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Using reservoirs to utilize floodwater resources without additional risks

Hao Ye

Supervisor: Pan Liu

Wuhan University

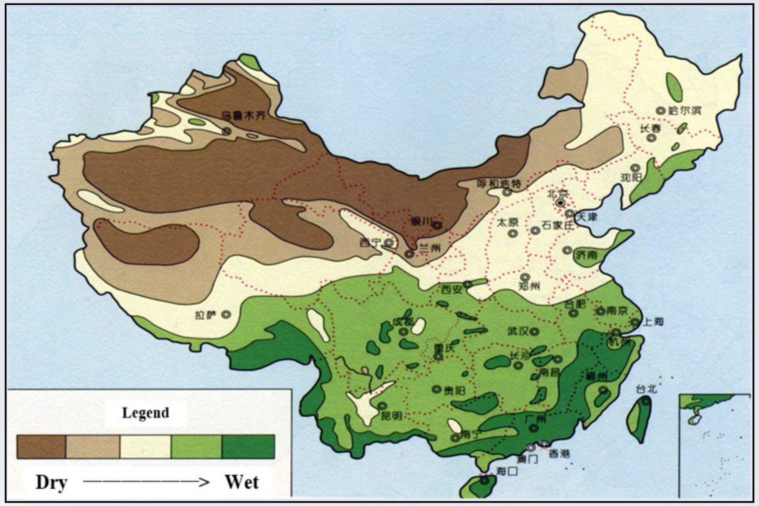
XVIII WORLD WATER CONGRESS
Water for All
Harmony between Humans and Nature
第18届
世界水资源大会
水与万物：
人与自然和谐共生

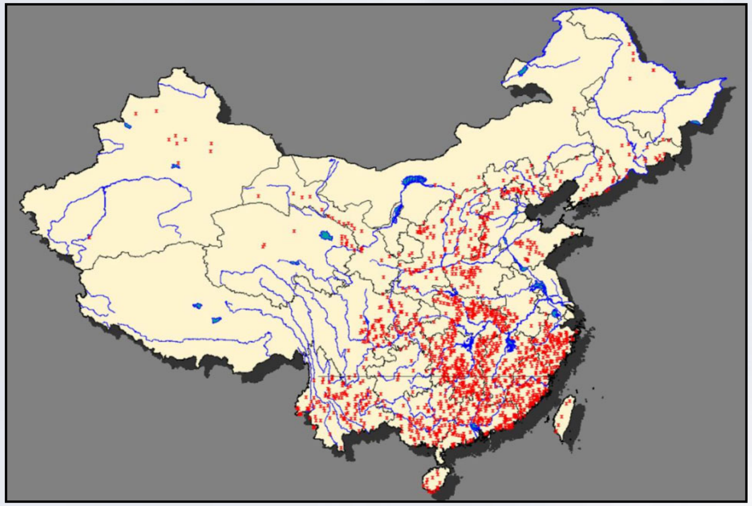
Content

- Background
- Seasonal flood limited water level for reservoirs
- Dynamic control of flood limited water level for reservoirs
- Refill operation for reservoirs
- Conclusions

Background

- Spatial-temporal distribution of water resources in China is uneven.
- More than 98,000 reservoirs have been constructed in China, with the total storage capacity of which is over 700 billion m³.
- How to manage these reservoirs to obtain comprehensive benefits is a key issue for hydrologists in China.

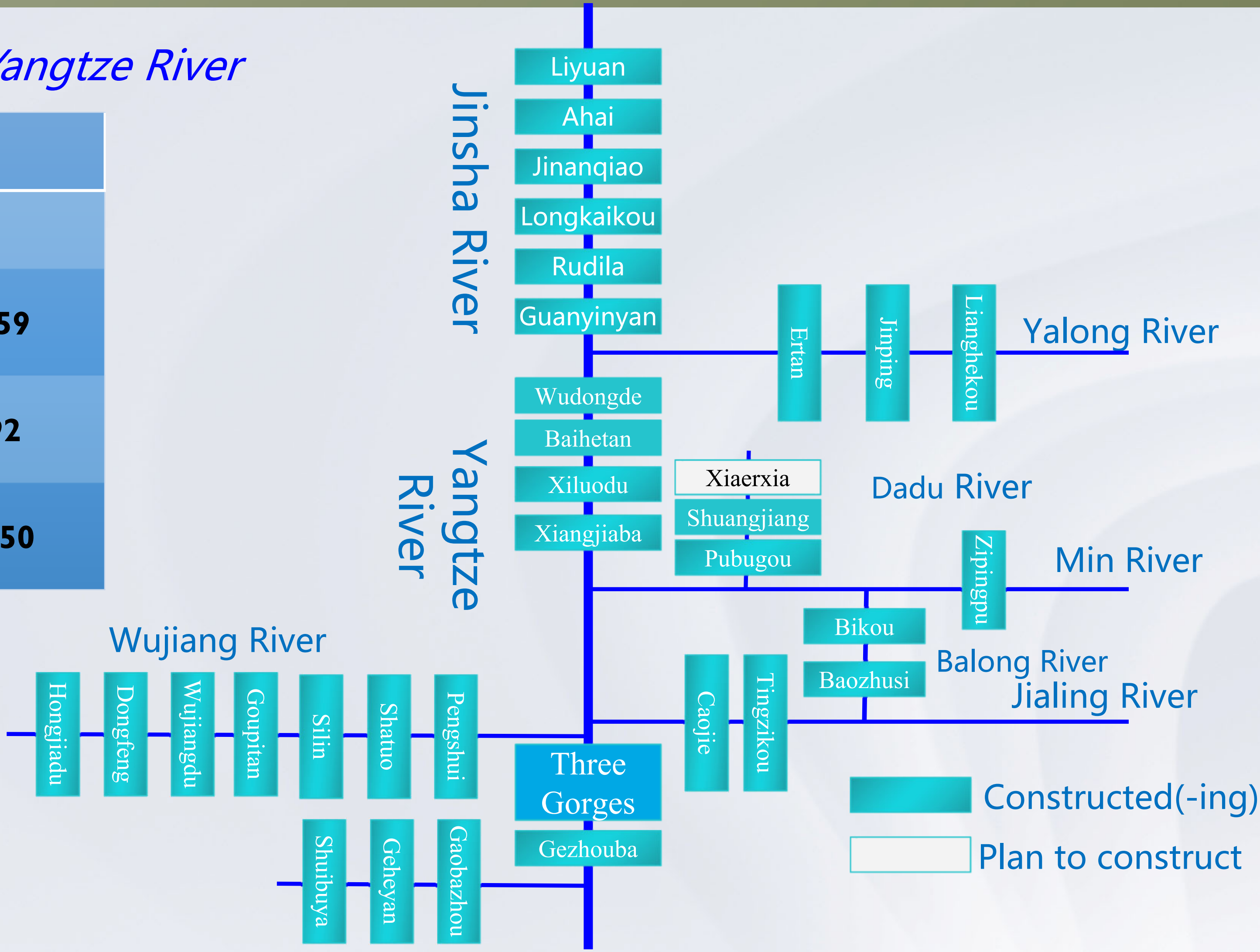




Background

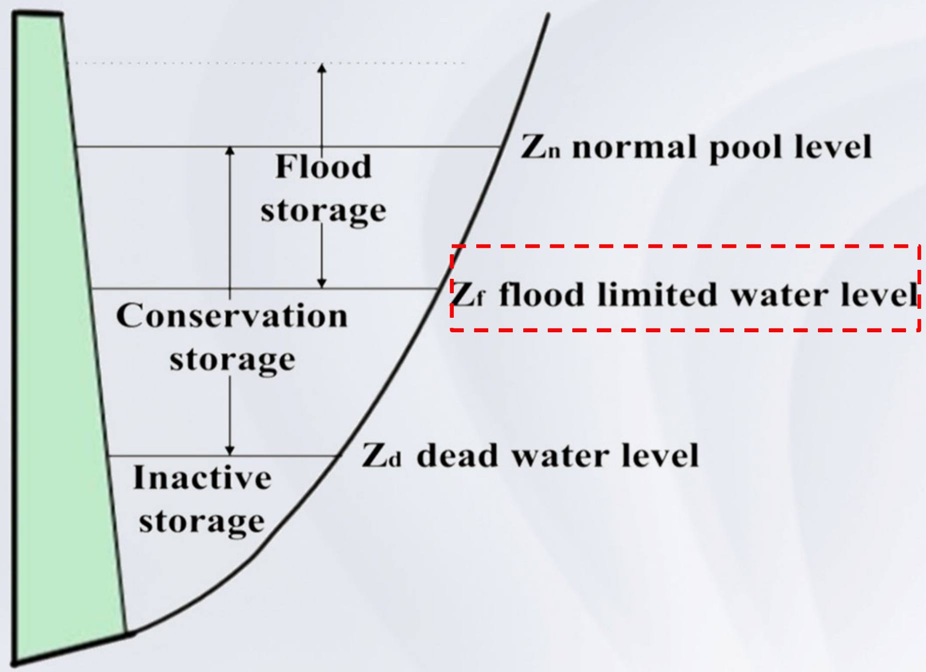
Reservoir system of Upper Yangtze River

Main Characteristics	
Num. (-)	30
Total Storage Capacity (billion m³)	156.59
Flood Control Capacity (billion m³)	51.92
Total Installed Capacity (MW)	113950

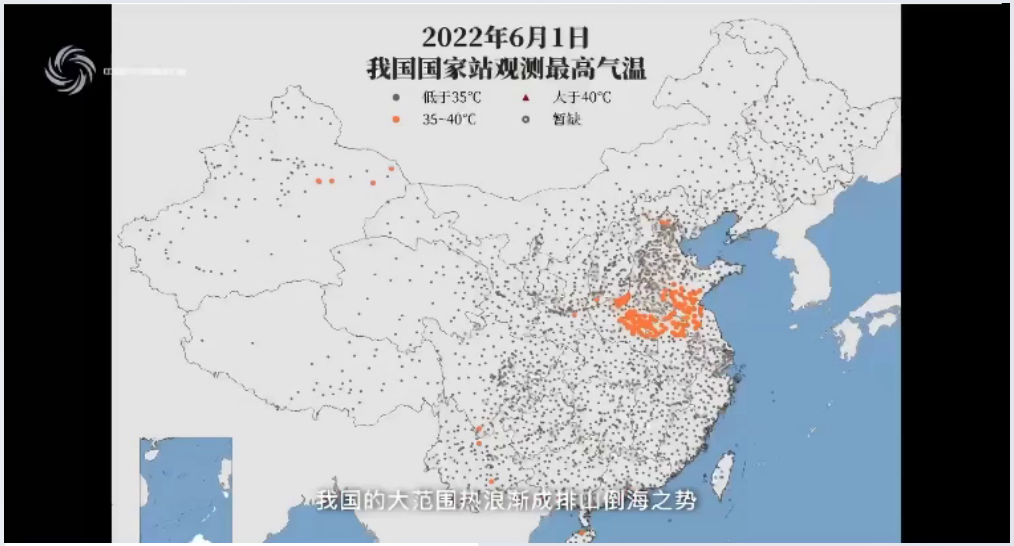


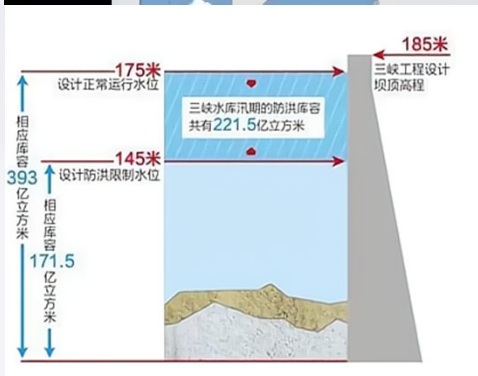
Flood limited water level (FLWL)

- According to the Chinese Flood Control Act, the water level of reservoir should be kept below the *flood limited water level* (FLWL) during the flood season.



Three Gorges Reservoir Faces Dilemma of Balancing Risks and Benefits in a Major Drought in the Yangtze River Basin in 2022





Risk

Ensuring safety

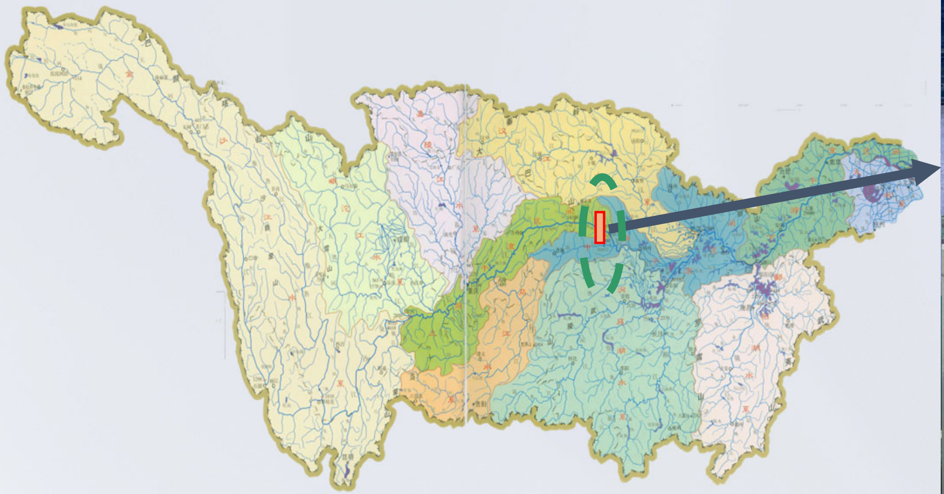
Benefit

Maximizing benefit

Additional five meters for TGR FLWL

Study area: Three Gorges Reservoir (TGR)

- TGR is a vitally important backbone project in the development and harnessing of the Yangtze River.
- TGR is the largest multi-purpose project in the world.



Study area: Three Gorges Reservoir (TGR)

The Three Gorges Reservoir

☐ Data

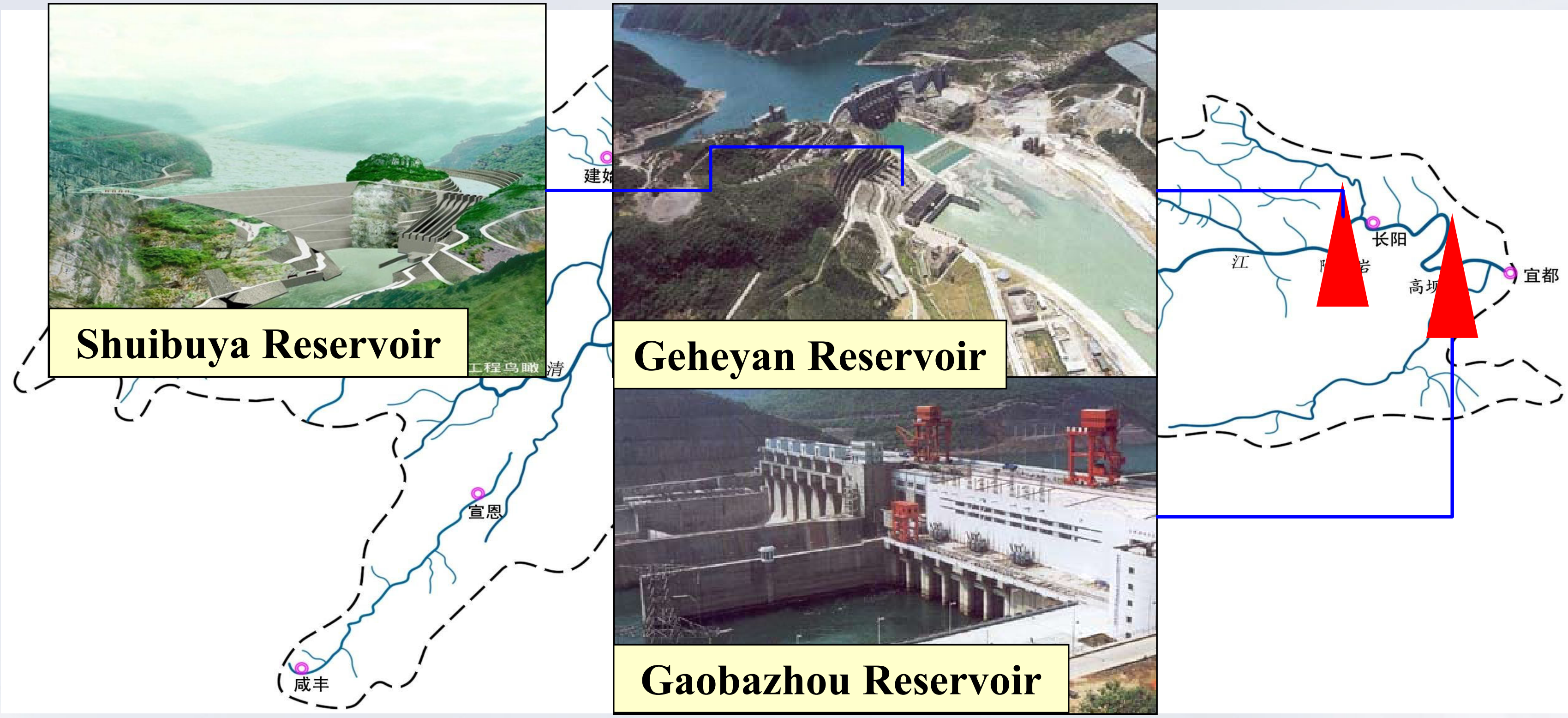
Observed streamflows of Cuntan and Wulong

Rainfall in the intervening basin

Streamflow with time interval of 6 hours from June to September (from 2003–2010) at the Yichang hydrological station

Study area: Qingjiang cascade reservoirs

- The Qingjiang River is one of the main tributaries of Yangtze River, with a basin area of 17,600 km².



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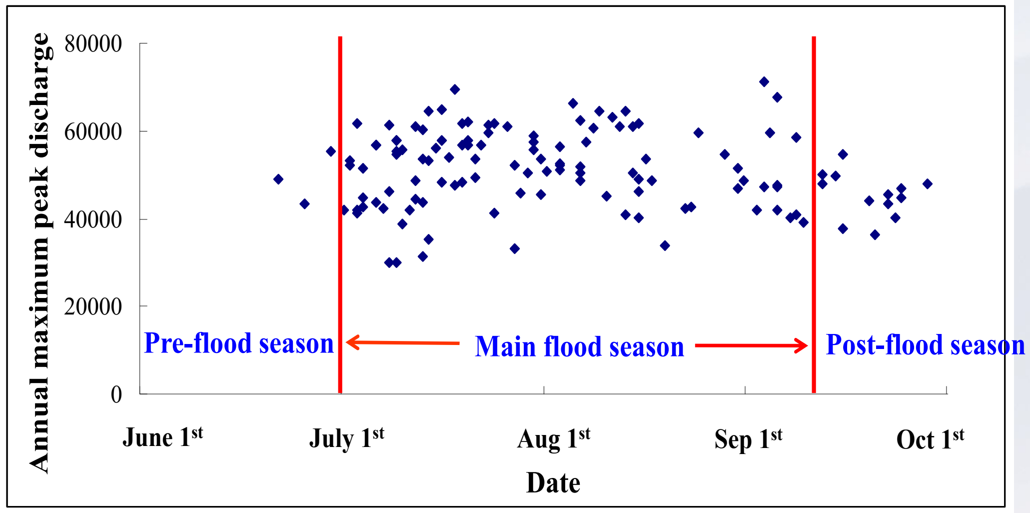
Flood seasonal segmentation

- Proper identification of flood seasonality is very important for water resources management.
- Many flood seasonal segmentation methods are used, i.e.

➢ Cause analysis of climatic and weather system

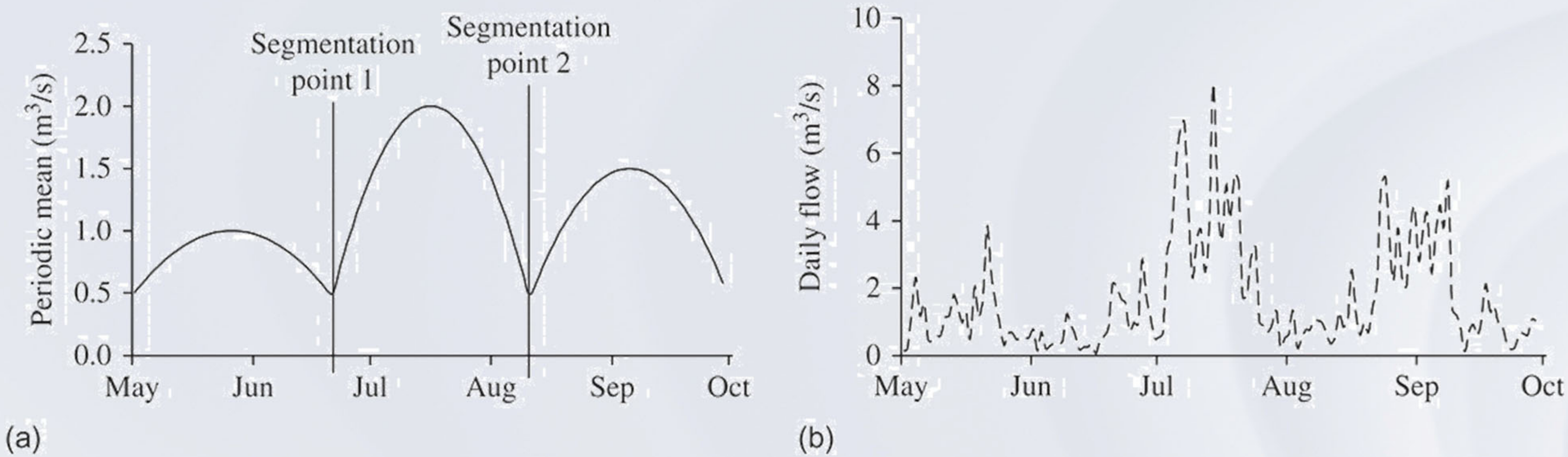
➢ Statistic analysis methods

- Rainfall-runoff statistics
- Fuzzy cluster analysis
- Directional statistics
- Relative frequency analysis
- Circular uniform distribution



Flood seasonal segmentation

● The probability change-point analysis-based method is objective and widely used in practice



$$L=\prod_{i=1}^{m_1-1}C_n^{x_i}p_1^{x_i}(1-p_1)^{n-x_i}\prod_{i=m_1}^{m_2-1}C_n^{x_i}p_2^{x_i}(1-p_2)^{n-x_i}\Lambda\prod_{i=m_q}^{m_{q+1}-1}C_n^{x_i}p_{q+1}^{x_i}(1-p_{q+1})^{n-x_i}$$

Flood seasonal segmentation

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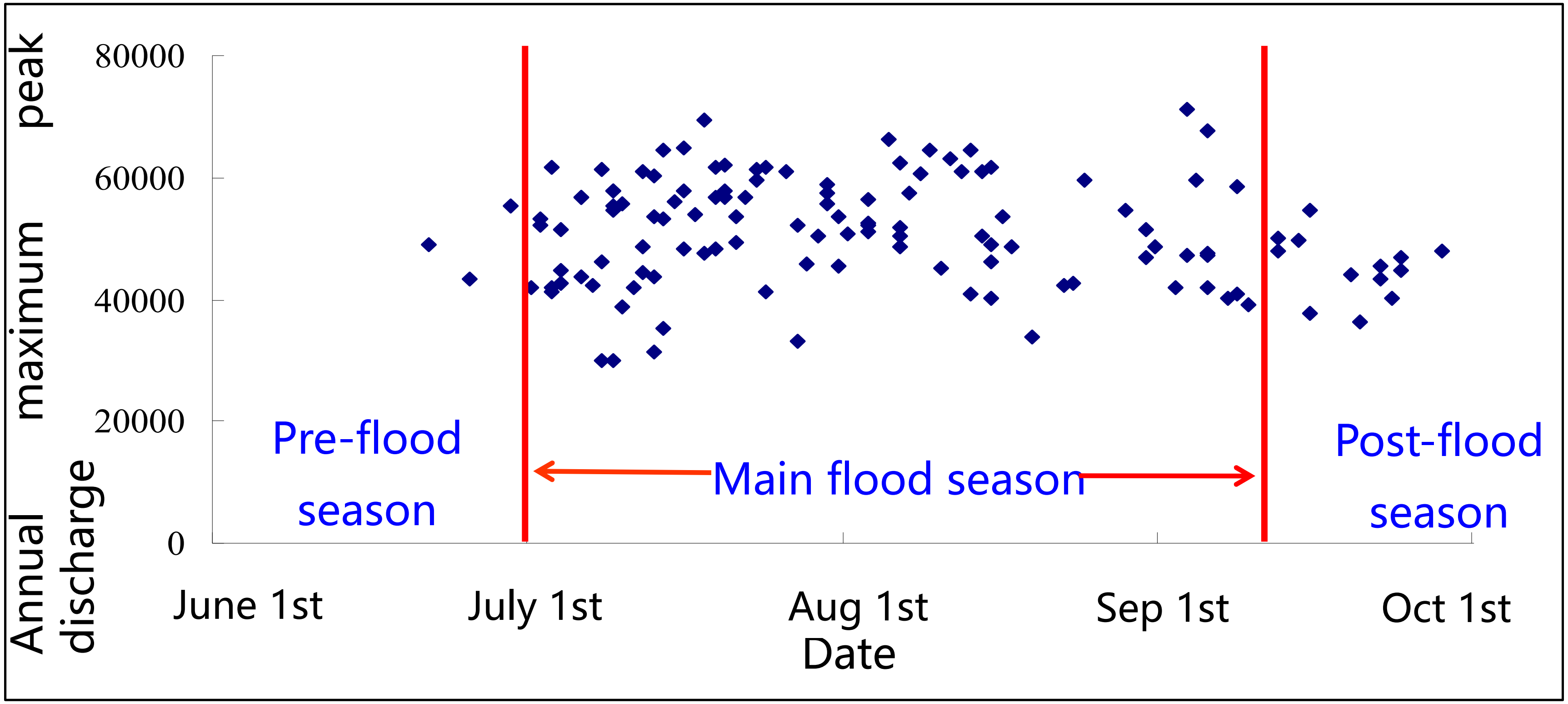
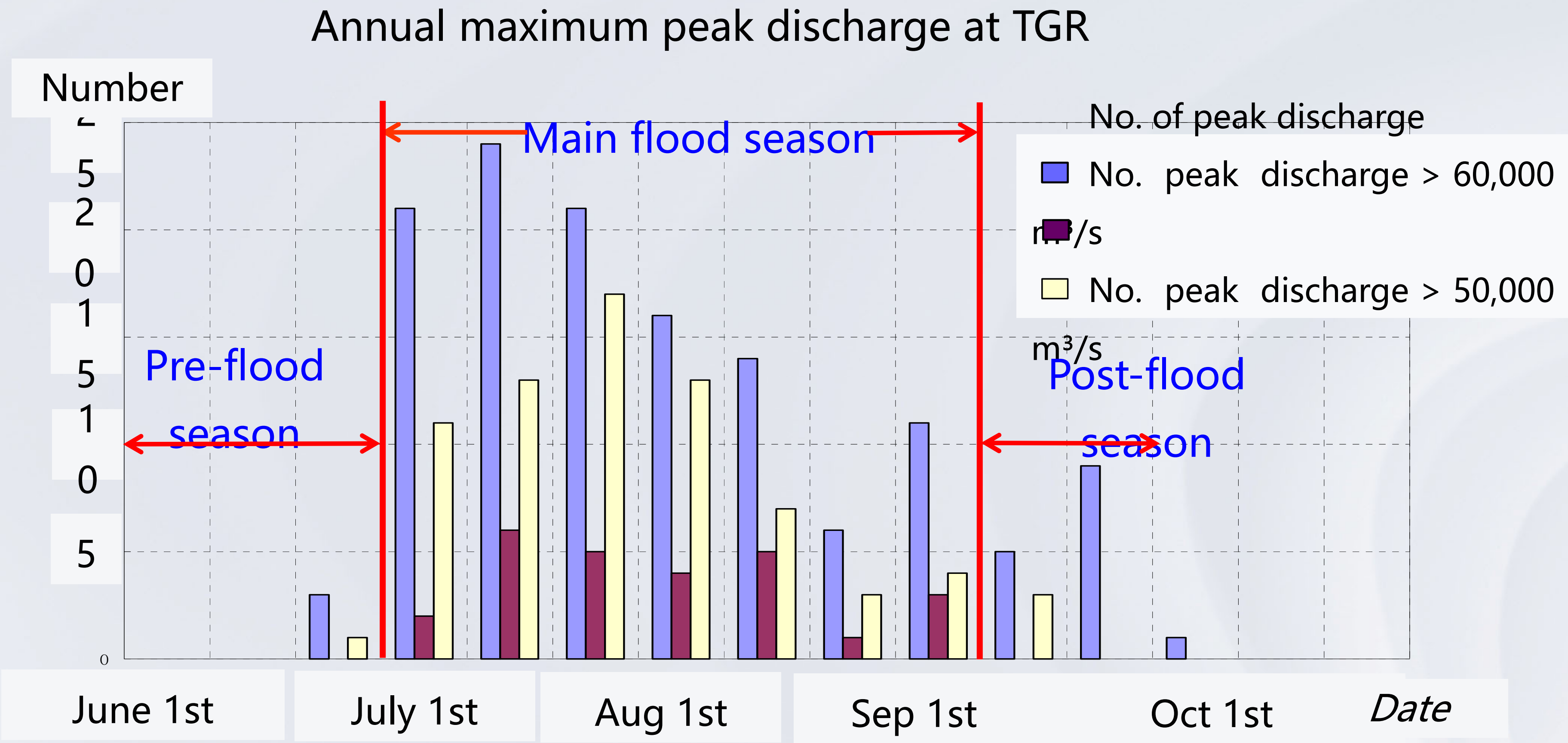
- **Based on the change-point analysis, the flood season of TGR can be divided into three sub-seasons.**



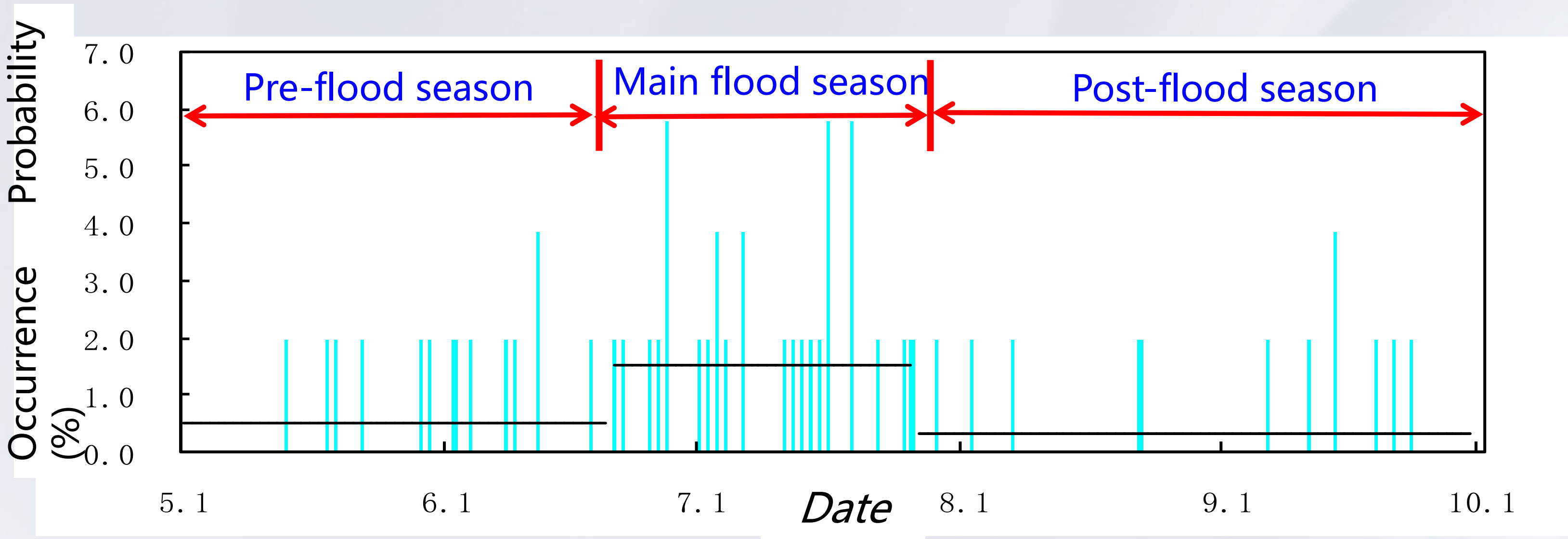
Flood seasonal segmentation of TGR



Flood seasonal segmentation of cascade reservoirs

- Based on the change-point analysis method, the flood season can be divided into three sub-seasons.

- **Pre-flood season: May 1st to June 20th.**
- **Main flood season: June 21st to July 31st.**
- **Post-flood season: Aug. 1st to Sep. 30th.**



Annual maximum peak discharge at Geheyan reservoir

Seasonal control of FLWL(SC-FLWL)

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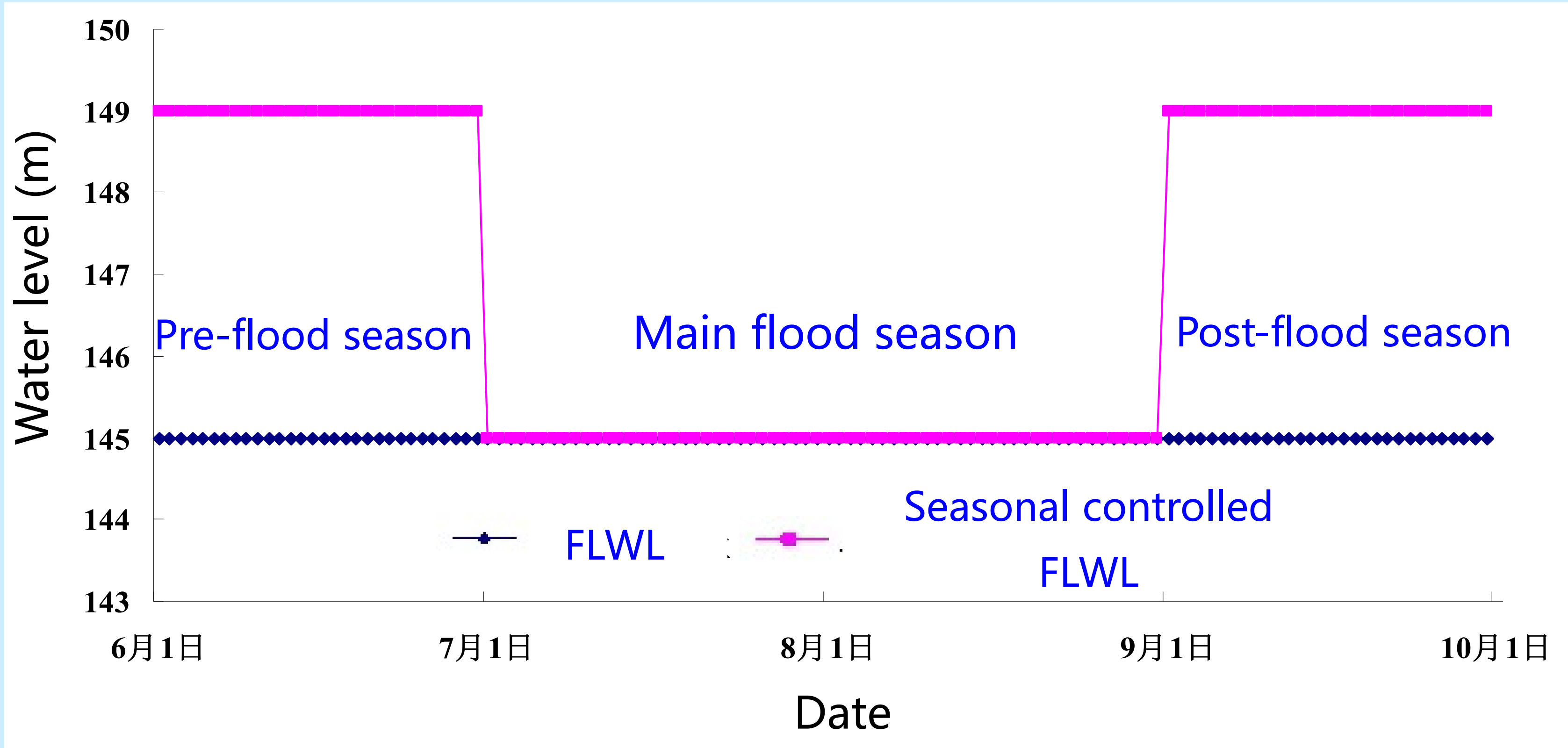
● Seasonal control reservoir's FLWL is a valuable and effective way to compromise between flood control and benefits.



SC-FLWL for TGR

● The flood limited water level (FLWL) of each sub-season can be derived by seasonal design flood and reservoir flood routing.

Seasonal controlled FLWL of TGR

Sub-season	Seasonal controlled FLWL (m)	Current FLWL (m)
Pre-flood season	149.0	145.0
Main flood season	145.0	145.0
Post-flood season	149.0	145.0

SC-FLWL for Qingjiang cascade resercoirs

- The flood limited water level (FLWL) of each sub-season can be derived by seasonal design flood and reservoir flood routing.

Seasonal controlled FLWL of Qingjiang cascade

	Seasonal controlled FLWL (m)		
Reservoir	Pre-flood season	Main flood season	Post-flood season
Shuibuya	397.0	391.8	397.0
Geheyan	198.0	192.2	198.0

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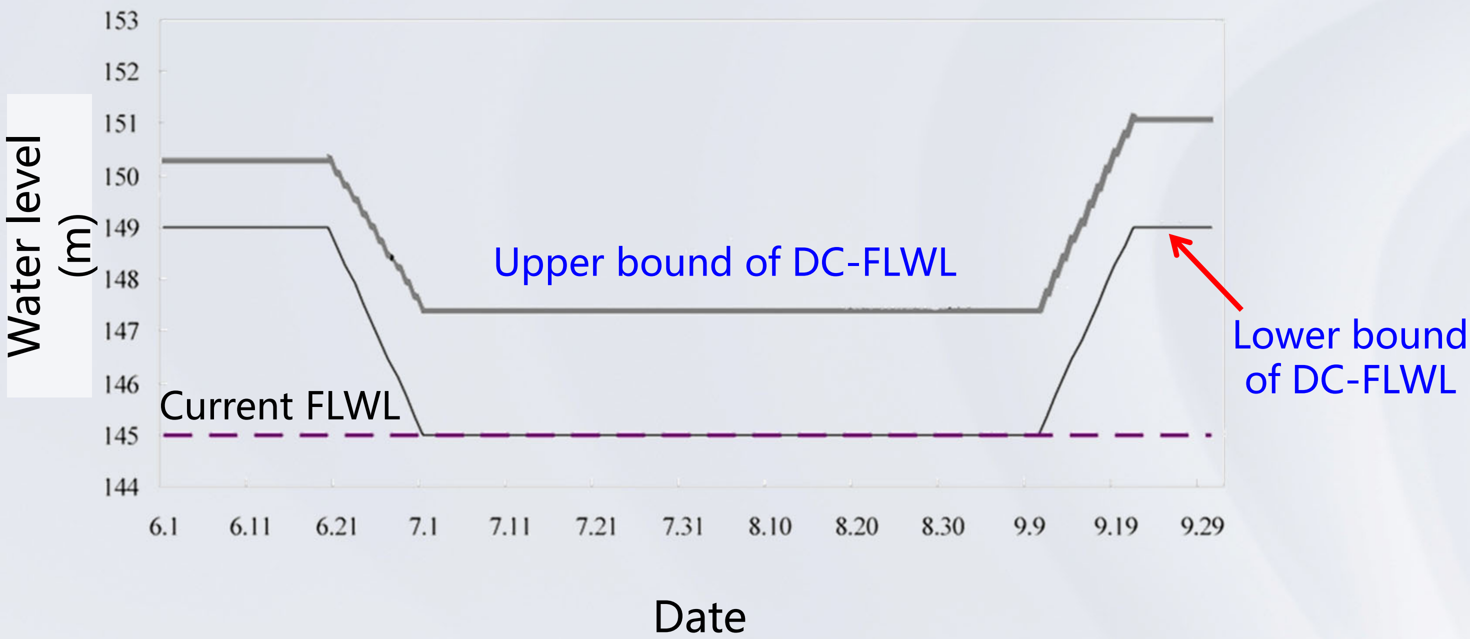
Dynamic control of flood limited water level (DC-FLWL)

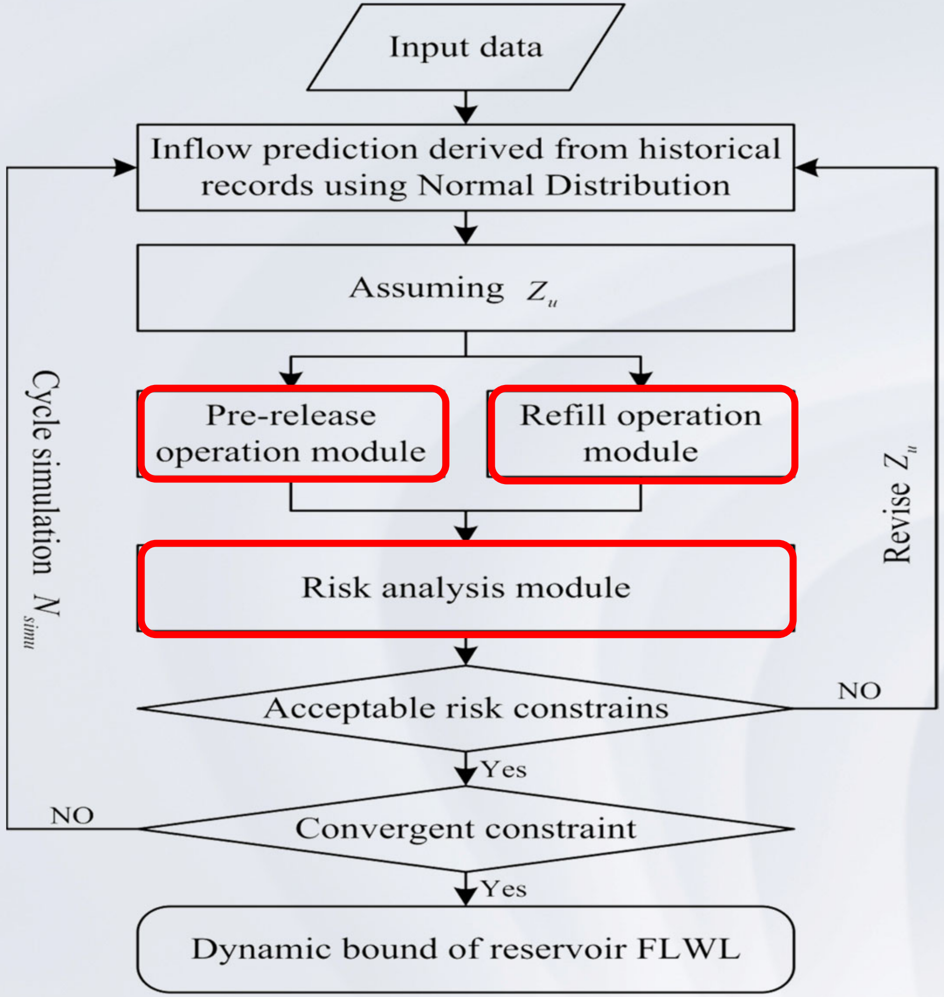
- A *dynamic control operation model* is proposed to derive the upper bound considering flood risk.



Dynamic control operation model for single reservoir

DC-FLWL consists of three modules:

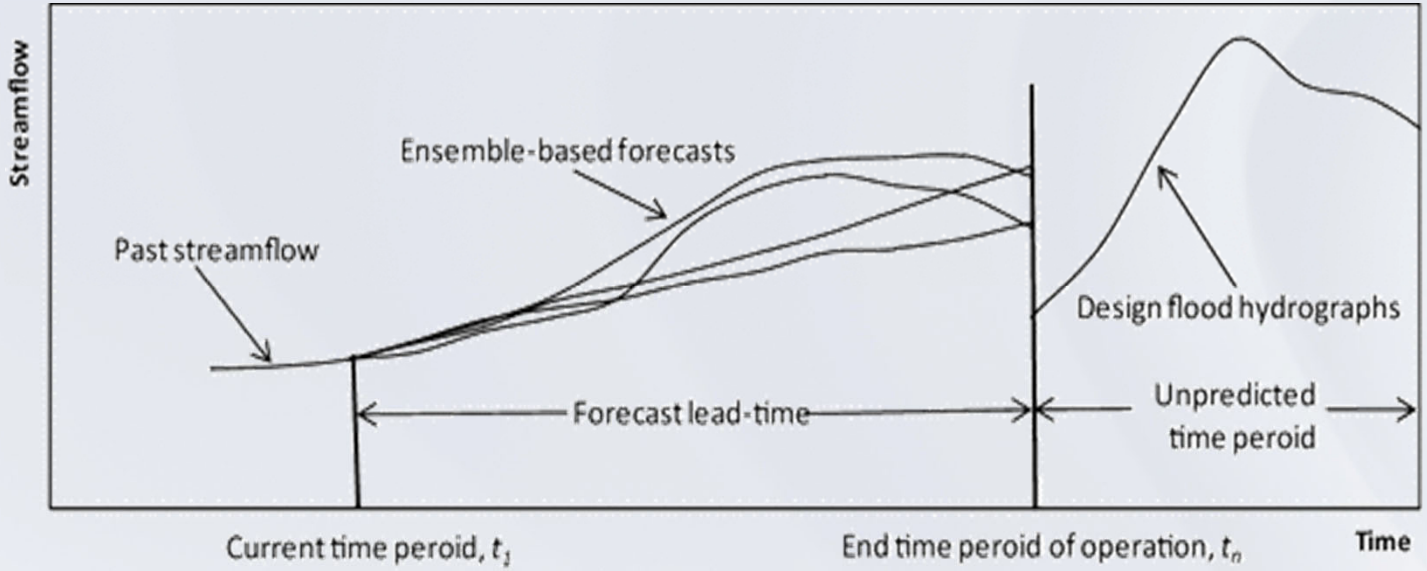
- *pre-release module*
- *refill operation module*
- *risk analysis module*



Flood risk analysis

● The future time is divided into two stages, the forecast lead-time and the unpredicted time by using the forecast horizon point

● Ensemble-based forecasts are used in the forecast lead-time, and the design flood hydrographs are used in the unpredicted time



Frame of the reservoir risk analysis using two stages within the forecast lead-time and the unpredicted time period

Flood risk analysis

- The risk1 within the forecast lead-time, which can be computed based on counting the failure numbers of scenarios
- The risk2 in the unpredicted time is estimated using the reservoir routing with the design flood hydrographs

Risk1

$$R_{1,down} = \Pr ob(R > Q_c) = \frac{\sum_{i=1}^{m} \#(R_{i,t} > Q_c, \forall \quad t = t_1, t_2, 6 \quad, t_n)}{m}$$

$$R_{1,up} = \Pr ob(Z > Z_c) = \frac{\sum_{i=1}^{m} \#(Z_{i,t} > Z_c, \forall \quad t = t_1, t_2, 6 \quad, t_n)}{m}$$

Risk2

$$R_{2,down} = \sum_{i=1}^{m} R_{down}(Z_{i,t_n}) P(Z_{i,t_n}) = \frac{\sum_{i=1}^{m} R_{down}(Z_{i,t_n})}{m}$$

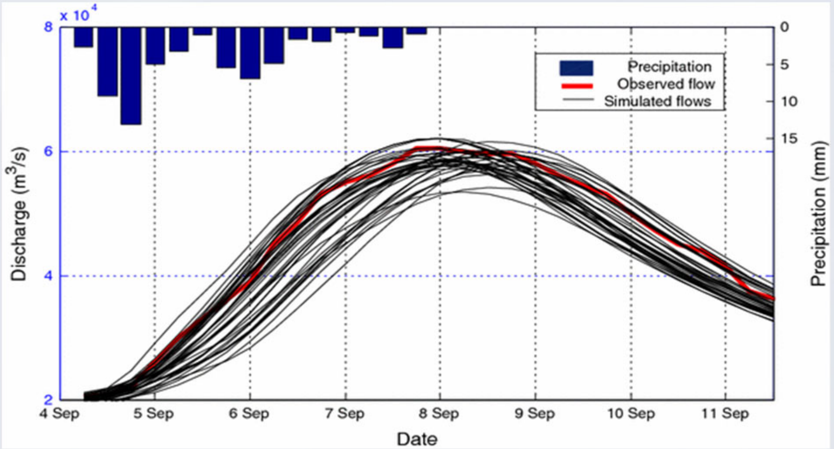
$$R_{2,up} = \sum_{i=1}^{m} R_{up}(Z_{i,t_n}) P(Z_{i,t_n}) = \frac{\sum_{i=1}^{m} R_{up}(Z_{i,t_n})}{m}$$

Total risk

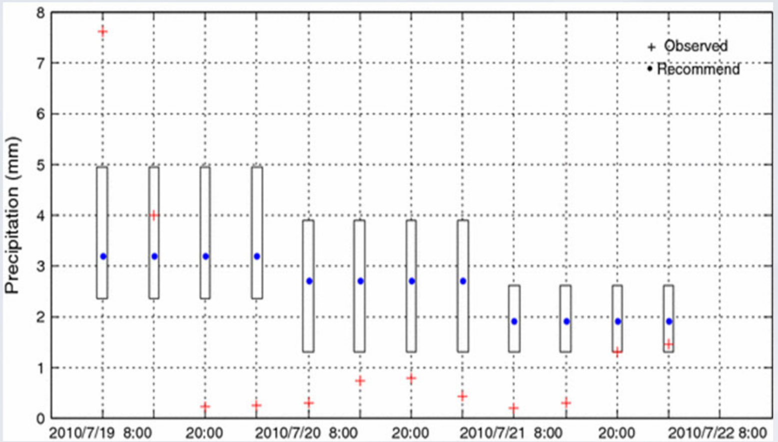
$$R_{down} = R_{1,down} + P(R_{2,down} \mid \overline{R}_{1,down}) = \frac{\sum_{i=1, i\in T}^{m} \#(R_{i,t} > Q_c, \forall \quad t = t_1, t_2, 6 \quad, t_n) + \sum_{i=1, i\notin T}^{m} R_{down}(Z_{i,t_n})}{m}$$

$$R_{up} = \frac{\sum_{i=1, i\in T}^{m} \#(Z_{i,t} > Z_c, \forall \quad t = t_1, t_2, 6 \quad, t_n) + \sum_{i=1, i\notin T}^{m} R_{up}(Z_{i,t_n})}{m}$$

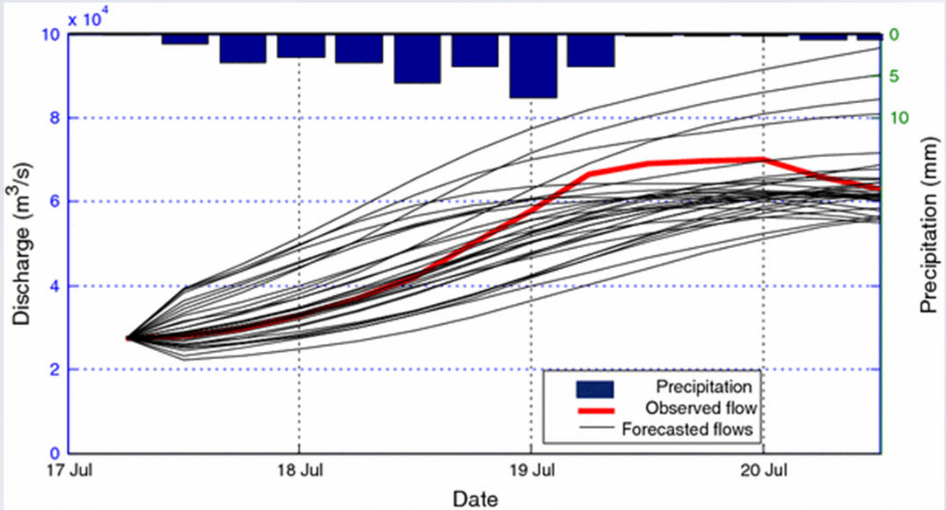
Flood risk analysis



Streamflow simulation of the TGR in 2004



Predicted precipitation at 2010 July 19



Forecasted streamflow of the TGR in 2010

Flood risk analysis

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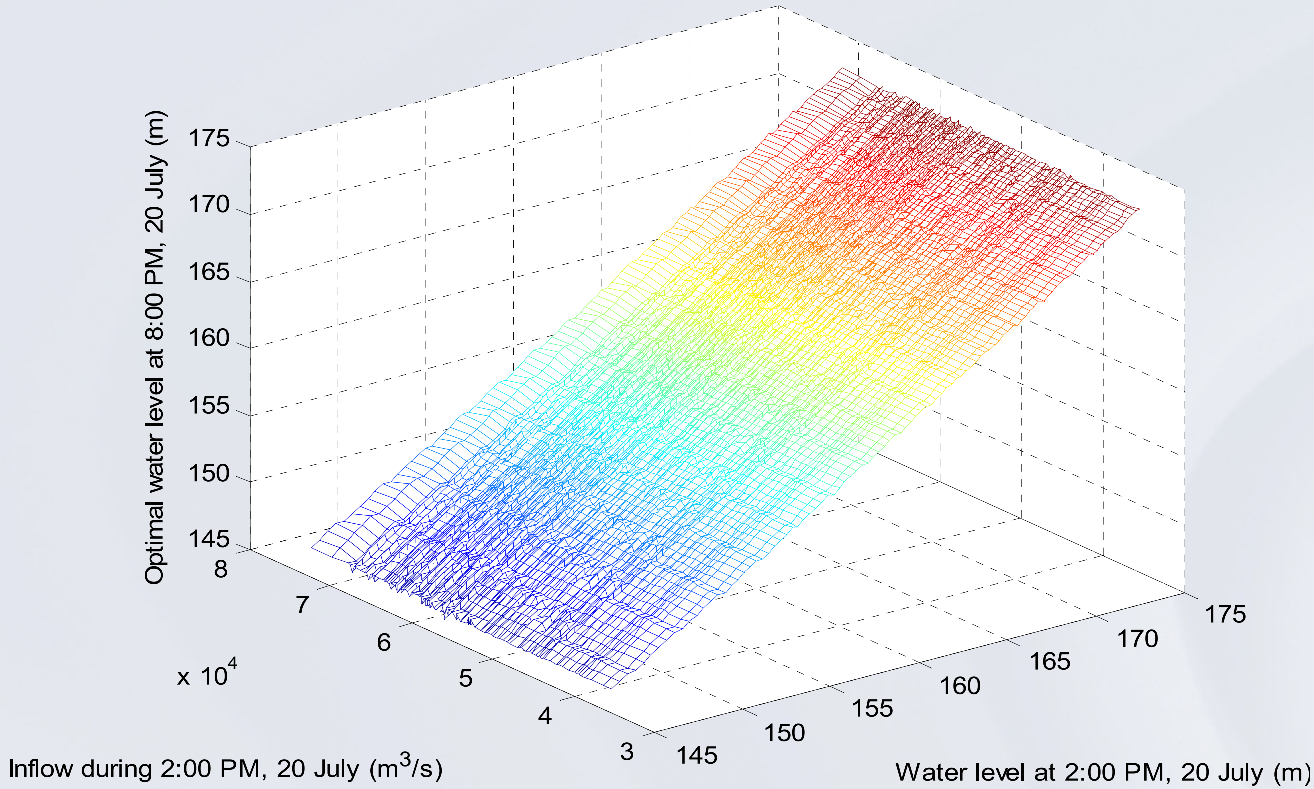
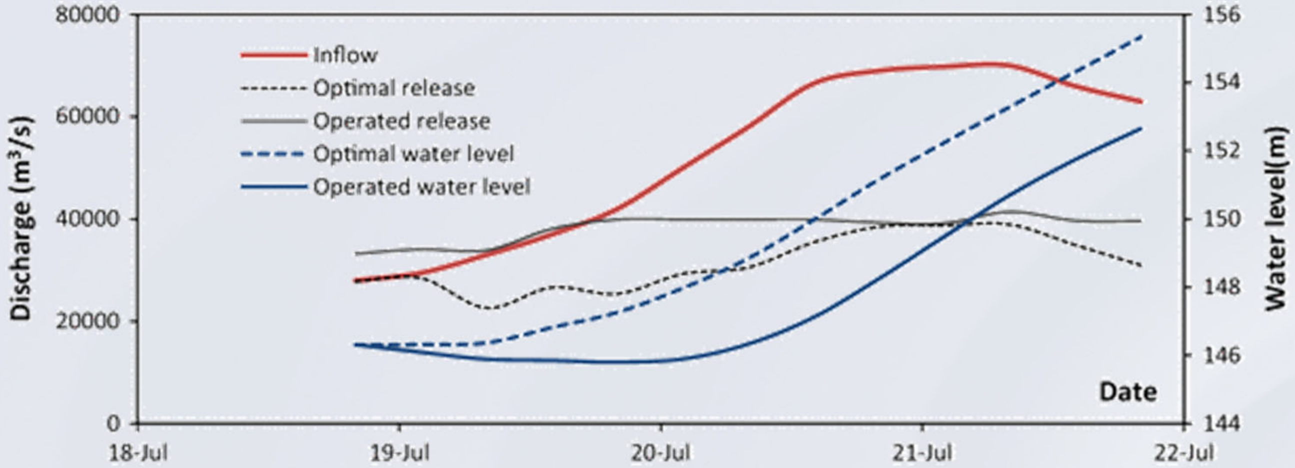


Optimal operating policy in the 2010-7-20 8:00

Sampling stochastic dynamic programming (SSDP) is used for optimization.

Flood risk analysis



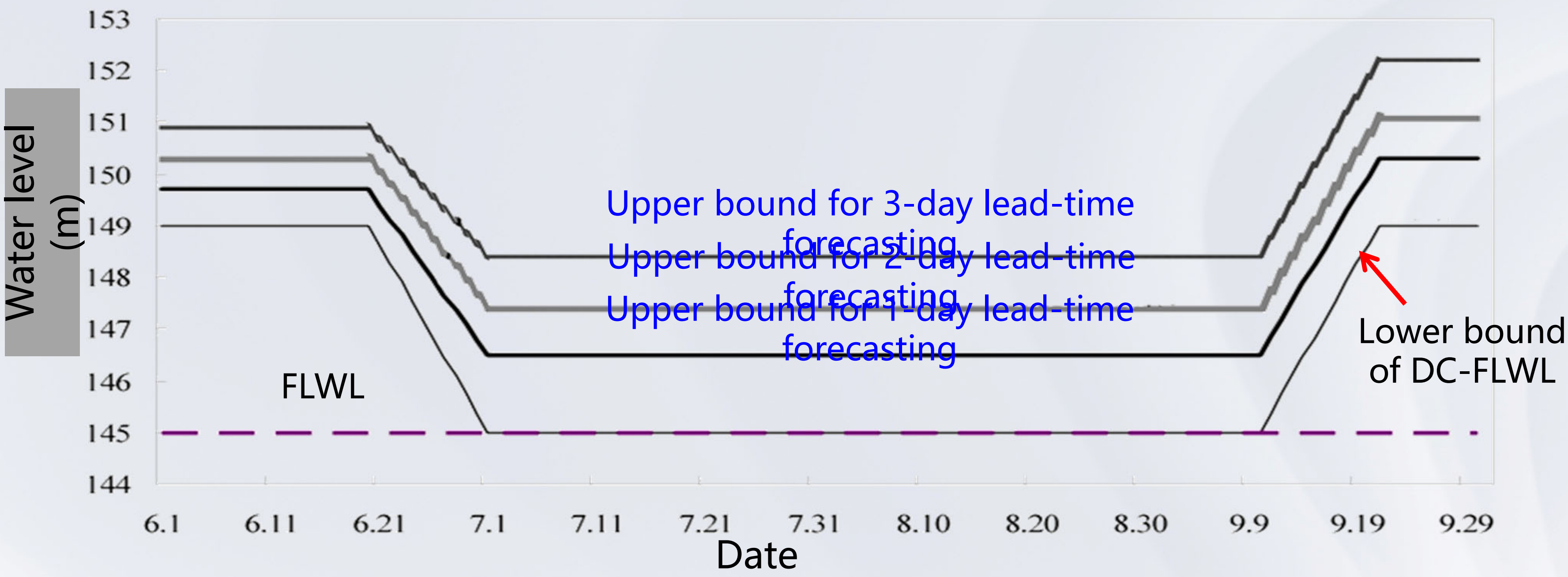
Optimal reservoir operation in the 2010-7-20 8:00

Table Risks and profits of four operation schemes for the 2010 floods

Schemes		Reservoir risk(%)		Hydropower generation (billion kWh)	End water level(m)
		Downstream	Upstream		
Operated scheme	Release control	-	2.39	1.44	152.41
	Water level control	3.46	-		
Optimized scheme	Release control	-	4.95	1.58	155.14
	Water level control	5.00	-	1.60	155.23

DC-FLWL for TGR

- The upper bounds at main flood season are 146.5m, 147.4m and 148.4m with 1-day, 2-day and 3-day lead-time forecasting, respectively.



DC-FLWL for TGR

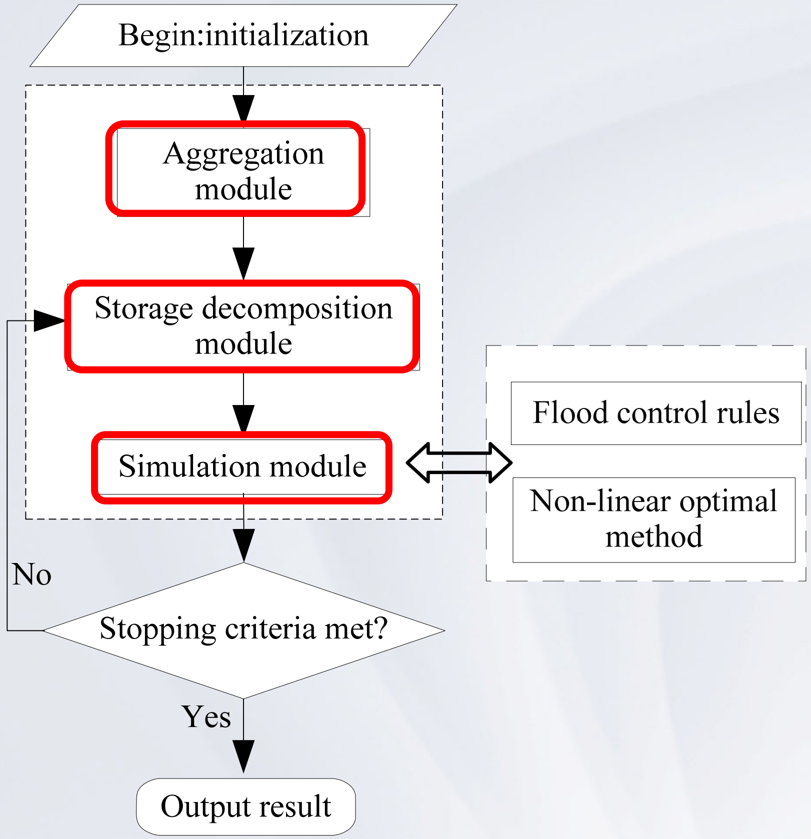
- Compared with the designed FLWL, the annual hydropower generation increment of DC-FLWL is 0.98–1.40 billion kW·h (an increment of 2.29–3.28%).

Economic Indicator		Designed FLWL=145m	DC-FLWL of TGR		
			1-day lead-time forecasting	2-day lead-time forecasting	3-day lead-time forecasting
Hydropower generation (billion kW·h)	Value	42.71	43.69	43.96	44.11
	Increment	-	0.98	1.25	1.40
	Rate	**-**	**2.29%**	**2.93%**	**3.28%**
Spilled water (billion m^3)	Value	48.26	46.51	46.25	46.72
	Increment	-	-1.75	-2.01	-1.54
	Rate	**-**	**-3.63%**	**-4.16%**	**-3.19%**

Dynamic control operation model for cascade reservoirs

- The proposed DC-FLWL model for cascade reservoirs consists of three modules:

1. Aggregation module
2. Storage decomposition module
3. Simulation module



DC-FLWL for cascade reservoirs

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- The aggregation module is used to estimate the maximum available flood prevention storage of the 'aggregated reservoir' in the cascade reservoir system.
- The storage decomposition module is used to find the flood prevention storage relationship between upstream and downstream reservoirs and allocate the maximum available flood prevention storage into individual reservoir units.

$$\int^{T_y} Q_{out,B}(t)dt - \int^{T_y} Q_B(t)dt = f_B(Z_B^{'}) - f_B(Z_B) \leq \int^{T_y} Q_{\max,B}dt - \int^{T_y} Q_B(t)dt = Q_{\max,B}T_y - \int^{T_y} Q_B(t)dt$$

- The simulation operation module is used to find and update the optimal storage allocation strategy in order to maximize the benefits of cascade reservoirs based on operation rules.

DC-FLWL for cascade reservoirs

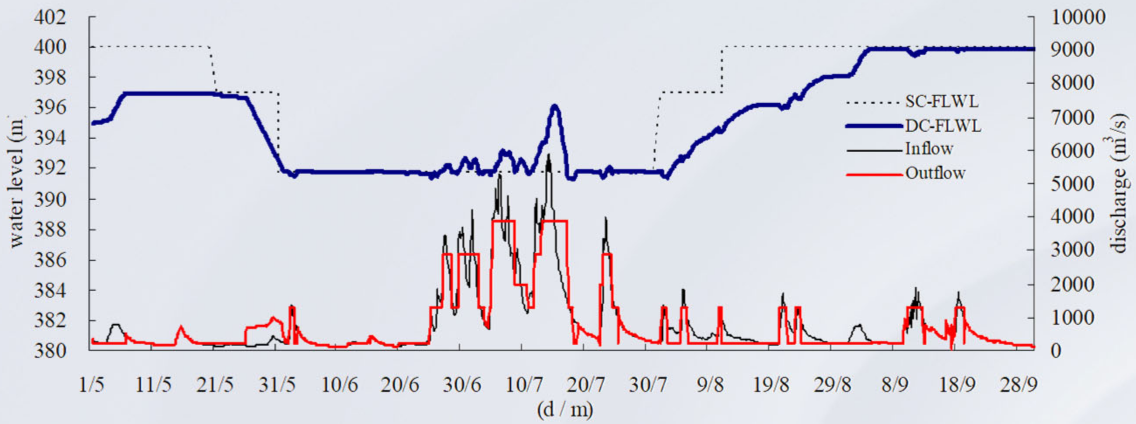
● The upper bounds of DC-FLWL for Shuibuya and Geheyan reservoirs

Reservoir	Pre-flood season (May 1st to June 20th)		Main flood season (June 21st to July. 31th)		Post-flood season (Aug. 1th to Sep. 30st)	
	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound
Shuibuya	400.00	397.00	394.58	391.80	400.00	397.00
Geheyan	200.00	198.00	194.96	192.20	200.00	198.00

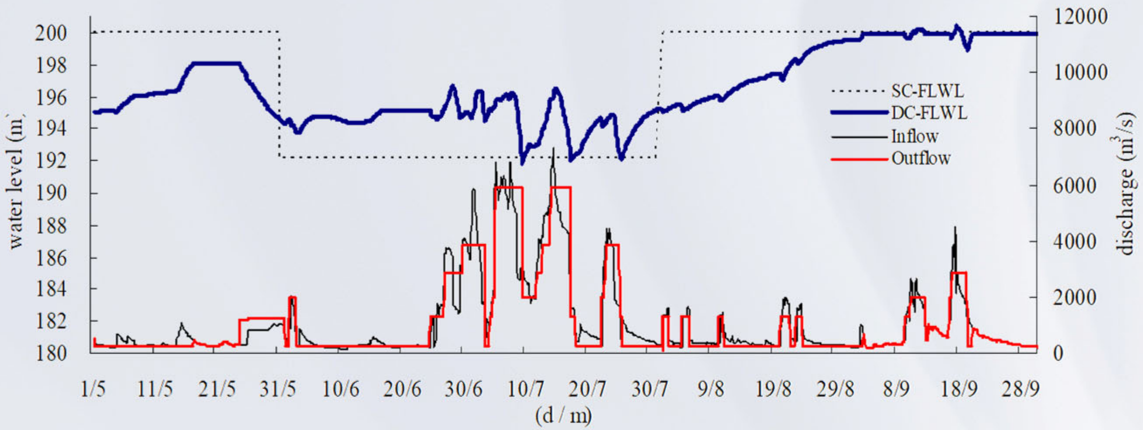
DC-FLWL for Qingjiang cascade reservoirs

Wet Year

Shuibuya reservoir



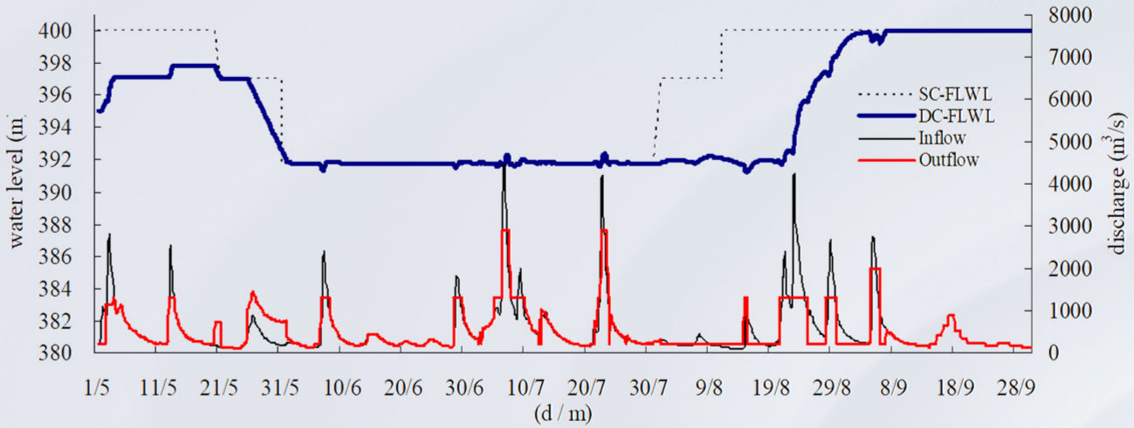
Geheyan reservoir



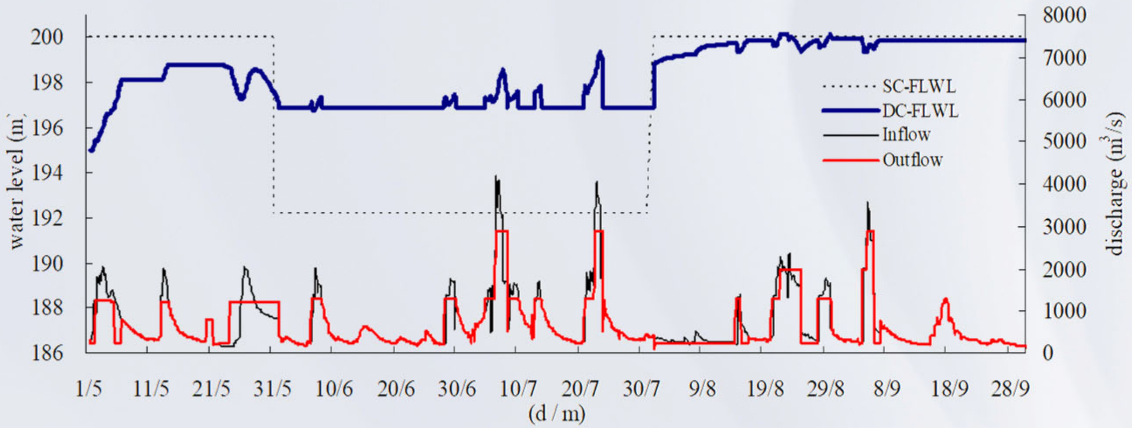
DC-FLWL for Qingjiang cascade reservoirs

Normal Year

Shuibuya reservoir



Geheyan reservoir



DC-FLWL for Qingjiang cascade reservoirs

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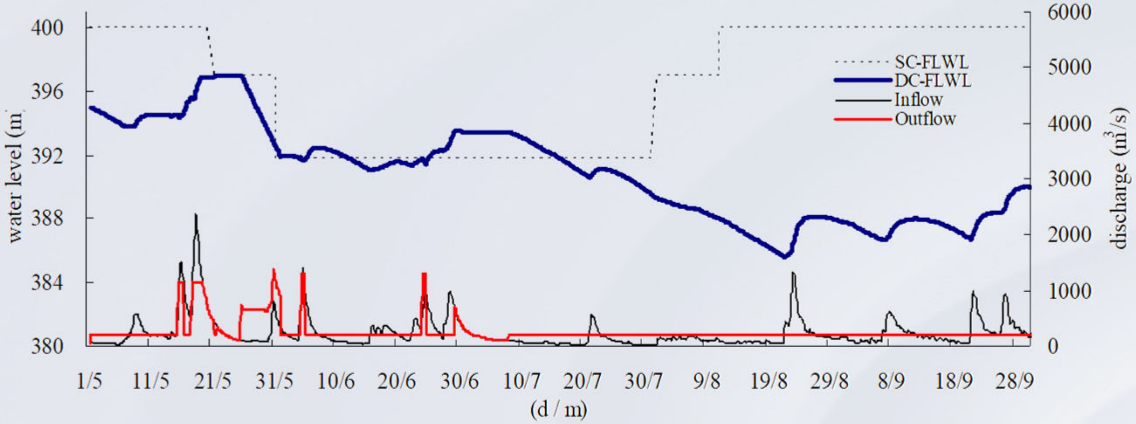
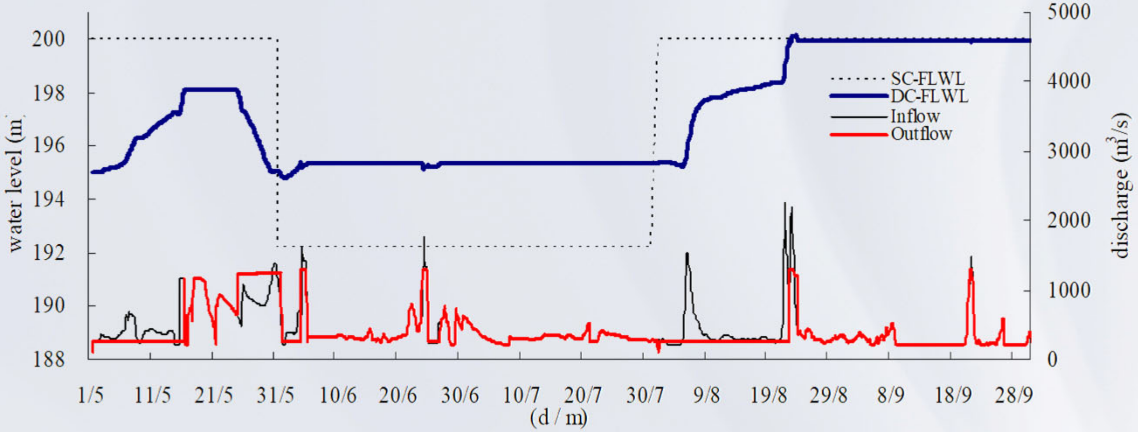
Dry Year

Shuibuya reservoir



Geheyan reservoir



DC-FLWL for Qingjiang cascade reservoirs

- The allowable pre-storage capacity allocated to the downstream reservoir is an optimal reservoir storage strategy during the flood season, which can generate more hydropower without reducing flood prevention standards.

- Compared with seasonal controlled FLWL, joint operation based on DC-FLWL for cascade reservoirs can generate 0.179 billion kWh (4.51%) more hydropower and increase water resource use rate by 2.73% annually.

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Refill operation

- The future operation horizon is divided into two stages, the forecast horizon(FH) and the remaining horizon(RH) by using the forecast horizon point
- Scenario-based forecasts are used in the forecast horizon, and historical streamflow is used in the remaining horizon

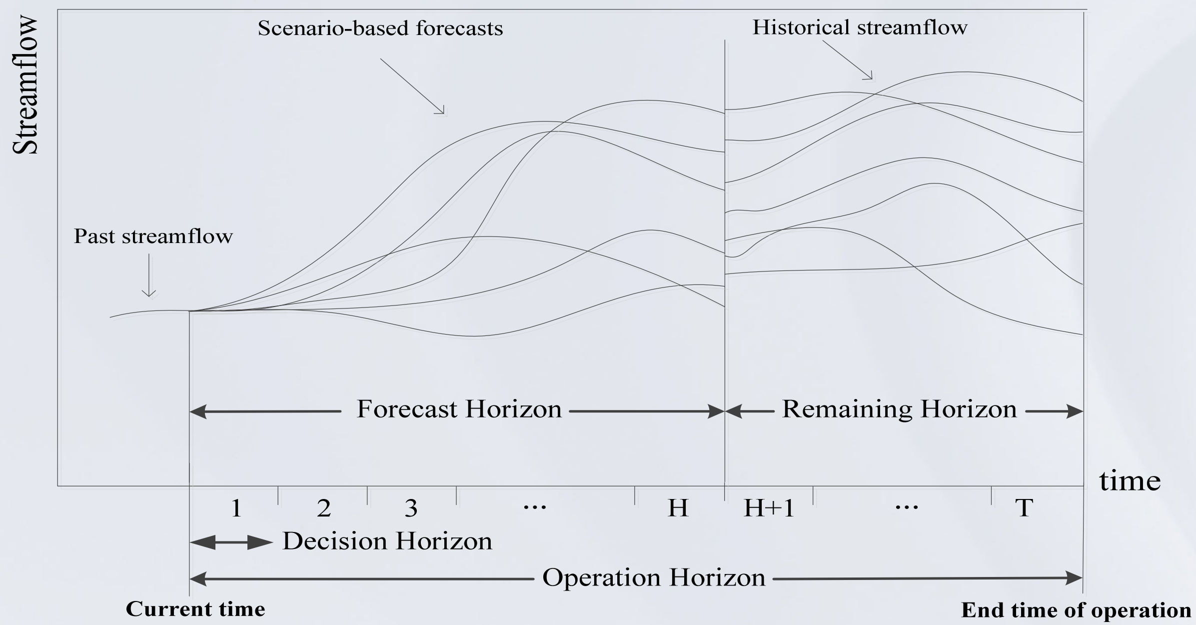

Fig Streamflow traces and reservoir operation rolling horizon decision making

Refill operation

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Deterministic dynamic programming(DDP)

require perfect forecast, difficult to generate one common operating trajectory for a cluster of streamflow

Explicit stochastic optimization(ESO)

discretization, maximize the expected benefit, curse of dimensionality

Implicit stochastic optimization(ISO)

the assumed sequences, poor correlation, amounts of trial and error processes

Hybrid two-stage methods: ESO-DDP, ISO-ESO, ISO-DDP

Table Comparison of the three hybrid two-stage stochastic methods

Hybrid methods	Stage	Algorithm	Periods of transition probability within one stage	Periods of transition probability of the two stages
ESO-DDP	FH	SSDP	Adjacent periods	H &RH
	RH	DDP	-	
ISO-ESO	FH	ISO-SURF	-	FH&H+1
	RH	SSDP	Adjacent periods	
ISO-DDP	FH	ISO-SURF	-	FH&RH
	RH	DDP	-	

Refill operation

Table Comparison of the simulated operation results of the six schemes

Scheme	Refill rate (%)	Hydropower generation (billion kWh)	Potential energy (billion kWh)	Total energy (billion kWh)	Mean final water level (m)	Maximum final water level (m)	Minimum final water level (m)
DDP	100	17.75	5.54	23.29	175	175	175
SDP	80.62	16.93	5.41	22.33	174.48	175	160.89
SSDP	93.80	17.29	5.51	22.81	174.91	175	169.21
ESO-DDP	93.02	17.18	5.42	22.59	174.53	175	155.49
ISO-ESO	26.36	16.62	5.15	21.78	173.47	175	166.89
ISO-DDP	97.67	17.34	5.54	22.88	174.99	175	174.86

- The DDP scheme performs best because it benefits of the perfect forecast.
- Compared with the DDP scheme, the SDP, SSDP, ESO-DDP, ISO-ESO, and ISO-DDP schemes decrease the refill rate by 19.38%, 6.20%, 6.98%, 73.64%, and 2.33%, respectively, and decrease the hydropower generation by 4.62%, 2.59%, 3.21%, 6.37%, and 2.31%, respectively.
- The results of the ISO-DDP scheme approximates those of the DDP scheme.

Refill operation

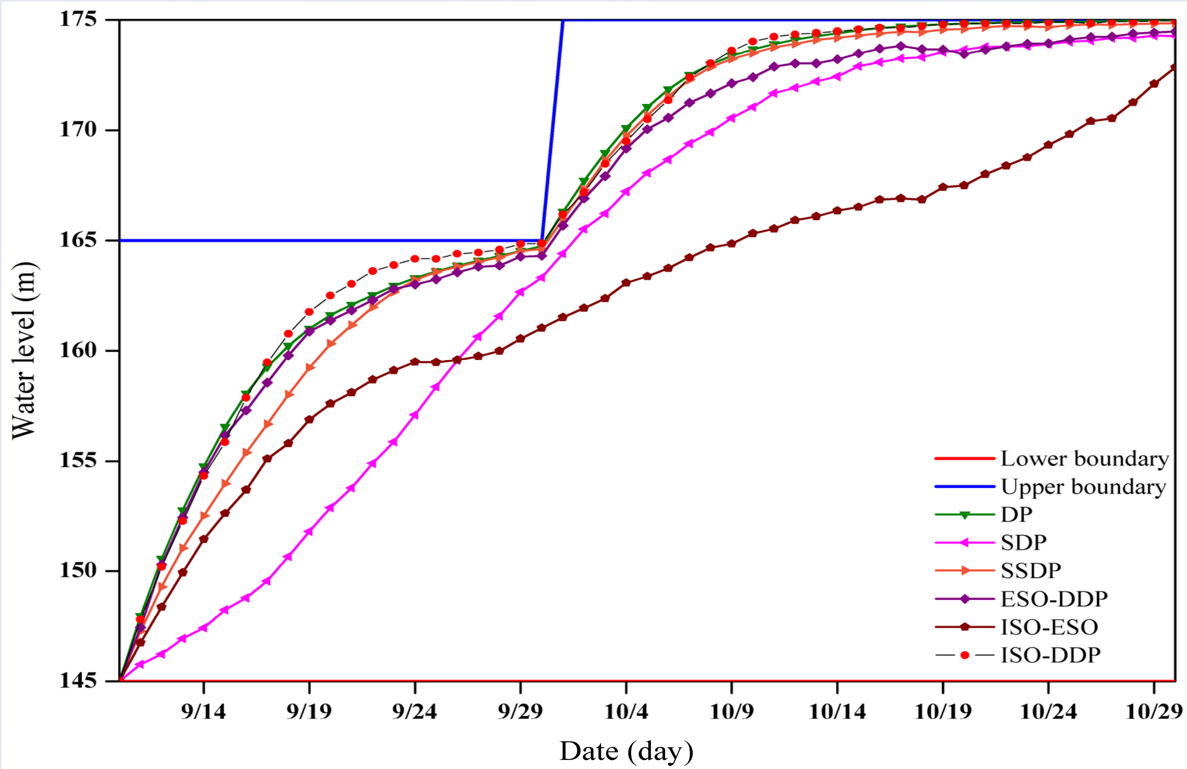

Fig Comparison of average water levels for the six operation methods

- The discharge in September is greater than in October, which contributes to the rapid rise of water level in September.

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Conclusions

- Seasonal control reservoir's FLWL is a valuable and effective way to compromise between flood control and benefits

- Compared with the designed FLWL, the annual hydropower generation increment of DC-FLWL is 0.98–1.40 billion kW·h for TGR

- Compared with seasonal controlled FLWL, joint operation based on DC-FLWL for cascade reservoirs can generate 0.179 billion kWh (4.51%) more hydropower and increase the water resource use rate by 2.73% annually for Qingjiang cascade reservoirs

- The proposed real-time refill operation model uses available streamflow information for the entire operation horizon. The ISO-DDP scheme decreased the refill rate only by 2.33% and decreased hydropower generation by 2.31% compared with the DDP scheme (100%)

Thank you for your attention!