



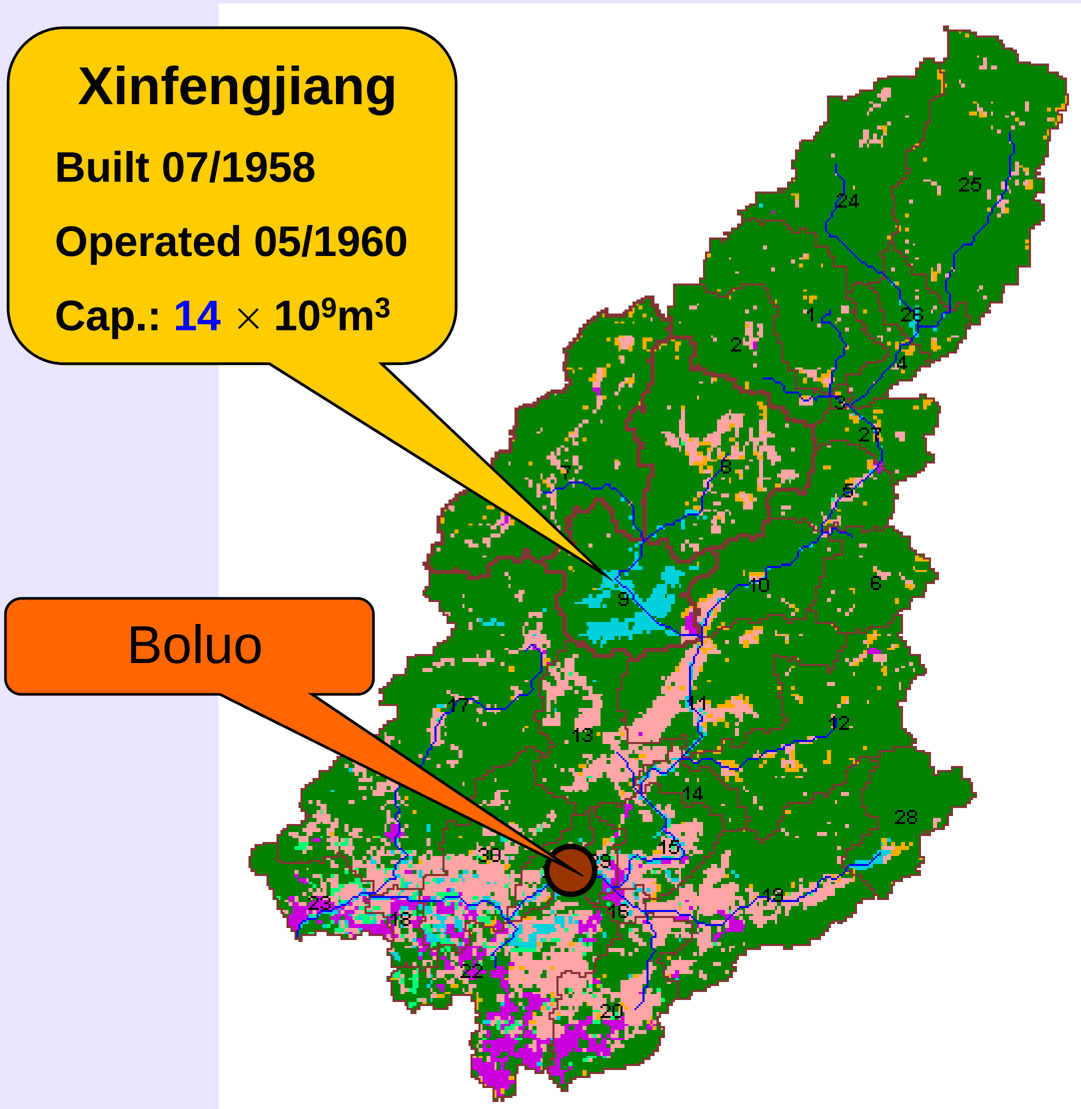
Spatial distribution of hydrologic components

Annual average (2000)

Soil Water (mm)



Reservoir operation - Reservoirs in ERB



Reservoir operation - simulated by SWAT

Controlled outflow with target release

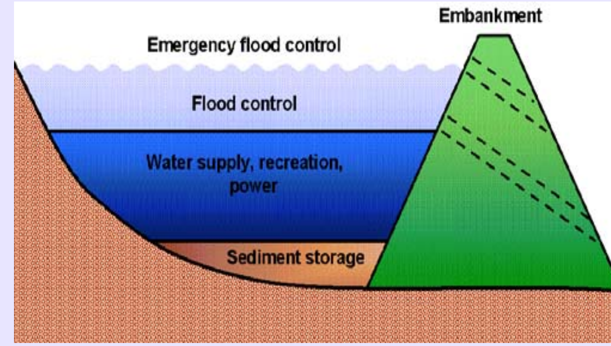
$$Outflow = \frac{V - V_{targ}}{ND_{targ}}$$

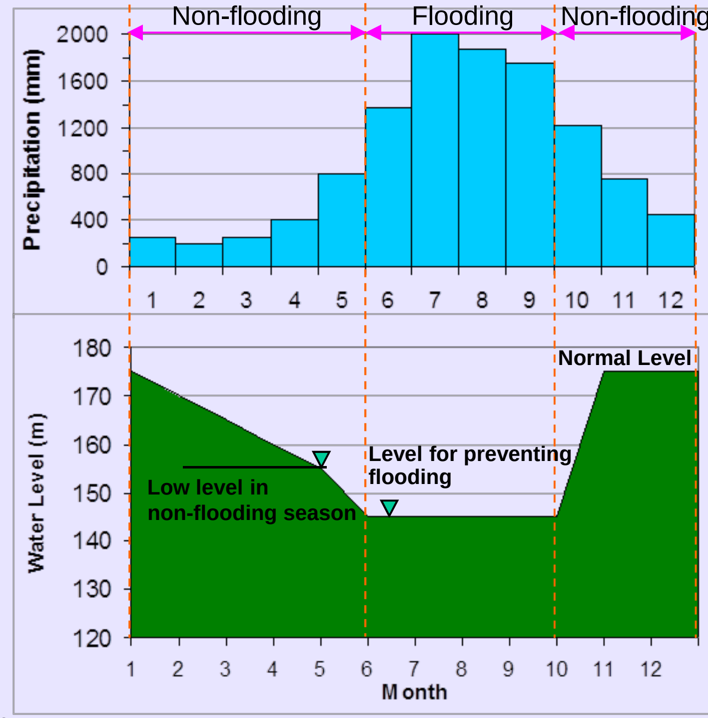
- $V_i = V_{i-1} + In - Evp - Seep$

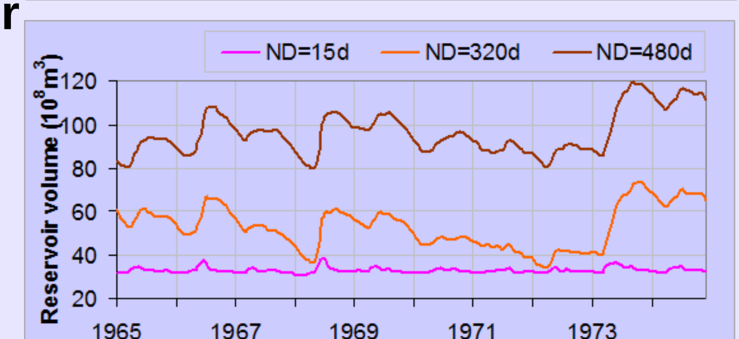
- V_{targ} **Target reservoir volume for a given day**

  The same value for all the days in each month

- ND_{targ} **Number of days required for the reservoir to reach target storage**

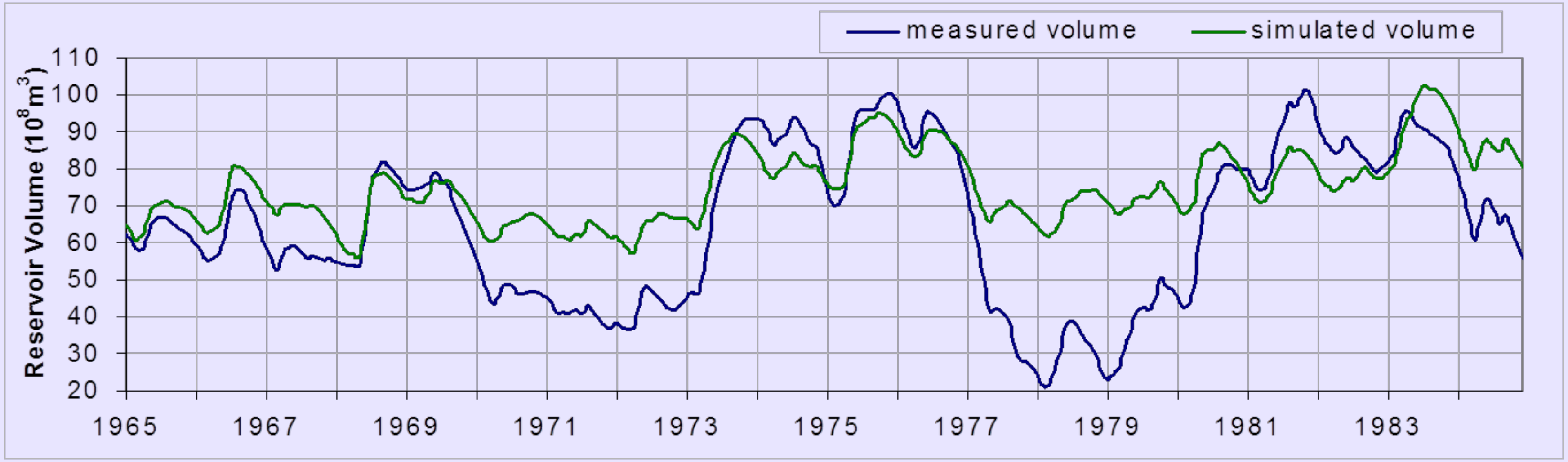




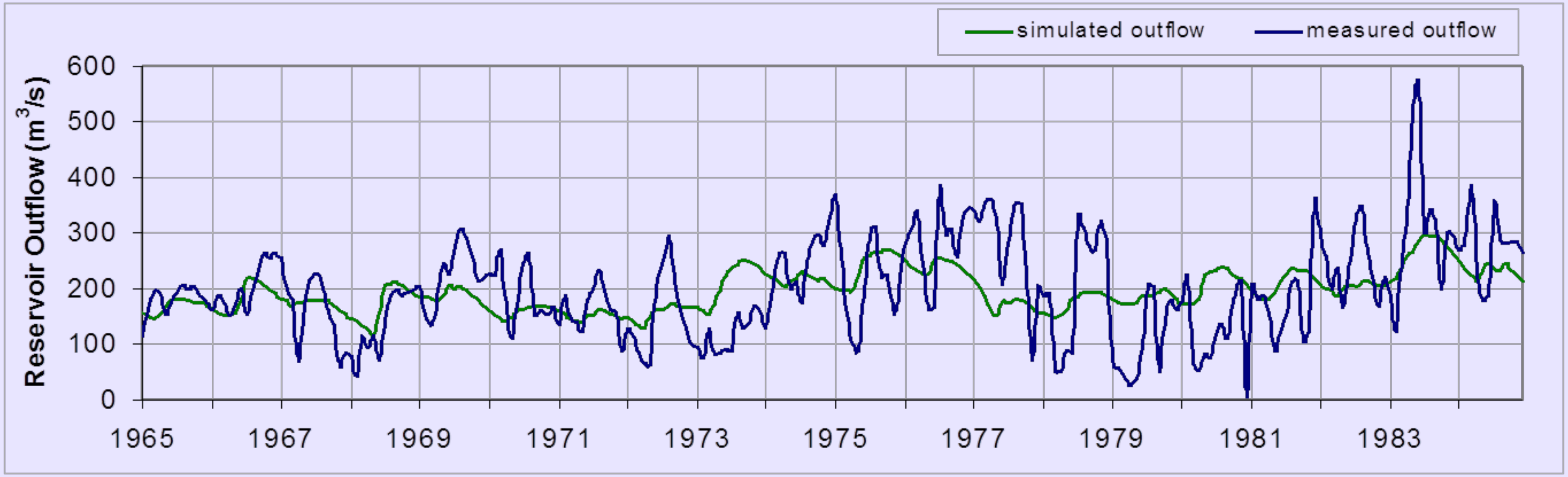


Reservoir operation - simulated by SWAT

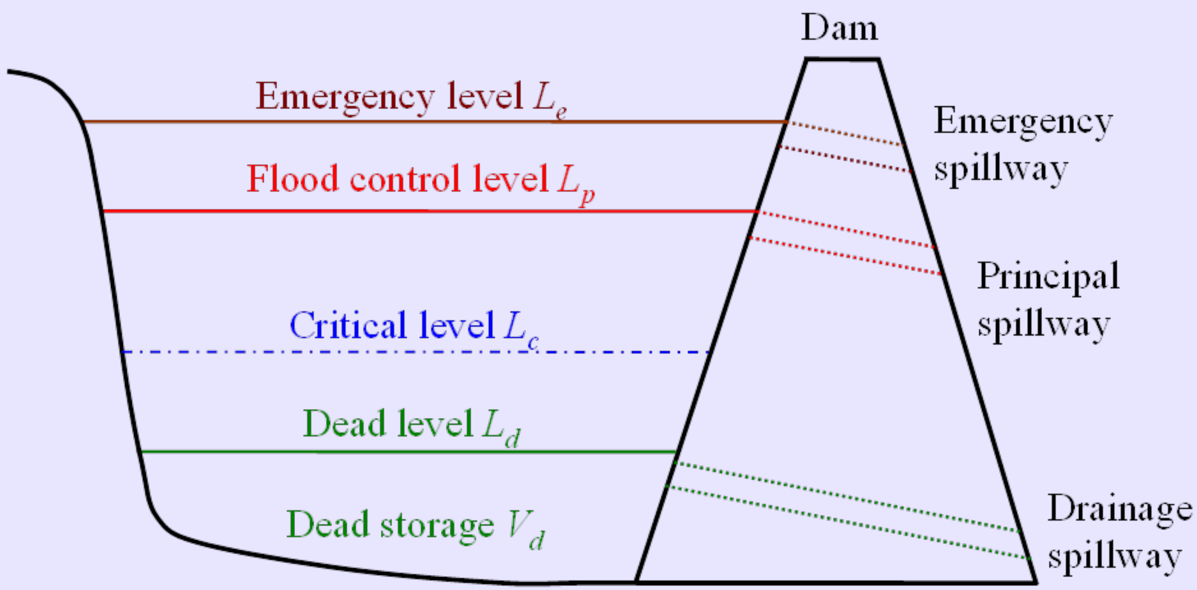
Volume



Outflow



A New Reservoir Simulation Scheme



Storage $V(i)$	**Operation Purpose and Equation for Computating Outflow, $O(i)$ (m³/d), on a given day i**
$V(i) > V_p$	flood control, $\frac{V(i)-V_p}{ND_{targ}}$
$V_p \geq V(i) > V_d$	hydropower generation, downstream water supply, and water resources, $\left(1+\left[\alpha\cdot\frac{V(i)-V_c}{\max\left[V_p-V_c, V_c-V_d\right]}+\beta\cdot\frac{\bar{I}_{30}(i)-I_{30}(i)}{\sigma_{30}(i)}\cdot\frac{V(i)-V_d}{V_p-V_d}+\gamma\cdot\frac{V(i)-V_p}{V_p-V_d}\right]\cdot k(mon)\right)\cdot\bar{O}(i)$
$V(i) \leq V_d$	0

Power **Supply** **Storage**

Comparison and Evaluation

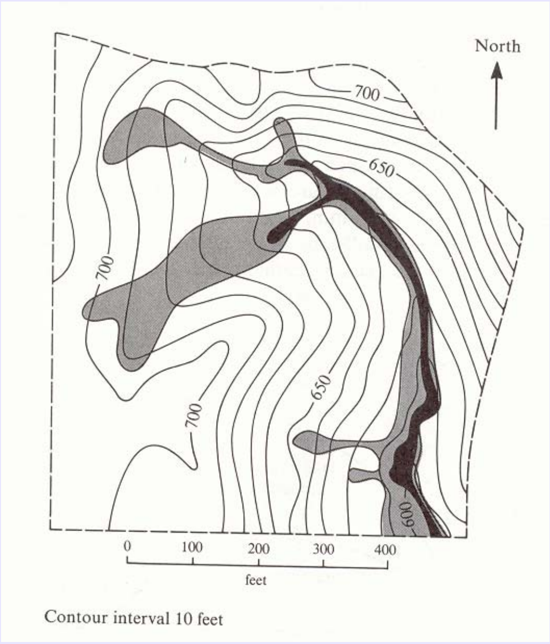
Variable	Scheme	Monthly Statistical Terms	
		RMSE	NSE
Storage	I (Target release)	1.87	0.28
	II (Mechanism based scheme)	1.57	0.50
Outflow	I	6.9	0.19
	II	6.0	0.38

Four hydrologic processes in SWAT

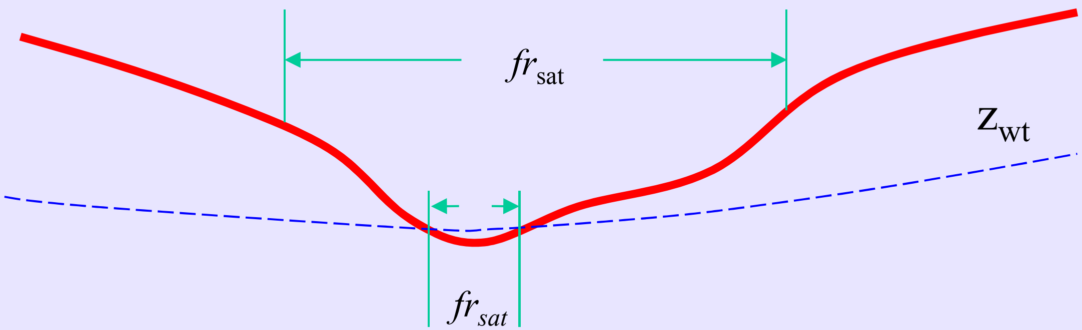
Hydrologic Processes	Calculation and Parameters involved		Limitations
Overland flow	$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S_a\right)}$	S_a	without considering direct overland flow from saturated area
Revap	$W_{revap} = \beta_{revap} \cdot E_0$	β_{revap}	• to be calibrated • time invariant • spatially unchanged
Baseflow	$Q_{b,i} = Q_{b,i-1} \cdot e^{-\alpha_{gw} \cdot \Delta t} + W_r \cdot (1 - e^{-\alpha_{gw} \cdot \Delta t})$	α_{gw}	to be calibrated $f(W_r)$
Percolation to deep aquifer	$w_{deep,mx} = \beta_{deep} w_{rchrg}$	β_{deep}	• to be calibrated • this amount of water is returned to hydrologic cycle only by pumping

Saturated Area and Water Table Depth

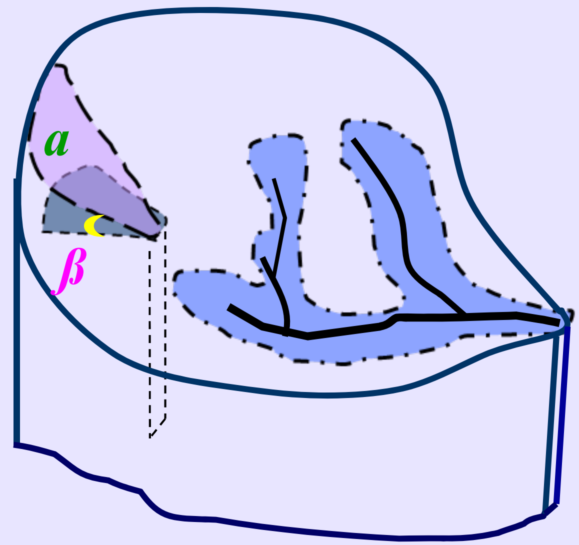
- **Saturated area and its expansion**
  (Dunne and Leopold, 1978)



- **Saturated fraction** $fr_{sat} = \dfrac{A_c}{A} = f(\lambda, \bar{z}, \xi)$



- **Topographic Index** $= \ln \dfrac{a}{\tan \beta}$



α is the upstream contributing area

tan*β* is the local slope

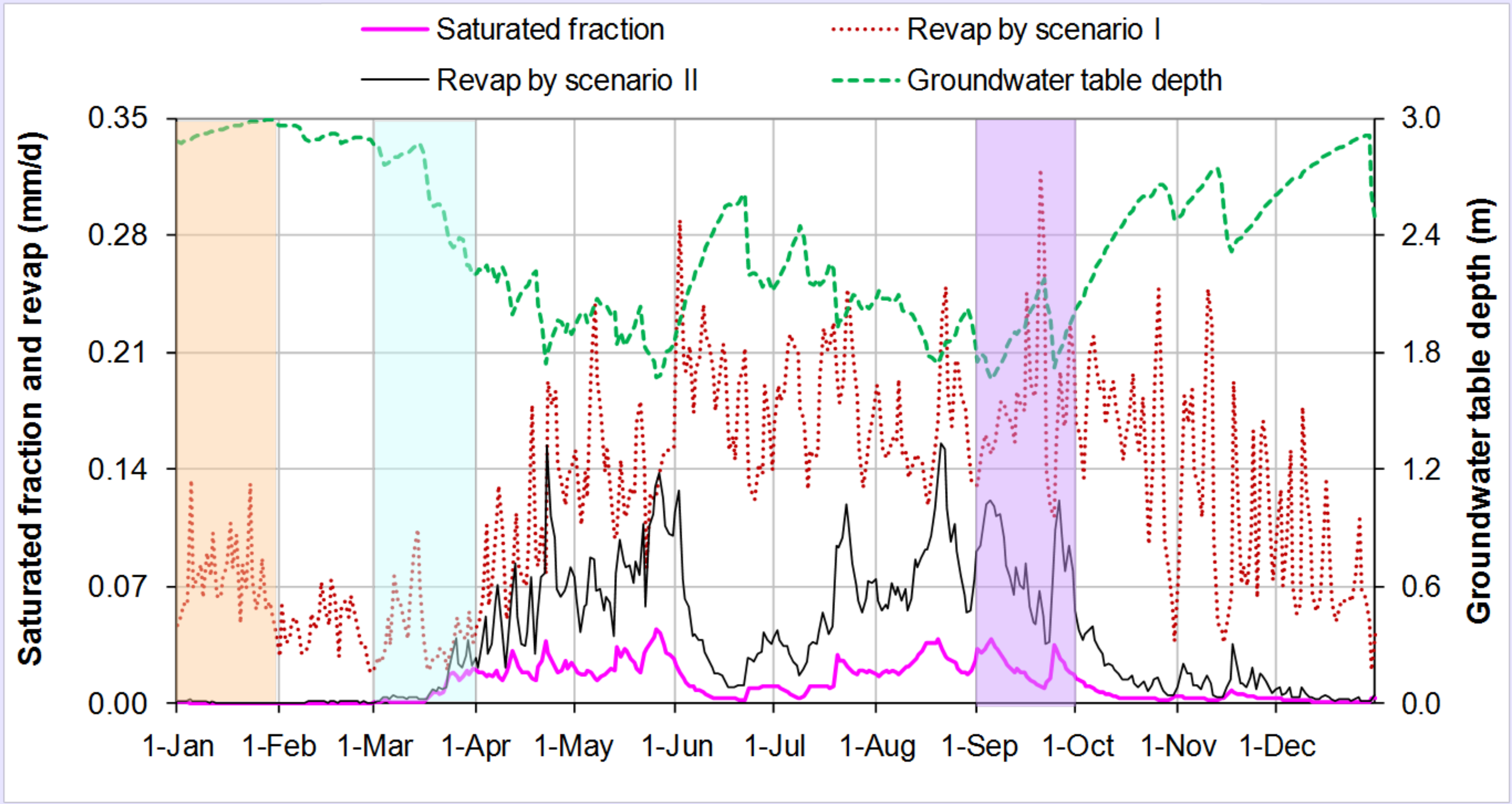
(Beven and Kirkby 1979)

Integrated of SWAT-TOPMODEL

Hydrologic Processes	Calculation and Parameters involved		Strengths
Revap	$W_{revap} = fr_{sat} \cdot E_0$	**Saturated fraction** $fr_{sat} = \frac{A_c}{A} = \int_{x \geq (\xi \cdot \bar{z} + \lambda)} f(x)dx$ $x = \text{Topographic Index} = \ln \frac{a}{\tan \beta}$ $f(x)$ **Probability distribution of TI** λ **Mean value of TI** $\bar{z}$ **Basin average water table depth** ξ **Decay factor of soil**	$fr_{sat} = f(\lambda, \bar{z}, \xi)$ **Temporal and spatial varying**
Baseflow	$Q_b = AT_0 e^{-(\lambda + \xi \cdot \bar{z})}$	$T_0 = k_{sx}(0)/\xi$ **Basin lateral transmissivity** $k_{sx}(0)$ **Saturated lateral hydraulic conductivity at the surface**	$Q_b = f(\lambda, \bar{z}, \xi)$
Overland flow	-	**Rainfall falling on the saturated area enters channel directly**	**Quick surface runoff**

Revap simulation

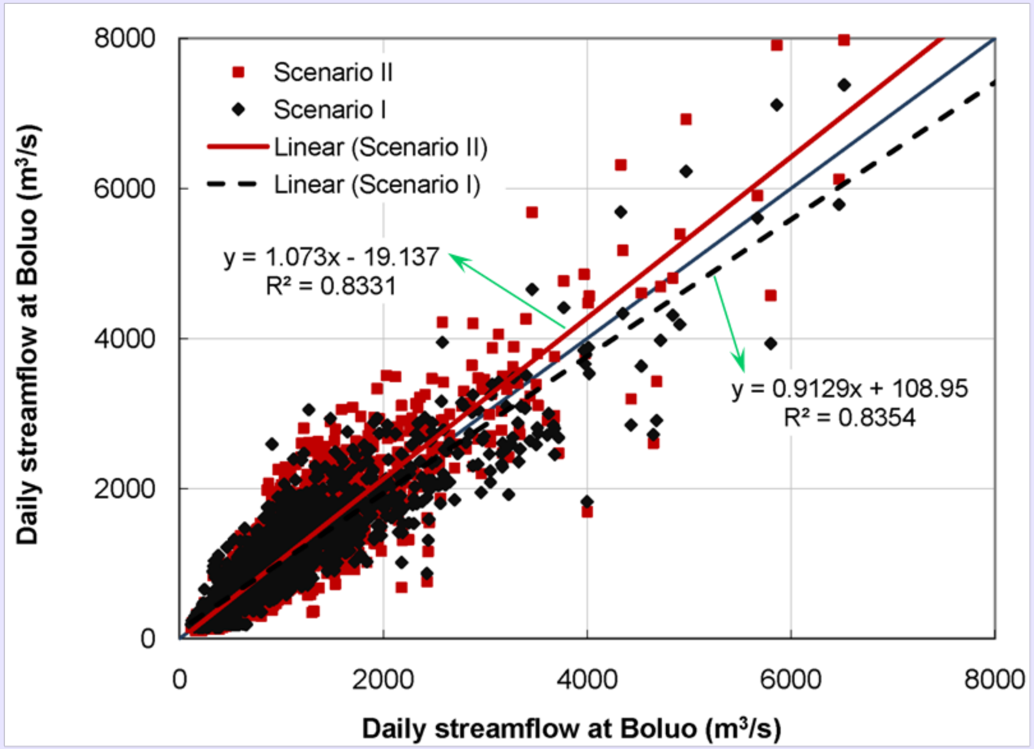
Scenario	Model	Revap	Comparison period
I	SWAT	f (PET)	Jan and Mar Mid Sep
II	SWAT-TOPMODEL	f (PET, fr_{sat})	



Evaluation

Scenario I: SWAT

Scenario II: SWAT-TOPMODEL



Model	Period	Mean		PB	NSE	R^2
		Observed	Simulated	(%)	D / M	D / M
SWAT	Calibration	818.64	831.17	1.53	0.84 / 0.93	0.84 / 0.93
	Validation	808.88	847.34	4.75	0.82 / 0.90	0.84 / 0.91
SWAT- TOPMODEL	Calibration	818.64	833.82	1.85	0.80 / 0.88	0.83 / 0.93
	Validation	808.88	854.05	5.59	0.77 / 0.82	0.84 / 0.91

Soil Erosion

Land Phase

Sediment in surface runoff (MUSLE)

$$sed = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG$$

$\boldsymbol{sed}$	mass of soil erosion (ton)
q_{peak}	peak runoff (m^3/s)
$area_{hru}$	area of HRU(ha)
K_{USLE}	soil erodibility factor
C_{USLE}	factor of land cover and management
P_{USLE}	conservation practice factor
LS_{USLE}	account for the factor of topography
$CFRG$	coarse fragment factor

Sediment Erosion

Land Phase

(2) Sediment in lateral & groundwater flow

$$sed_{lat} = \frac{(Q_{lat} + Q_{gw}) \cdot area_{hru} \cdot conc_{sed}}{1000}$$

sed_{lat}	sediment loading in lateral and groundwater flow (ton)
Q_{lat}	lateral flow for a given day (mm H_2O)
Q_{gw}	groundwater flow for a given day (mm H_2O)
$area_{hru}$	area of the HRU (km^2)
$conc_{sed}$	concentration of sediment in lateral and groundwater flow (mg/L)

Sediment Erosion

Water Phase

$$conc_{sed,ch,mx} = c_{sp} \cdot v_{ch,pk}^{\ spexp}$$

$$\begin{cases} v_{ch,pk} = \dfrac{q_{ch,pk}}{A_{ch}} \\ q_{ch,pk} = prf \cdot q_{ch} \end{cases}$$

$conc_{sed,ch,mx}$ maximum conc. of sed. transported (ton/m^3 or kg/L)

C_{sp} coefficient defined by the user

$v_{ch,pk}$ peak channel velocity (m/s)

$Spexp$ exponent defined by the user

normally varies between 1.0 and 2.0 and was set at 1.5 in the original Bagnold stream power equation (Arnold et al., 1995).

prf peak rate adjustment factor

q_{ch} average rate of flow (m^3/s)

A_{ch} cross-sectional area of flow

Sediment Erosion

Water Phase

$conc_{sed,ch,i} > conc_{sed,ch,mx}$ deposition is the dominant process and the net amount of sediment deposited

$$sed_{dep} = \left(conc_{sed,ch,i} - conc_{sed,ch,mx}\right) \cdot V_{ch}$$

$conc_{sed,ch,i} < conc_{sed,ch,mx}$ degradation is the dominant process and the net amount of sediment reentrained

$$sed_{deg} = \left(conc_{sed,ch,mx} - conc_{sed,ch,i}\right) \cdot V_{ch} \cdot K_{CH} \cdot C_{CH}$$

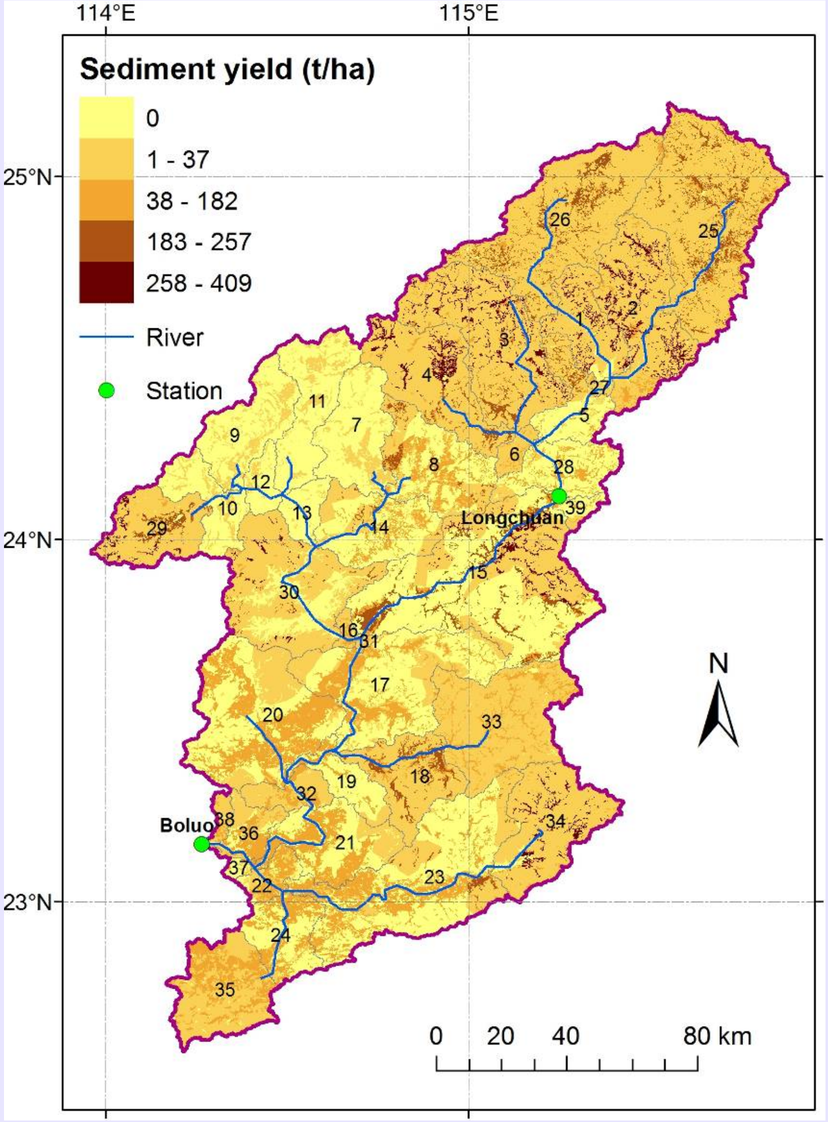
K_{CH} is the channel erodibility factor (cm/hr/Pa)

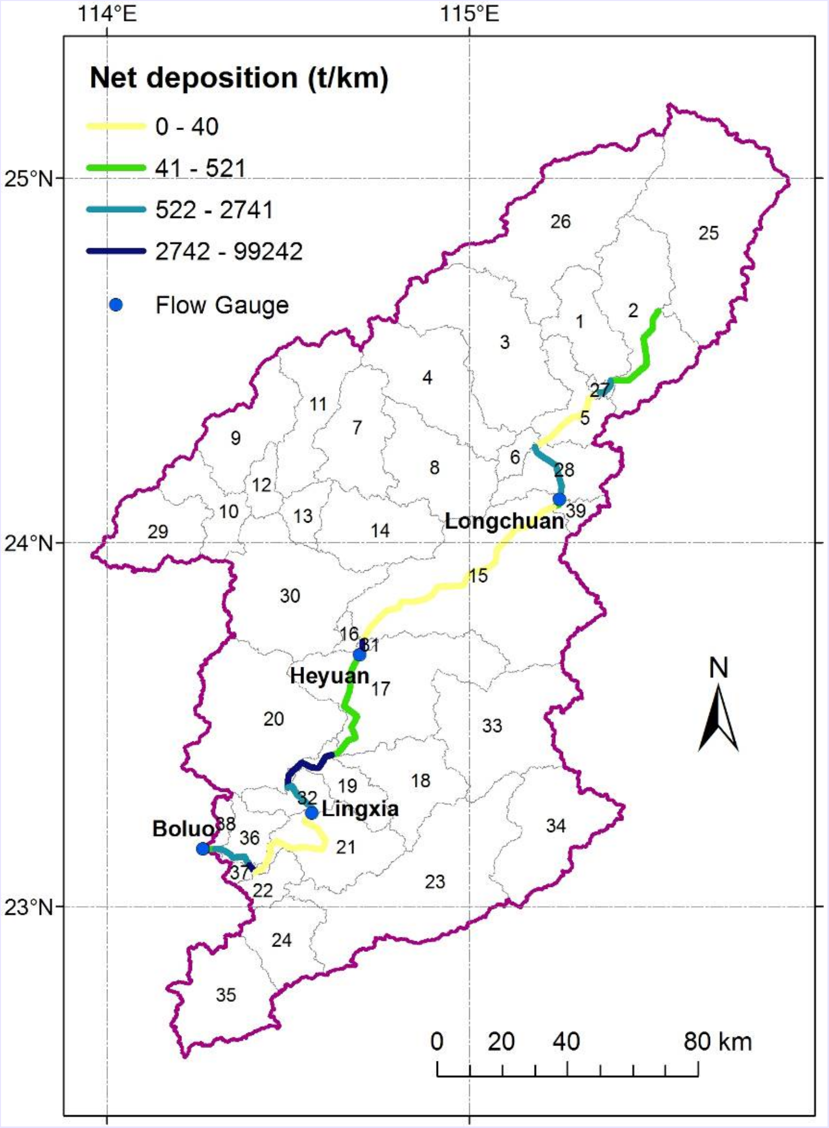
C_{CH} is the channel cover factor

Final amount of SS $$sed_{ch} = sed_{ch,i} - sed_{dep} + sed_{deg} \quad \text{(ton)}$$

Sed. transported out of the reach $$sed_{out} = sed_{ch} \cdot \frac{V_{out}}{V_{ch}} \quad \text{(ton)}$$

Soil Erosion and Sediment Transport





Water Quality

NPS and PS Pollution

Land Phase (NPS)

- **The transport of nutrients from land areas into streams and water bodies is a normal result of soil weathering and erosion processes**

- **Governing movement of mineral and organic forms of nitrogen and phosphorus from land areas to the stream network**

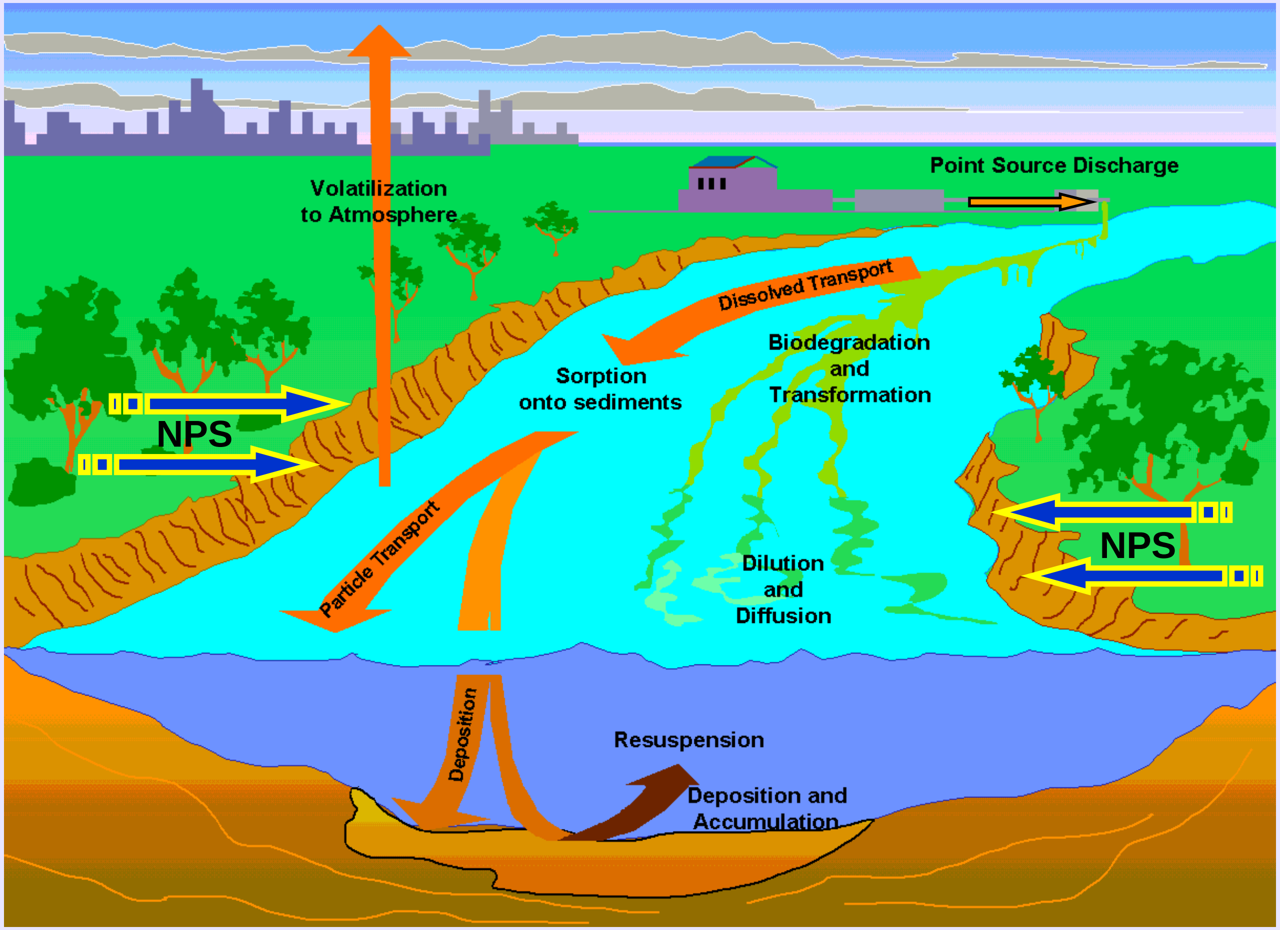
Land Phase { **N & P cycle** / **N & P loadings**

NPS and PS Pollution

Water Phase

- Determine the loadings of water, sediment, nutrients and pesticides to the main channel in land phase hydrologic cycle

- Keep track mass flow and models the transformation of chemicals in the stream



NPS: Loadings from land areas

PS: Loadings from sources not associated with a land areas

NPS and PS Pollution

Water Phase (NPS & PS)

Parameters which affect water quality and can be considered pollution indicators include nutrients, total solids, biological oxygen demand and microorganisms (Loehr, 1970; Paine, 1973).

The SWAT in-stream water quality algorithms incorporate constituent interactions and relationships used in the QUAL2E model (Brown and Barnwell, 1987).

NPS and PS Pollution

Water Phase (NPS & PS)

(0) Alge

Simulate algal growth in the stream

Why?

- **During the day, algae increase the stream's DO via photosynthesis.**
- **At night, algae reduce the stream's DO via respiration.**
- **As algae grow and die, they form part of the in-stream nutrient cycle.**

How?

Growth and decay of algae/chlorophyll *a* is calculated as a function of the growth rate, the respiration rate, the settling rate and the amount of algae present in the stream.

NPS and PS Pollution

Water Phase - N

(1) orgN

orgN → NH_4^+

algal biomass N → orgN

orgN settling (sed.) ↓

$$\Delta orgN_{str} = \left(\alpha_1 \cdot \rho_a \cdot algae - \beta_{N,3} \cdot orgN_{str} - \sigma_4 \cdot orgN_{str}\right) \cdot TT$$

$\Delta orgN_{str}$	change in organic nitrogen concentration (mg N/L)
α_1	fraction of algal biomass that is nitrogen (mg N/mg algal biomass)
ρ_a	local respiration or death rate of algae (day^{-1} or hr^{-1})
$algae$	algal biomass concentration at the beginning of the day (mg alg/L)
$\beta_{N,3}$	rate constant for hydrolysis of orgN to ammonia N (day^{-1} or hr^{-1})
$orgN_{str}$	organic nitrogen concentration at the beginning of the day (mg N/L)
σ_4	rate coefficient for organic nitrogen settling (day^{-1} or hr^{-1})
TT	flow travel time in the reach segment (day or hr)

NPS and PS Pollution

Water Phase - P

(1) orgP

orgP → soluble inorganic P

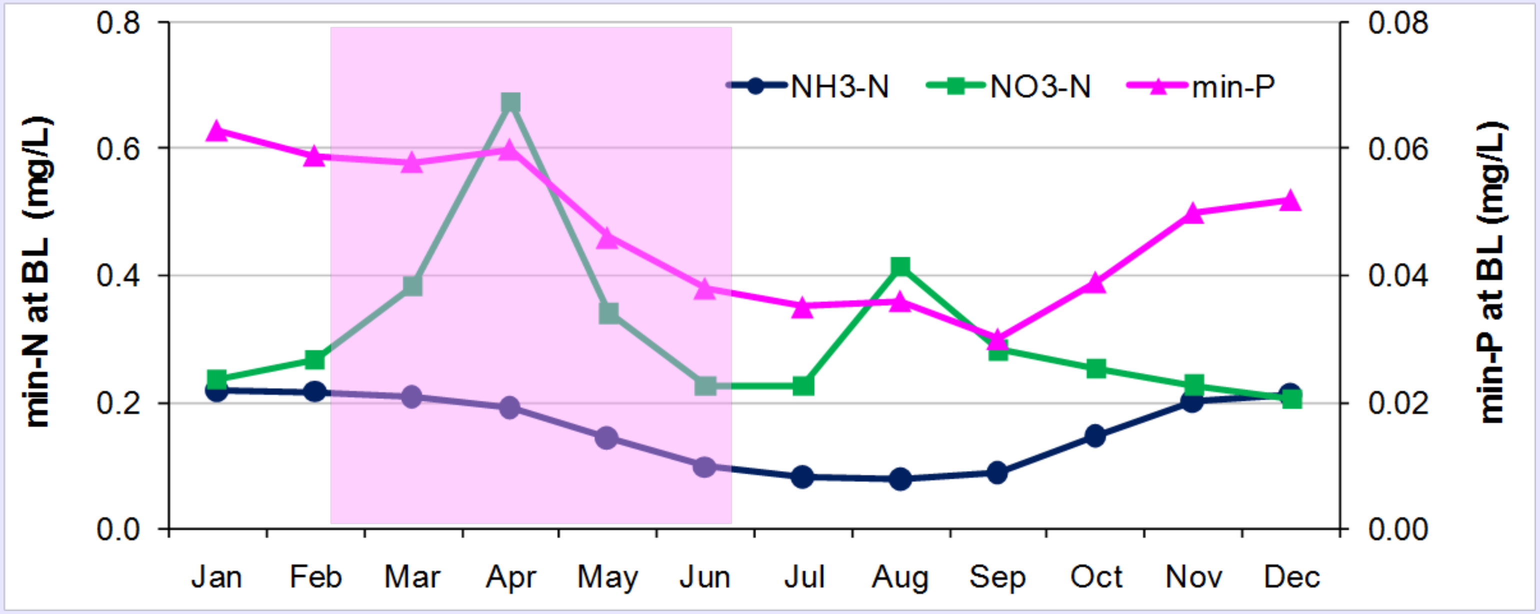
algal biomass P → orgP

orgP settling (sed.) ↓

$$\Delta orgP_{str} = \left(\alpha_2 \cdot \rho_a \cdot algae - \beta_{P,4} \cdot orgP_{str} - \sigma_5 \cdot orgP_{str}\right) \cdot TT$$

$\Delta orgP_{str}$	change in organic P concentration (mg P/L)
α_2	fraction of algal biomass that is P (mg P/mg alg biomass) <user defined>
ρ_a	local respiration or death rate of algae (day^{-1} or hr^{-1})
$algae$	algal biomass concentration at the beginning of the day (mg alg/L)
$\beta_{P,4}$	rate constant for mineralization of organic phosphorus (day^{-1} or hr^{-1})
$orgP_{str}$	organic P concentration at the beginning of the day (mg P/L)
σ_5	rate coefficient for organic phosphorus settling (day^{-1} or hr^{-1})
TT	flow travel time in the reach segment (day or hr)

Seasonal variation of stream water quality



NH3-N: constant PS load

Low conc. in wet season

Critical period for nutrient:

Ending of dry season →

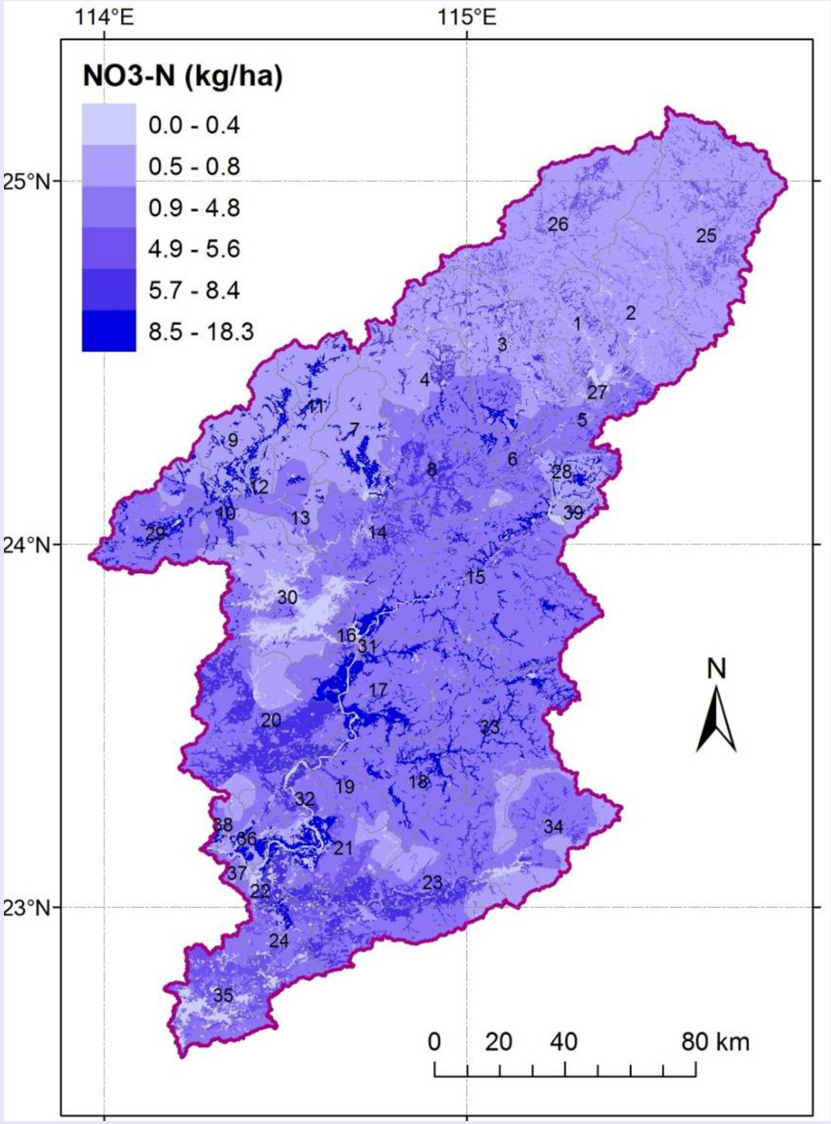
Beginning of wet season

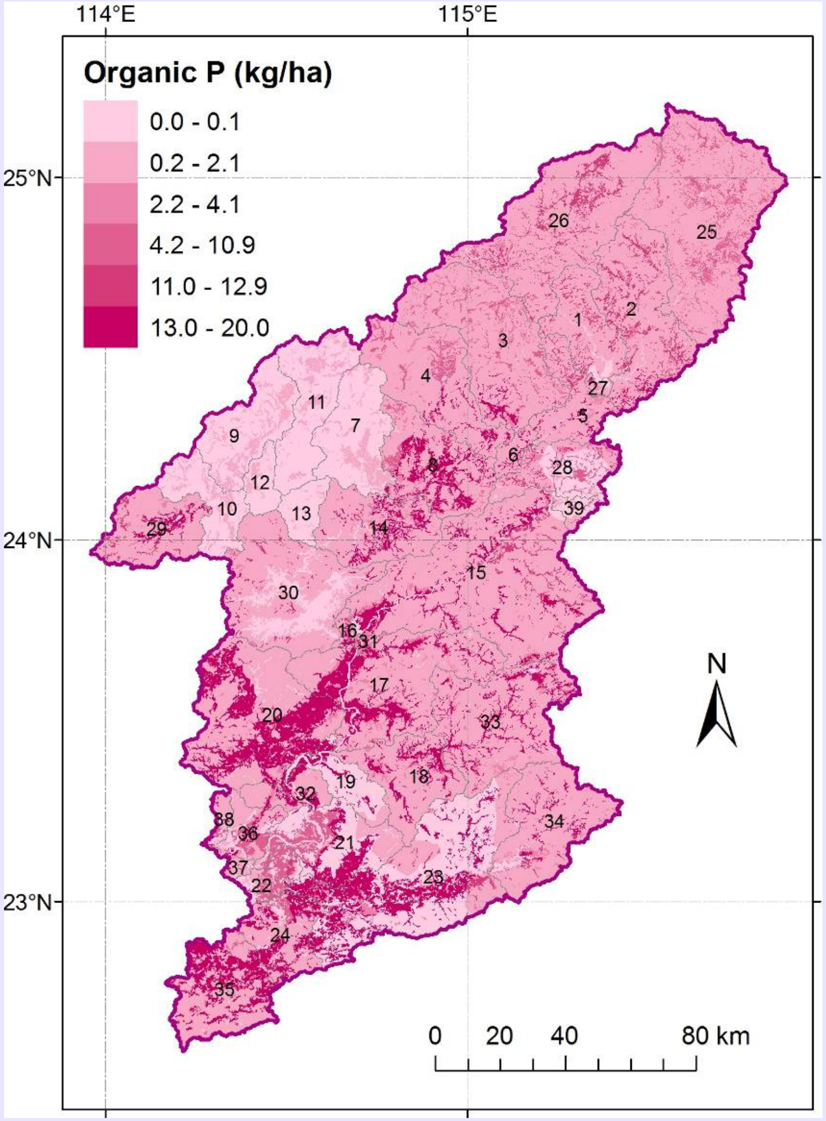
NO3-N: PS and NPS loads

Planting & Fertilization (Apr & Aug)

Eluviation (Mar)

NPS pollution load





Conclusions

This study focused on the improvement of our understanding of the integrated terrestrial processes over the East River

(Water, Sediment, Nutrients, Reservoir operation and Land management)

- **Water resources:** **to overcome the projected water shortage induced by the drought condition as in 1963, 70% conservative capacity of Xinfengjiang reservoir would be filled**

- **Reservoir simulation:** **A mechanism-based numerical scheme for a multiyear and multipurpose reservoir is developed**

- **Model integration:** **Hydrologic representation in SWAT are enhanced physically by integrating TOPMODEL features**

- **Sediment & Water quality:** **Soil erosion and NPS pollution features are analyzed, with identification of critical area and critical period**

Thank you !