XVIII
World Water Congress
International Water Resources Association (IWRA)

Streamflow and flood simulations driven by satellite remote sensing

Di Long

Tsinghua University

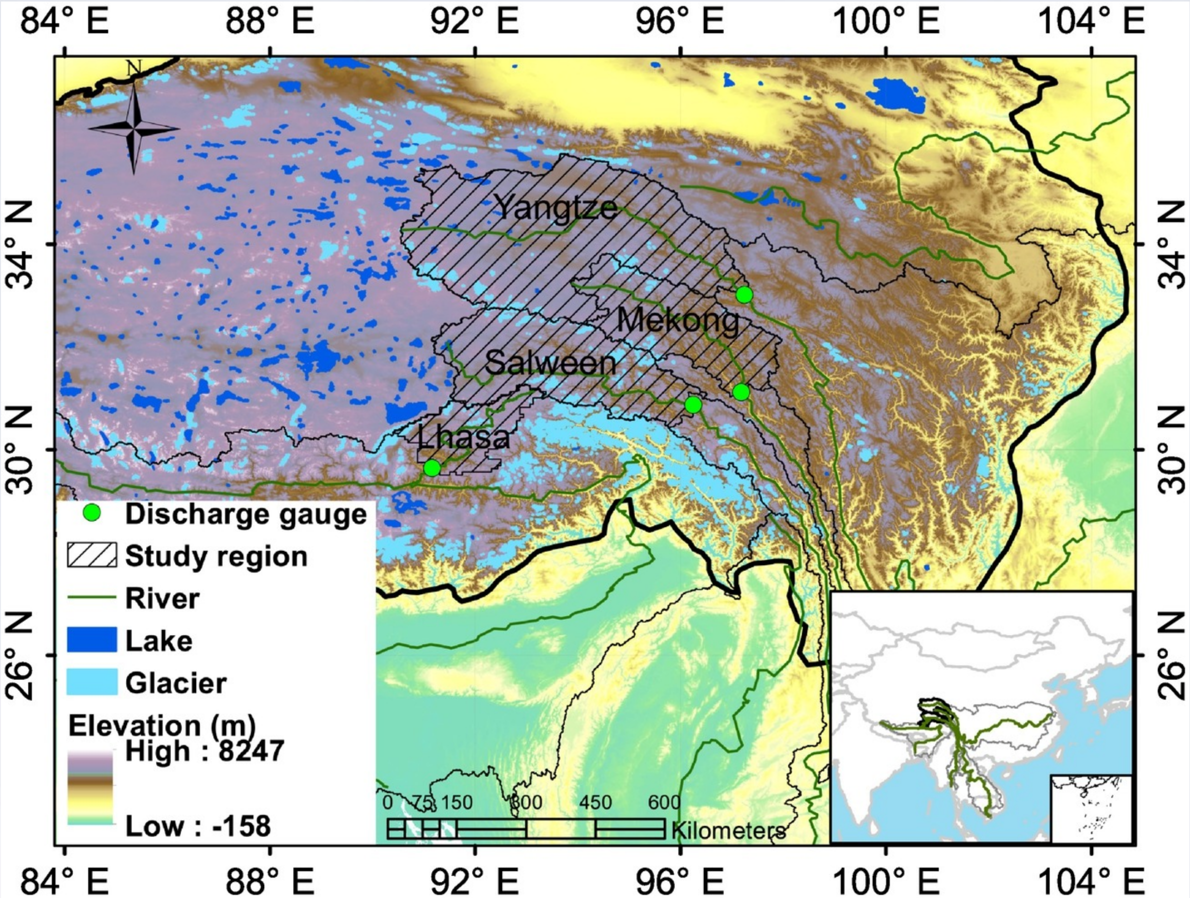
XVIII
WORLD WATER CONGRESS
Water for All
Harmony between Humans and Nature

第18届
世界水资源大会
水与万物：
人与自然和谐共生

Content

- Introduction
- Data and methodology
- Results
- Conclusion

Introduction



Gauging stations (green circles), basin boundaries, lakes (dark blue), and glaciers (light blue) on the TP

- Four rivers including headwaters of three transboundary rivers (i.e., the tributaries of the **Brahmaputra**, **Salween**, and **Mekong**) and one major river (the **Yangtze River** in China) originating from the TP
- It is difficult to estimate discharge because methodologies relying on ground-based measurements are not applicable in ungauged basins
- **Daily continuous** discharge estimation through **model calibration/data assimilation** in poorly gauged or ungauged basins is much more valuable in facilitating water resource management and mitigating flood disasters

Data and Methodology: Data

High-resolution scenes

- Inclusive of multiple sources (see Figure)
- For accurate derivation of river widths used in model calibration

Snow data

- Derived using empirical equations from snow depth provided by WestDC (Dai et al., 2015; Dai et al., 2012)
- To calibrate snow melt parameters

CREST-RS model forcing data

- Precipitation: GSMaP
- LST: MODIS MOD11A1 and MYD11A1
- Air temperature: ERA-Interim
- PET: Famine Early Warning Systems

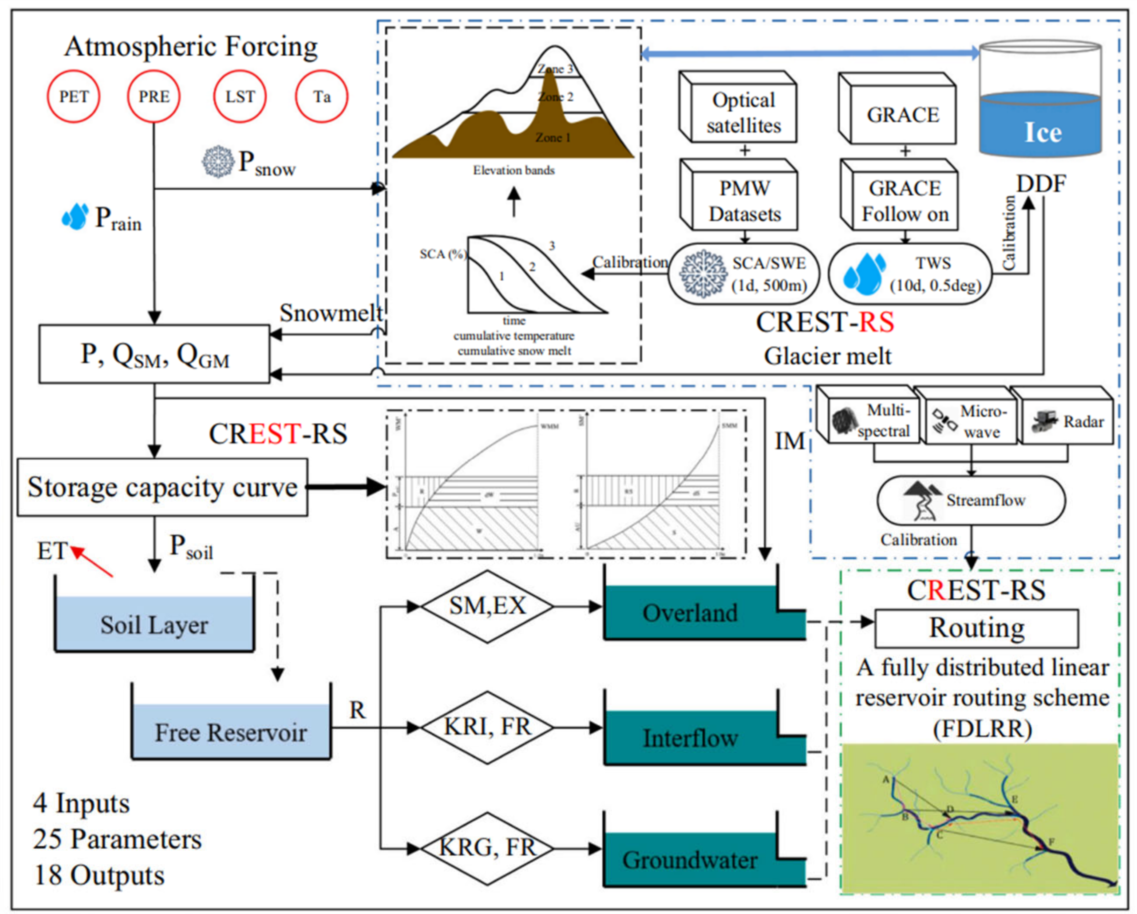
Auxiliary data

- DEM (From DRT): to delineate model flow directions
- Daily in-situ discharge data (obtained from gauge stations): used in validation

Site	Data source	Date	ID	Spatial Resolution
Lhasa	GeoEye-1	2009/11/4	10504100020C6500	2 m for multispectral bands
	WorldView-2	2010/9/28	1030010007600100	2 m for multispectral bands
	GeoEye-1	2010/12/7	10504100012E0400	2 m for multispectral bands
	WorldView-2	2011/2/2	1030010008028700	2 m for multispectral bands
	GeoEye-1	2011/11/26	1050410000F8CD00	2 m for multispectral bands
	IKONOS	2012/2/23	1060010007504100	4 m for multispectral bands
	GeoEye-1	2012/12/20	1050410000D66500	2 m for multispectral bands
	WorldView-2	2014/3/6	103001002D547100	2 m for multispectral bands
	GeoEye-1	2014/10/20	10504100118AD900	2 m for multispectral bands
	IKONOS	2014/10/25	106001000953A900	4 m for multispectral bands
Salween	QuickBird	2013/01/22	1010010011072700	2.4 m for multispectral bands
	WorldView-2	2013/05/01	1030010022843900	2 m for multispectral bands
	WorldView-2	2013/11/18	10300100295F1F00	2 m for multispectral bands
	GeoEye-1	2014/01/15	1050410004C3ED00	2 m for multispectral bands
	WorldView-2	2014/02/21	103001002CB81F00	2 m for multispectral bands
Mekong	RapidEye-5	2009/08/06	20090806_045707_4753408_RapidEye-5	5 m for multispectral bands
	RapidEye-5	2009/08/06	20090806_045708_4753407_RapidEye-5	5 m for multispectral bands
	IKONOS	2009/09/05	1060010004E50600	4 m for multispectral bands
	QuickBird	2009/11/30	101001000AB2E200	2.4 m for multispectral bands
	GeoEye-1	2011/10/21	1050410000A2AB00	2 m for multispectral bands
	WorldView-2	2012/01/01	103001000F61A600	2 m for multispectral bands
Yangtze	GeoEye-1	2010/05/06	1050410001BF8A00	2 m for multispectral bands
	WorldView-2	2010/10/18	1030010006B29B00	2 m for multispectral bands
	WorldView-2	2011/02/13	10300100090C1700	2 m for multispectral bands
	RapidEye-2	2012/05/25	20120525_052824_4754308_RapidEye-2	5 m for multispectral bands
	RapidEye-1	2012/09/05	20120905_051023_4754308_RapidEye-1	5 m for multispectral bands
	RapidEye-4	2012/09/13	20120913_051356_4754308_RapidEye-4	5 m for multispectral bands
	RapidEye-5	2012/10/22	20121022_051356_4754308_RapidEye-5	5 m for multispectral bands
	QuickBird	2014/12/12	1010010013367500	2.4 m for multispectral bands

High-resolution scenes used in this study

Data and Methodology: CREST-RS model



Structure of the CREST-RS model that uses four types of forcing data with 25 parameters and 18 outputs

CREST-RS

Advantages

- Driven and calibrated by remote sensing data
- Free of limitations imposed by in-situ gauge data

Four modules

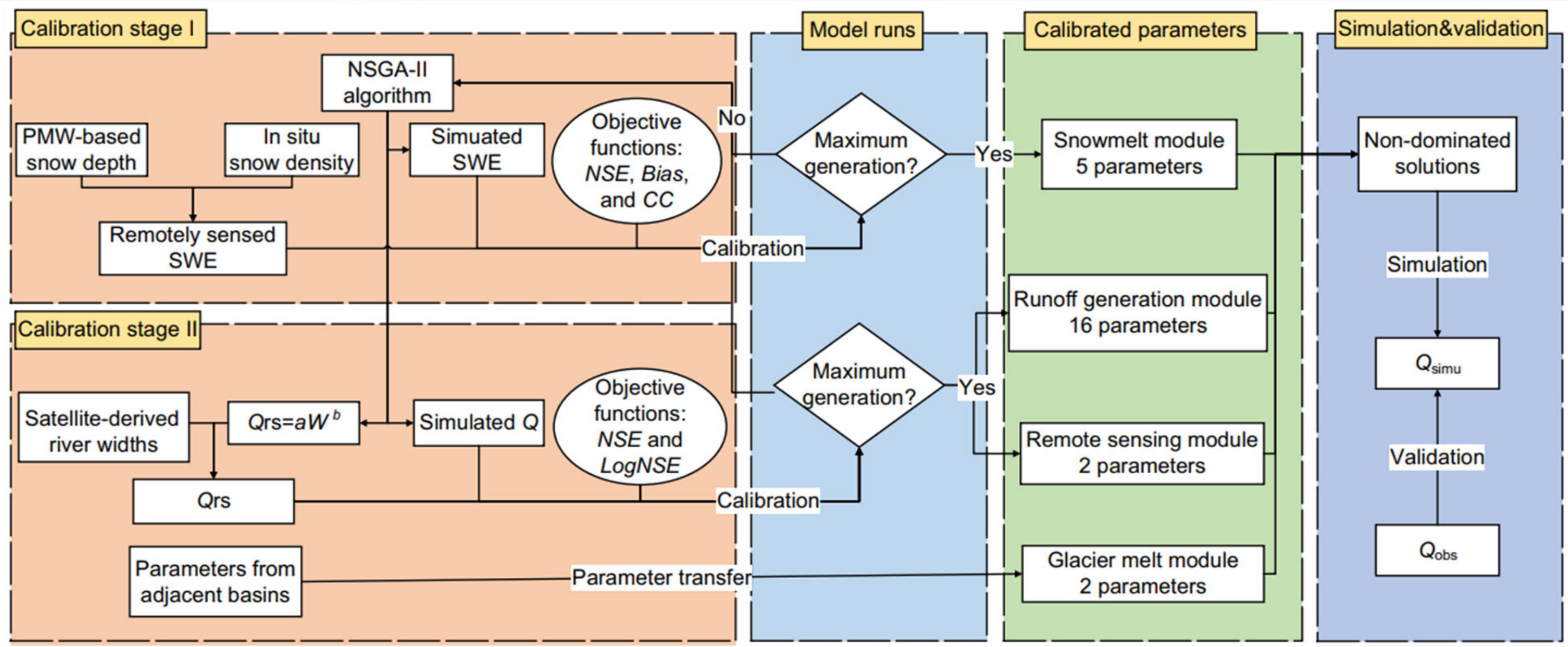
- **Snow melt module** & **Glacier melt module**: enables expansion to include high-mountain cryospheric regions
- **Runoff generation and routing module**
- **Remote sensing river discharge module**: allow using river width/level for calibration

CREST-RS model forcing data

- **Precipitation**: GSMaP
- **LST**: MODIS MOD11A1 and MYD11A1
- **Air temperature**: ERA-Interim
- **PET**: Famine Early Warning Systems

Data and Methodology: Two-step calibration

XVIII World Water Congress
International Water Resources Association (IWRA)



Flowchart of the two-step calibration strategy for CREST-RS model

Parameter transfer

Transferring parameters from adjacent basins for **glacier melt parameters** (2 parameters)

- Lhasa River and headwaters of Salween River: from headwaters of the Brahmaputra River
- Headwaters for the Mekong and Yangtze rivers: from Han et al. (2019)

Step 1

Calibration of parameters pertaining **snow accumulation and melt** (5 parameters)

- **SWE** as calibration reference
- *NSE*, *CC* and *Bias* as objective functions
- NSGA-II as optimization algorithm

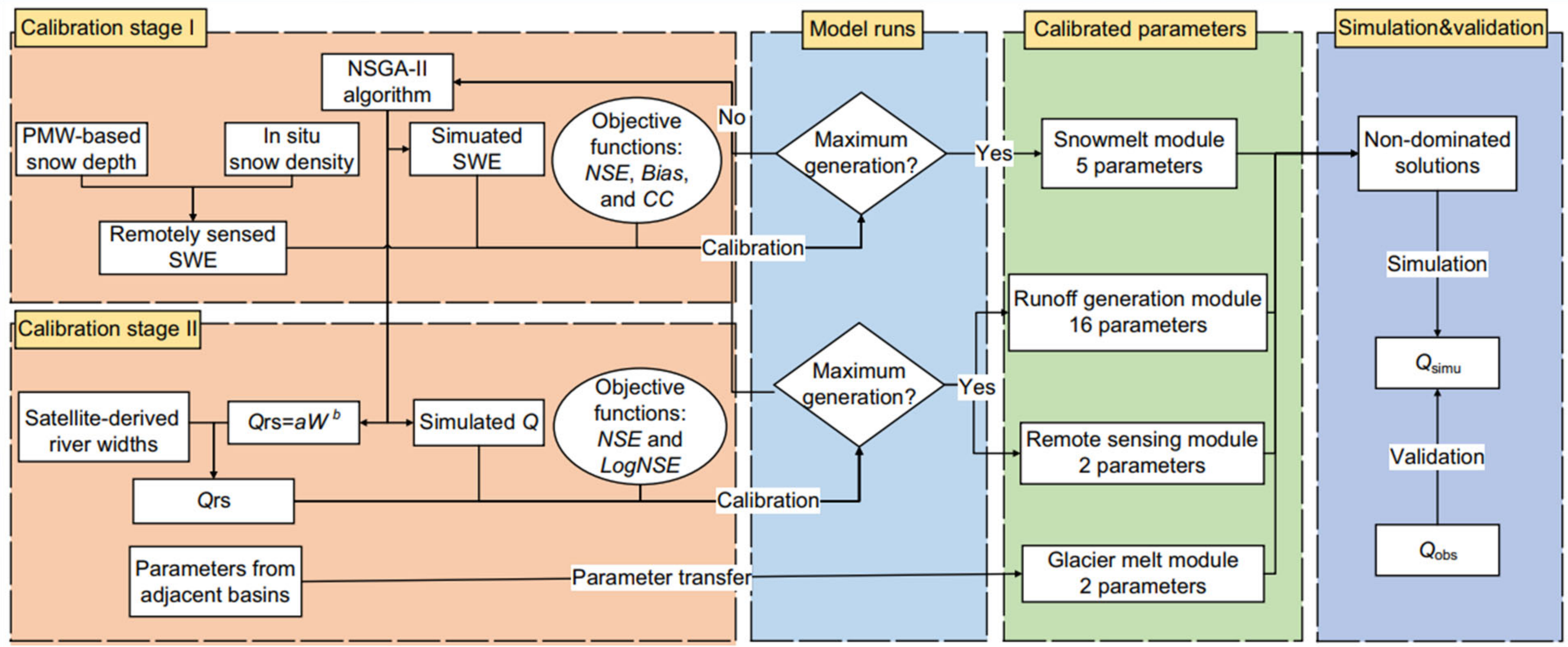
Step 2

Calibration of **runoff generation and routing parameters**, and **remote sensing river discharge parameters** (16+2=18 parameters)

- **River discharge** as calibration reference
- *NSE* and *LogNSE* as objective functions
- NSGA-II as optimization algorithm

Data and Methodology: Two-step calibration

XVIII World Water Congress
International Water Resources Association (IWRA)



Flowchart of the two-step calibration strategy for CREST-RS model

Interconnection in Step 2

The remote sensing discharge is interconnected with the simulated discharge

- Two Remote sensing module parameters (a and b) is inherited in the calibration reference

$Q_{rs} = aW^b \, (b = 8/3 \text{ for triangular cross-sections})$

- Bounding a and b is essential

Bounding a and b

Bounded by three additional equations:

$$Q = a_1 D^{b_1} \quad D = \frac{D_{\max}}{W_{\max}^2} W^2 \quad Q = a_1 \left(\frac{D_{\max}}{W_{\max}^2} \right)^{b_1} W^{2b_1}$$

- Based on well-agreed ranges of a_1 and b_1, bounds for a and b can be mathematically determined

Human intervention

To further improve the reliability of simulation, two principles of human intervention were adopted:

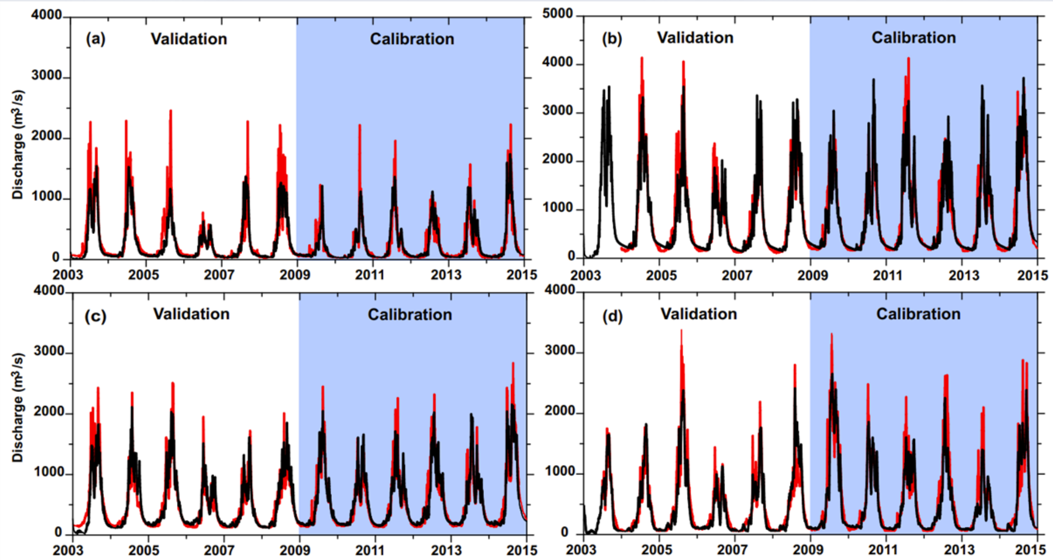
- Simulation must be covered by the minimum and maximum discharges obtained using an empirical approach

$Q = 0.23 W^{1.46} V^{1.39}$

- Simulation-based retrieval of KE must fall in [0.3, 1] (KE is the factor converting potential ET to actual ET)

Results: Calibration using gauged discharge (S1)

XVIII World Water Congress
International Water Resources Association (IWRA)



Simulated discharge from model calibration using gauged data for the four river basins: (a) Lhasa River, (b) headwaters of the Salween, (c) Mekong, and (d) Yangtze rivers.

Scenario 1

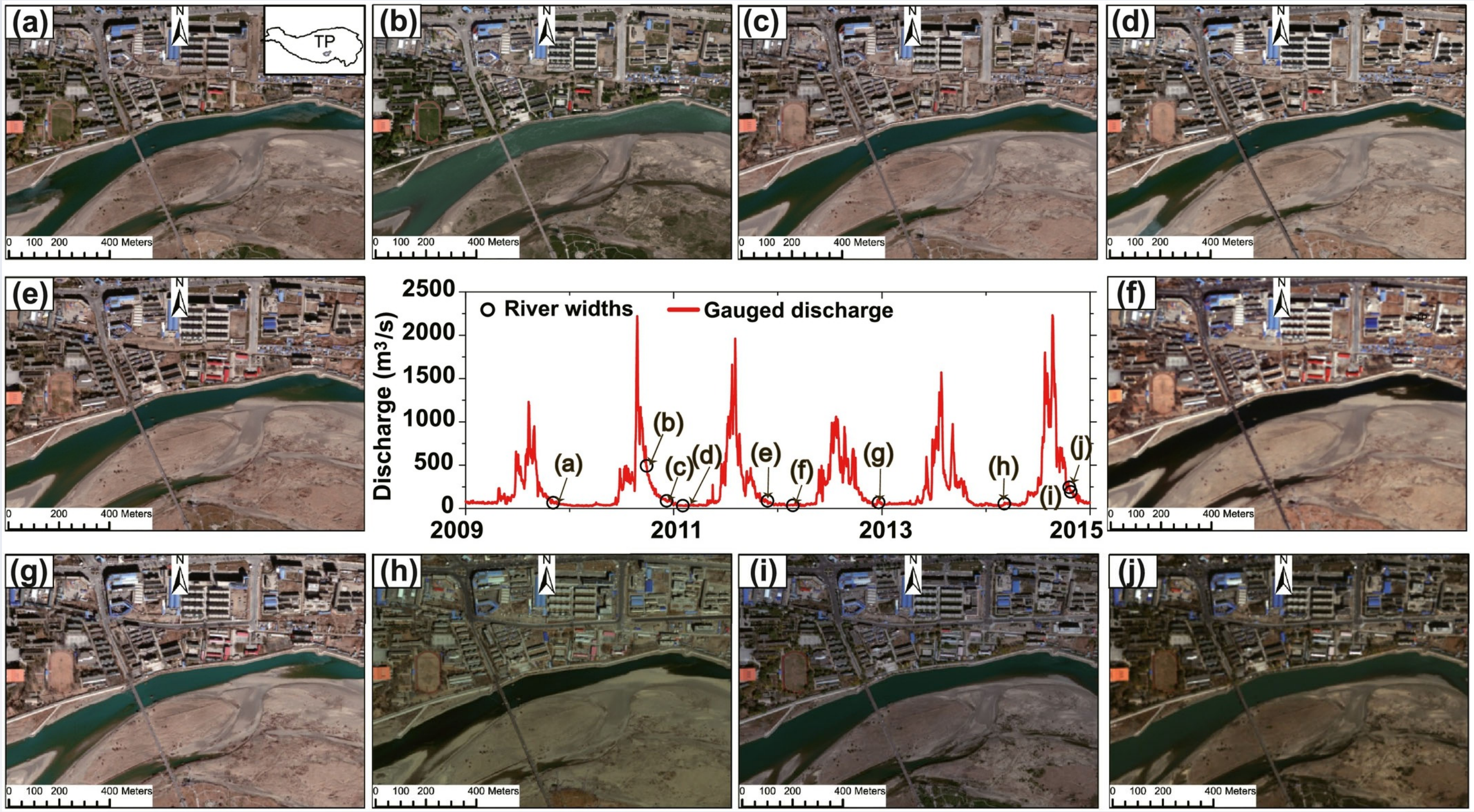
Model is calibrated using in-situ discharge data as do traditional approaches

- *NSE* and *LogNSE* > 0.8 for the four river basins
  --- proving the applicability of the model in TP
- Relatively **lower performance** metrics of the Lhasa River possibility due to its **small basin area** (~ 31,000 km^2) and **limited spatial resolution of forcing data** (e.g., 0.1° for GSMaP)
  --- not due to the capability of this model

Site	References	No. of widths	No. of solutions	*NSE* (–)	*LogNSE* (–)	*Bias* (–)
Lhasa	Gauge	0	8	0.80	0.89	−0.15
	Commercial	10	10	[0.49, **0.77**, 0.77]	[0.19, **0.82**, 0.88]	[−0.42, **−0.15**, −0.03]
	Landsat	57	12	[0.68, **0.81**, 0.83]	[−0.35, **0.71**, 0.82]	[−0.37, **−0.10**, 0.01]
Salween	Gauge	0	15	0.87	0.91	−0.06
	Commercial	5	4	[0.49, **0.85**, 0.88]	[0.16, **0.90**, 0.90]	[−0.44, **−0.09**, 0.13]
	Landsat	32	6	[0.72, **0.87**, 0.87]	[0.74, **0.83**, 0.89]	[0.01, **0.11**, 0.27]
Mekong	Gauge	0	1	0.86	0.89	0.04
	Commercial	5	8	[0.42, **0.63**, 0.68]	[0.48, **0.59**, 0.63]	[−0.19, **−0.04**, 0.04]
	Landsat	38	2	[0.51, **0.67**, 0.78]	[0.65, **0.77**, 0.83]	[−0.31, **−0.25**, −0.18]
Yangtze	Gauge	0	10	0.88	0.87	−0.05
	Commercial	8	6	[0.29, **0.72**, 0.72]	[0.48, **0.74**, 0.77]	[−0.29, **0.01**, 0.30]
	Landsat	28	7	[0.70, **0.81**, 0.83]	[0.46, **0.50**, 0.52]	[0.19, **0.23**, 0.30]

Performance metrics under Different scenarios for the four river basins

Results: Calibration with high-resolution images (S2)



Ten high-resolution images used for model calibration in the Lhasa River basin. (a)–(j) are the remotely sensed widths in chronological order. Most of the satellite images are distributed in low flow periods with little cloud contamination.

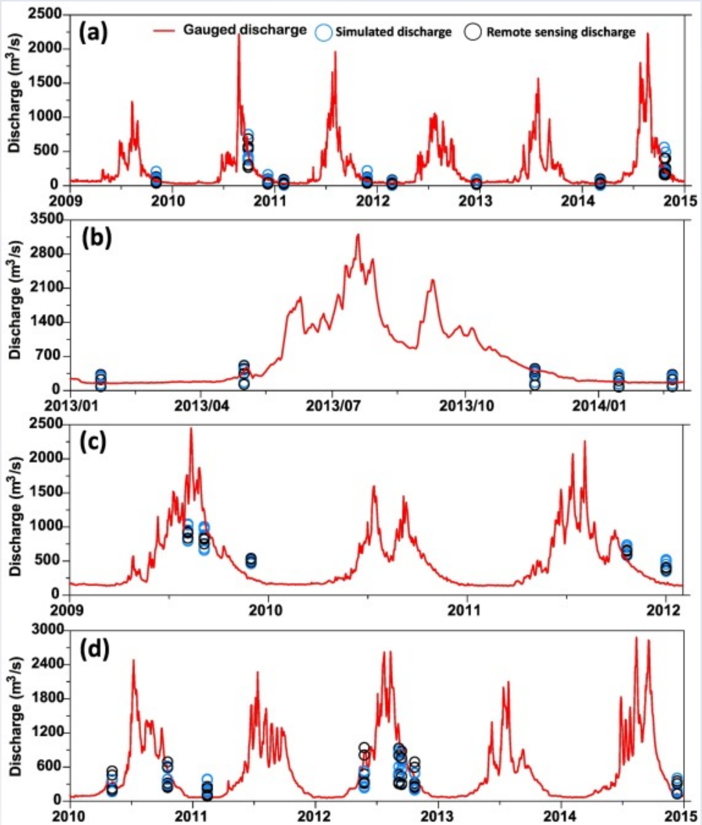
Scenario 2

Model is calibrated using high-spatial-resolution images, to test the feasibility of calibration with river widths

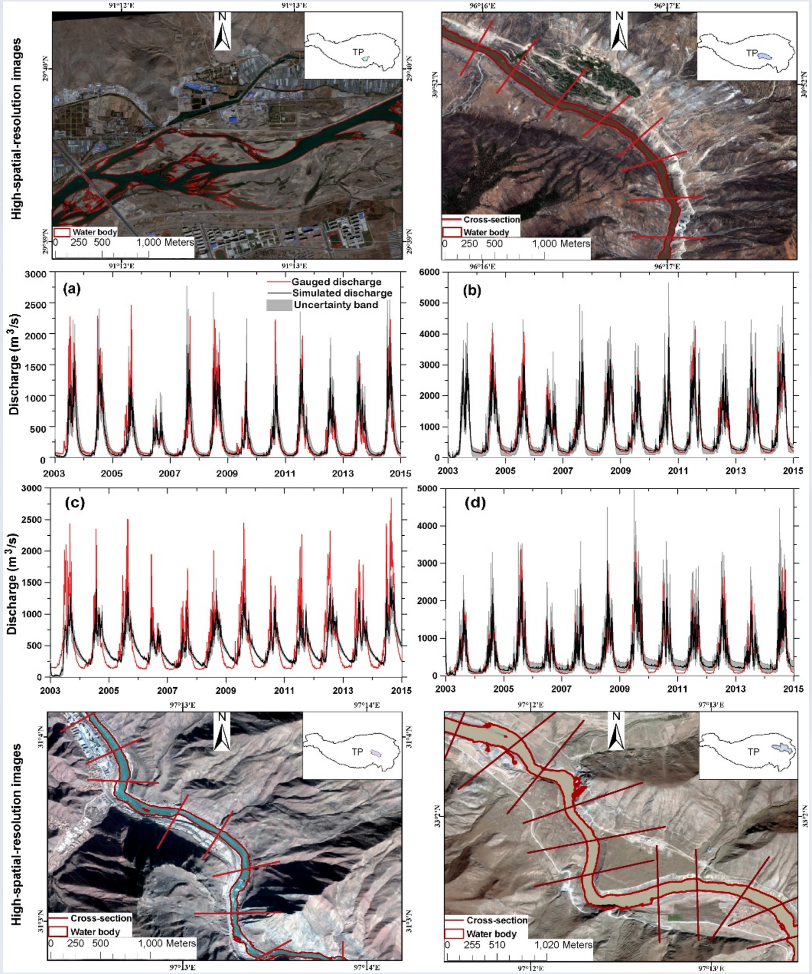
- **For Lhasa River whose river width was ~ 100 m**: width was obtained from the RivWidth software
- **For the headwaters of the Salween, Mekong, and Yangtze rivers whose river widths were ~ 50 m or even smaller**: widths were taken average of 20 cross-sections manually demarcated
- On the left is the example of the Lhasa River

Results: Calibration with high-resolution images (S2)

XVIII World Water Congress
International Water Resources Association (IWRA)



Comparison between discrete simulated discharge and remote sensing discharge that were date-paired



Simulation results and river width cross-sections for the four river basins

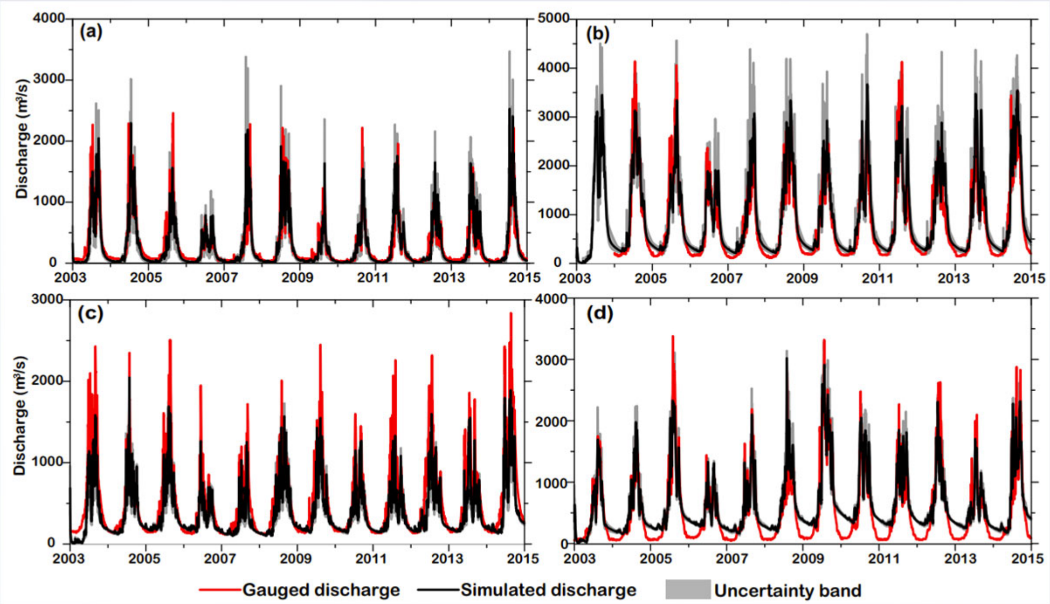
Scenario 2

Model is calibrated using high-spatial-resolution images, to test the feasibility of calibration with river widths

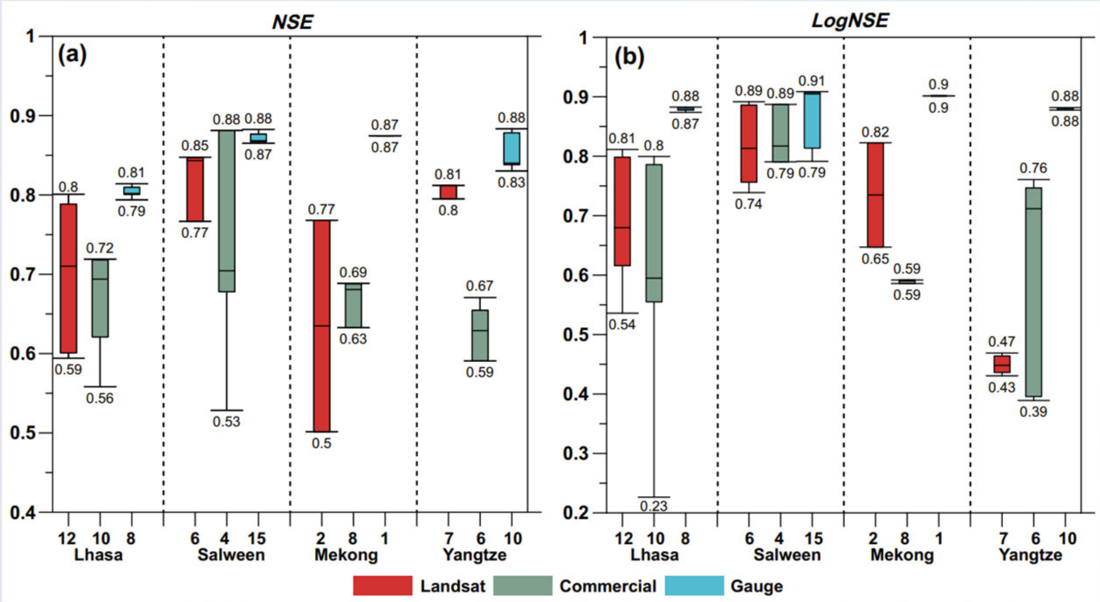
- *NSE* for the ensemble mean of the simulated discharge was 0.77, 0.85, 0.63, and 0.72 for each of the four basins
- Slight underestimation of peak flows and over-estimation of low flows were observed to some extent
- Performance might be constrained by limited numbers of available observations from these high-spatial-resolution satellites

Results: Calibration with Landsat images (S3)

XVIII World Water Congress
International Water Resources Association (IWRA)



Simulation results under Scenario 3



Boxplots for performance metrics under different scenarios

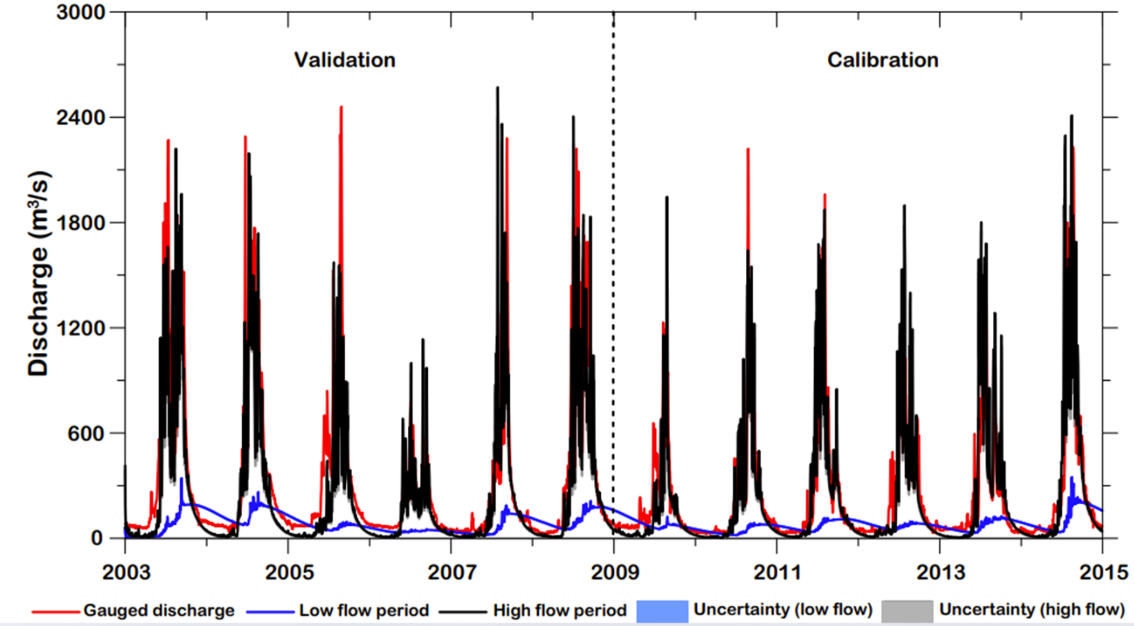
Scenario 3

Model is calibrated using Landsat images, as a complementary experiment of Scenario 2

- *NSE* for the Lhasa River, headwaters of the Salween and the Yangtze rivers reached 0.8 or even higher, followed by the headwaters of the Mekong River (~ 0.7)
- Despite of relatively low spatial resolution (30 m) of Landsat observations, the performance was possibly compensated by the increased numbers of derived widths

Results: Calibration with widths of contrary CVs (S4)

XVIII World Water Congress
International Water Resources Association (IWRA)



Simulation results under Scenario 3

Scenario 4

Model is calibrated using two sets of river widths that have contrary coefficient of variation (CV) (high flow period for the high CV; low flow period for the low CV)

- Model calibration with widths with **higher CV** (i.e., the high flow period) produced **better** results
- Model calibration with widths with **lower CV** (i.e., the low flow period) produced **worse** results
- Variability in river width is an important influence on model calibration

Period	Calibration references	No. of widths	*CV* of widths	No. of solutions	*NSE* (–)	*LogNSE* (–)	*Bias* (–)
Calibration					[0.54, **0.58**, 0.62]	[0.05, **0.19**, 0.26]	[–0.06, **–0.04**, –0.03]
Validation	Widths in high flow periods	4	0.35	5	[0.67, **0.70**, 0.72]	[0.15, **0.26**, 0.33]	[–0.22, **–0.21**, –0.20]
Entire period					[0.63, **0.66**, 0.69]	[0.12, **0.25**, 0.31]	[–0.15, **–0.14**, –0.13]
Calibration					[–0.19, **–0.19**, –0.19]	[–0.26, **–0.26**, –0.25]	[–0.67, **–0.67**, –0.67]
Validation	Widths in low flow periods	6	0.10	5	[–0.27, **–0.27**, –0.27]	[–0.49, **–0.48**, –0.48]	[–0.73, **–0.73**, –0.73]
Entire period					[–0.22, **–0.22**, –0.22]	[–0.34, **–0.34**, –0.33]	[–0.71, **–0.71**, –0.70]

Discussion

XVIII World Water Congress
International Water Resources Association (IWRA)

- **CREST-RS** with **remotely sensed river widths** as the primary model calibration reference could generate discharge with **NSE reaching ~0.8**, thereby proving the feasibility of the developed approach in **poorly gauged basins** without discharge measurements
- Model calibration with river widths is applicable even in small rivers with **narrow widths** (e.g., ~ 50 m). **SAR** data and **high-spatial-resolution images** from commercial satellites and CubeSats could be promising supplements to the already abundant sources of optical and infrared images
- **CREST-RS** is a distributed hydrological model that is coupled with a snow and glacier module and a remote sensing river discharge module, thereby allowing its application in **cryospheric** and/or poorly **gauged regions**
- With the launch of the **SWOT** mission, **water levels** and **widths** for rivers as narrow as **100 m** or even less could be available, which would provide much more accurate remotely sensed used for model calibration/data assimilation

Thanks for Listening!

XVIII World Water Congress
International Water Resources Association (IWRA)

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