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11-15 Sept, Beijing

Current and future Hydrological models in large river basins

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Outline:

- Challenges in large river basins
- Traditional and current use of hydrological models
- Limitations/bottlenecks and future outlook in hydrological modeling

Water crises is among the top global issues the world faces

The famous Davos Forum - gathers leaders from the global political, business, academic, media and other fields to discuss the most pressing issues facing the world

1. Water crises
2. Spread of infectious diseases
3. Weapons of mass destruction
4. Interstate conflict
5. Failure of climate-change adaptation
6. Energy price shock
7. Critical information infrastructure breakdown
8. Fiscal crises
9. Unemployment or underemployment
10. Biodiversity loss and ecosystem collapse

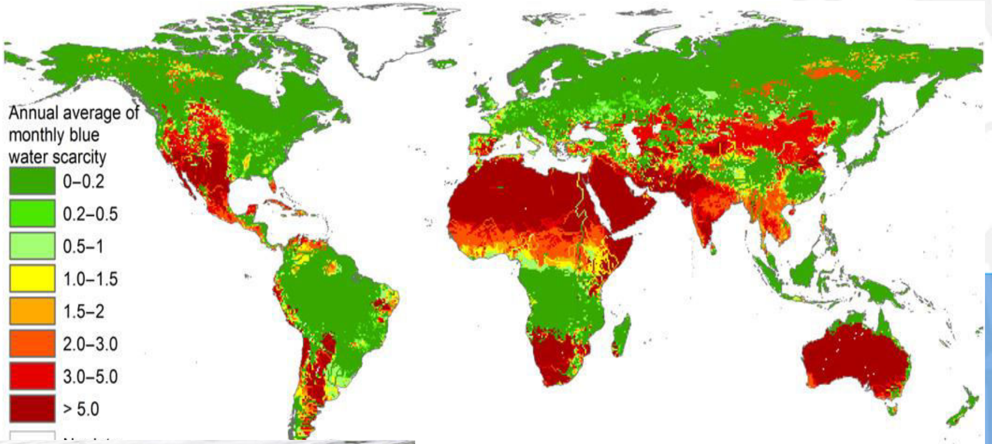
1. 水危机
2. 传染病的传播
3. 大规模杀伤性武器
4. 国家间冲突
5. 气候变化适应政策的失败
6. 能源价格震荡
7. 关键信息基础设施崩溃
8. 财政危机
9. 失业或就业不足
10. 生物多样性丧失和生态系统崩溃

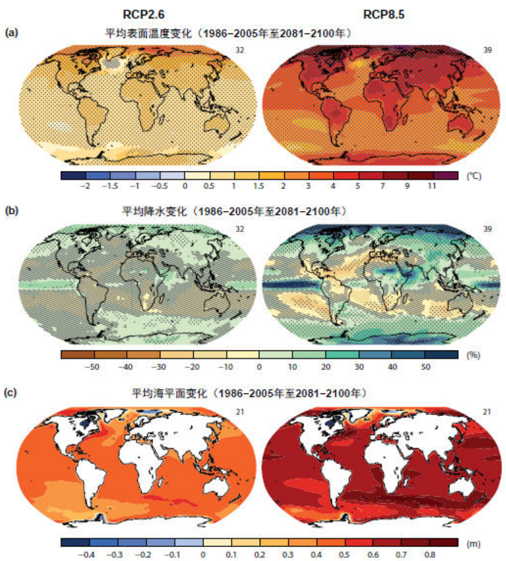
World Economic Forum (2015)

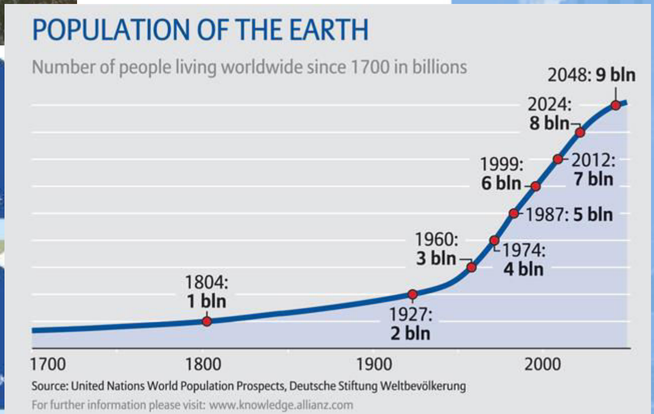
世界经济论坛(2015)

Causes of water crisis/security

- Poor distribution
- Poor management
- Environmental change
- Population increase







Challenges in large river basins

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Secretary-General António Guterres stressed before the Council

- 75% of UN Member States share rivers or lake basins with their neighbours,
- There are more than 270 internationally shared river basins,
- Water disputes and even wars occur between countries, regions and even neighborhoods，

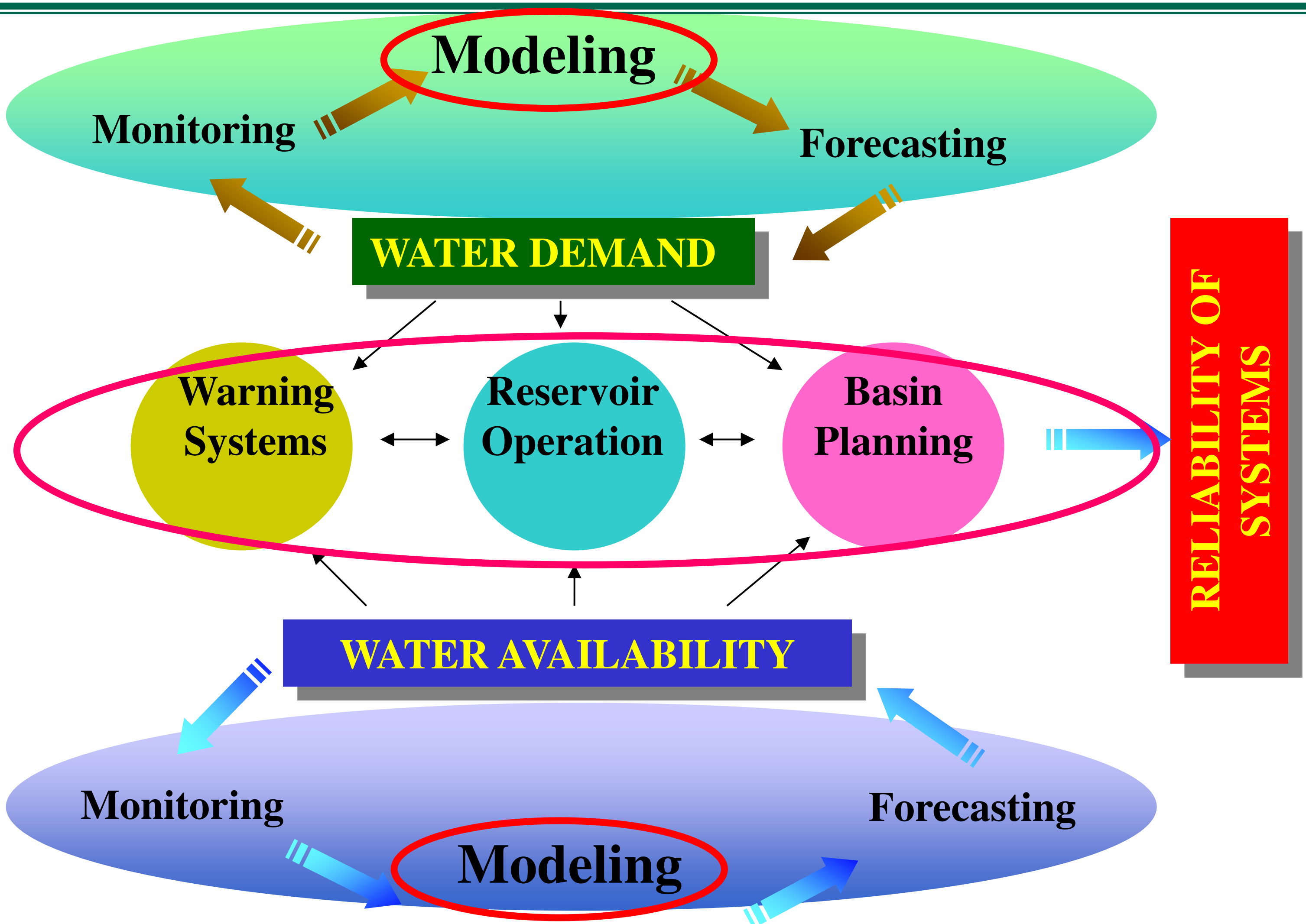
Water security and water resources management of large river basins are global strategic issues

How to Move Forward – Cooperative Basin Management

- **Shared Vision**:
  - Need a common understanding of cooperative management objectives. The importance of trust between parties, willingness to share information and the need for transparency are critical elements in the development of a shared vision.
- **Political Commitment and Public Support**:
  - Sustained political commitment and broad based public support are crucial to achieve success;
- **Broad Based Partnerships**:
  - Partnerships can expedite the move from planning to implementation;
- **Environmental Management**:
  - Should be integrated into cooperative programs;
- **Conflict resolution mechanisms.**

source

Water resources management system



Why water resources management?

We cannot "create" water but we can/need redistribute it in time & space

History of model development

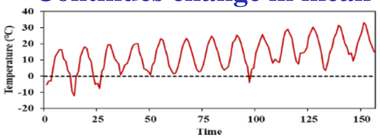
Theory (physics)	Hydrologic Models	Purposes
1800, 1900 Chezy formula, 1749 Dalton equation, 1802 Darcy law, 1856 Saint-Venant, 1871 Manning formula,1891 Green & Ampt,1911 Richards, 1931 Horton, 1933	Rational model, 1850 →	Urban design
	Sherman, 1932 Unit hydrograph →	Hydrological design Flood event forecasting
	Gumbel, 1941 Extreme flow analysis, →	Hydrological design
	…..	
1950, 1960 Philip, 1954	Lumped conceptual Modeling (HBV) →	Design, forecasting
1970, 1980	Physical based Distributed Modeling →	Research+ Management
1990	Macroscale distributed modeling →	Impact+ Management

Traditional and current use of hydrological models

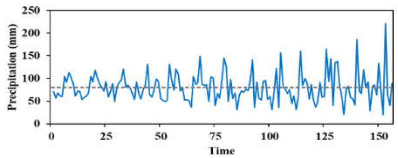
- **Traditional use of hydrological models:**
  - Filling the gaps, extending the discharge times series
  - Flow prediction in ungauged basins
  - Flow (flood) forecasting
- **Use of hydrological model in a changing world:**
  - Assessment of hydrological impact of climate change
  - Assessment of hydrological impact of human activities
- **Challenges of modeling techniques:**
  - Transferability of hydrological models in the nonstationary conditions
  - Limitations/Bottlenecks in process-based hydrological modeling
  - Limitations/Bottlenecks in data-driven models
  - … …

Non-stationary processes and relationship

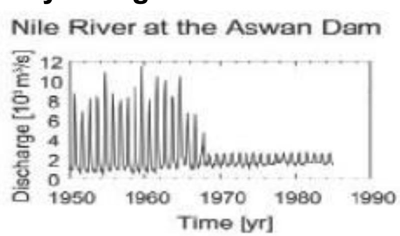
- Continues change in mean



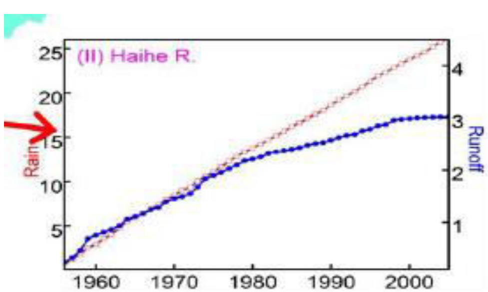
- Continues change in variability



- **Sudden change of hydrological** condition



- Change in P-Q relationship



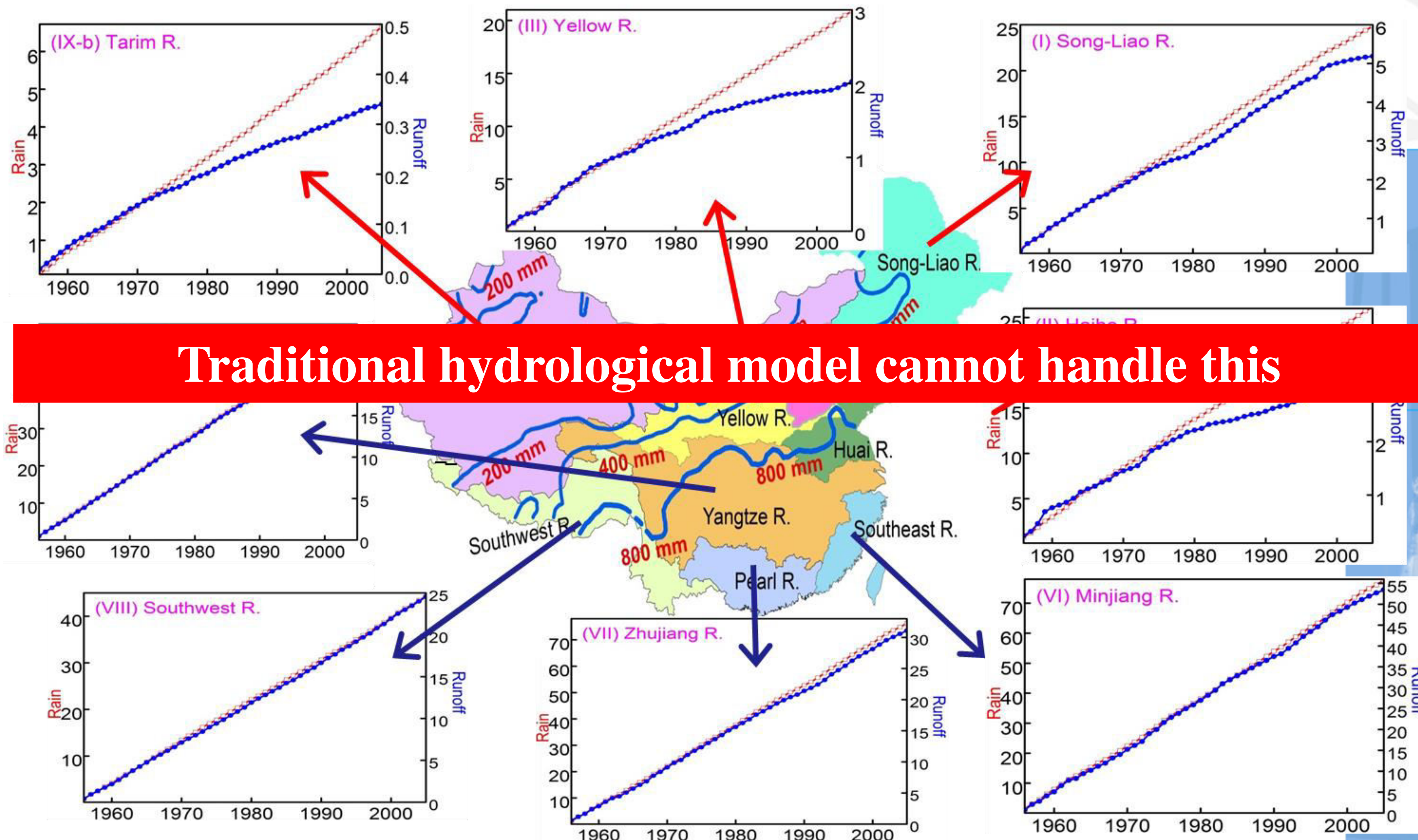
- **First moment nonstationarity**
- **High moment (also distribution) nonstationarity**
- **Relationship nonstationarity**

Water resources Assessment, forecast

Frequency analysis, Hydrological design

Impact study management

Non-stationary processes and relationship



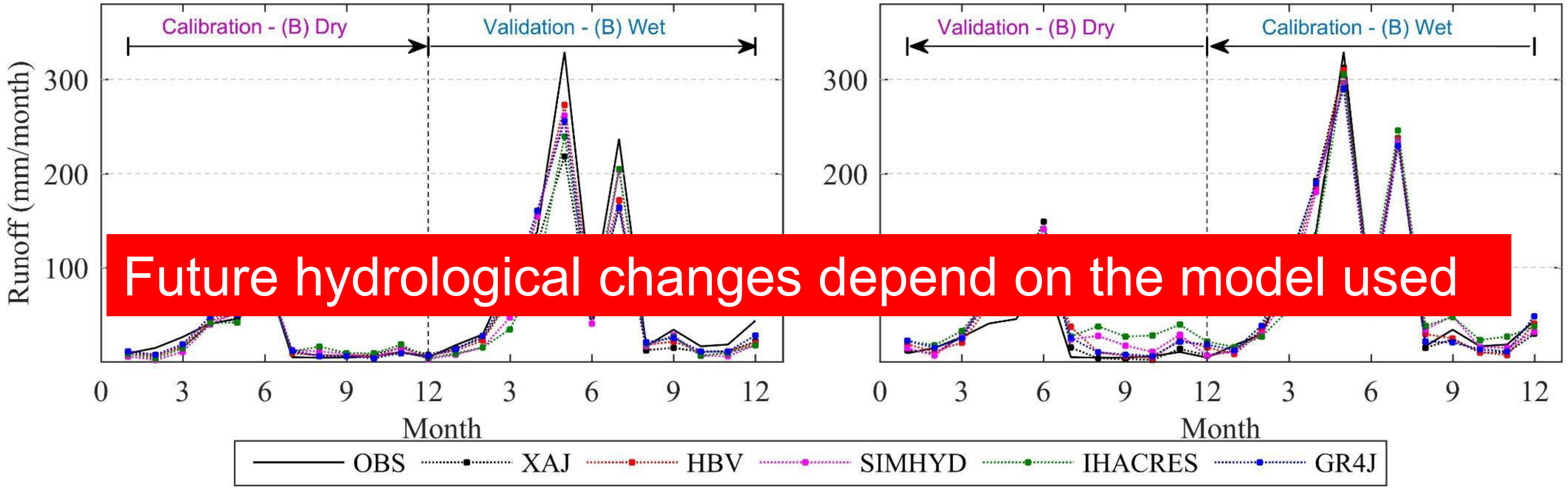
Traditional hydrological model cannot handle this

Modeling of non-stationary conditions

➢ How have we been doing?

➢ Standard procedure

- Select and calibrate a hydrological model using historical hydrological data
- Using different methods to build future climate change scenarios
- Run the calibrated model with climate scenarios as input to simulate future hydrological scenarios
- Compare the model simulations with that of reference period

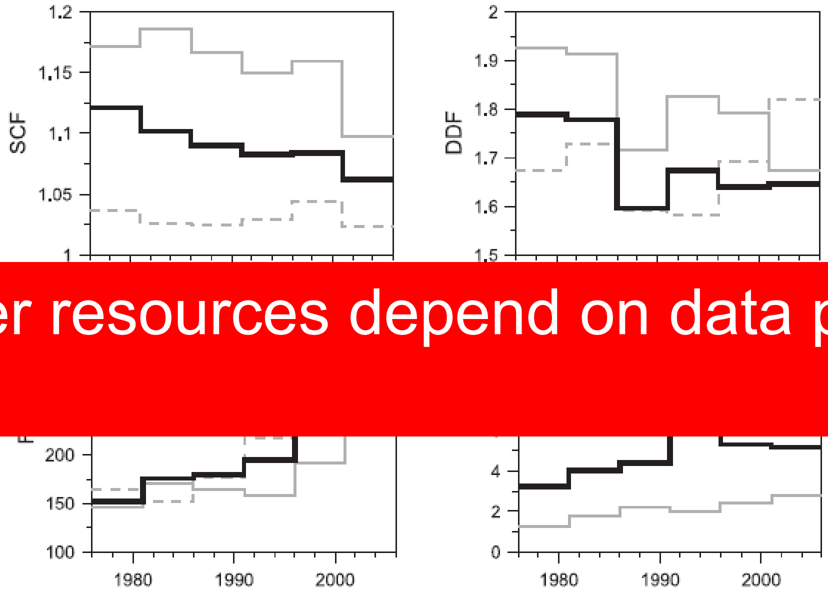


Future hydrological changes depend on the model used

Modeling of non-stationary conditions

- **Up to 10 years ago:**

- Same hydrological model when calibrated using different periods of historical data produced very different results for the same climate scenario



Future water resources depend on data period used for model calibration

Figure 4. Model parameters (snow correction factor SCF, degree-day factor DDF, maximum soil moisture storage FC, and nonlinearity parameter of runoff generation *B*) of the 5 year calibration periods averaged over the 273 Austrian catchments (black lines), averaged over the wetter catchments (solid grey lines), and averaged over the drier catchments (dashed grey lines).

Transferability of models to non-stationary conditions

Reasons？

Lack of transferability !

In other words, all published hydrological response results under future climate change scenarios are problematic (including the relevant content of the IPCC report)

Strength & limitations of process-based models

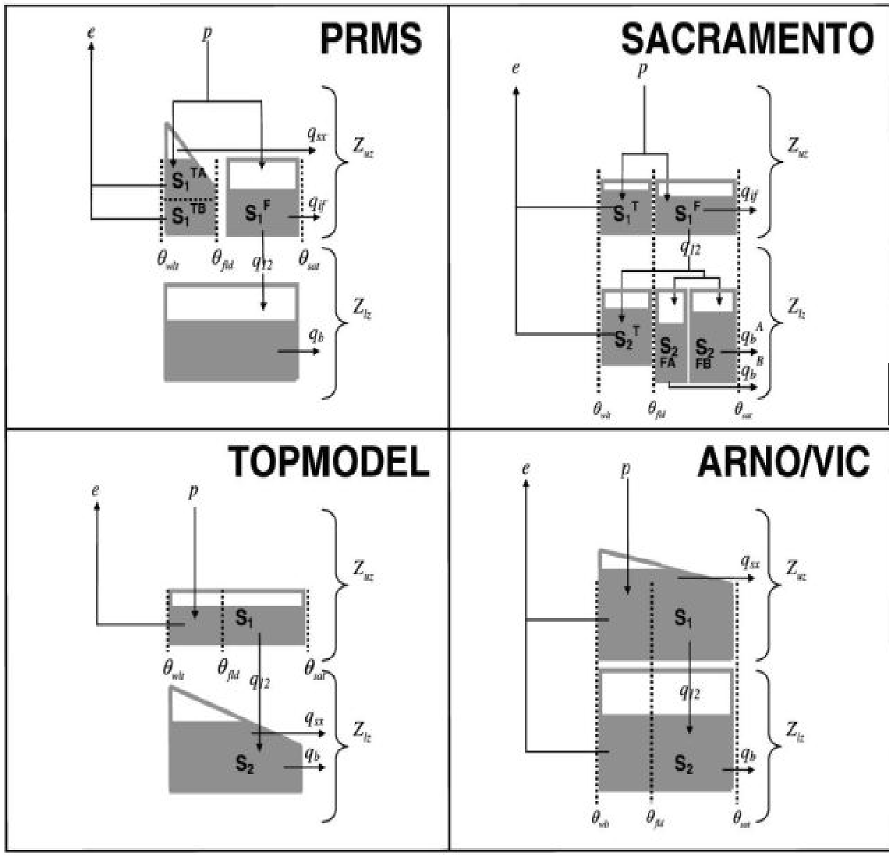
- **Strength of Process-based models:**
  - **Technical perspective**
    - Predicts even with limited data availability,
  - **Scientific perspective**
    - Respects physical laws
    - Provides interpretable intermediate variables
    - Allows declaration and testing of hypotheses
  - **Outcome perspective**
    - Permits interpretation and narration of model logic

- **Limitations of Process-based models:**
  - Complexity,
  - Number of (often poorly known) parameters,
  - Different embedded hypotheses—not always clearly stated—that lead to differing outcomes
  - Application conditions

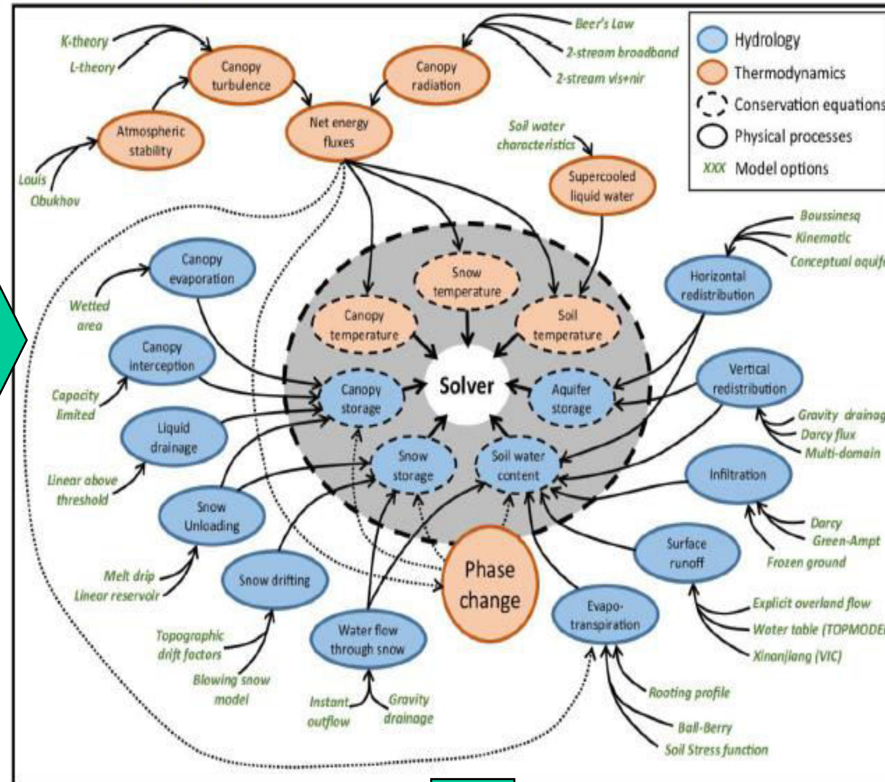
https://doi.org/10.1038/s43017-023-00450-9

Necessity for flexible model structures

Fixed model structure



SUMMA (Clark et al., 2016)



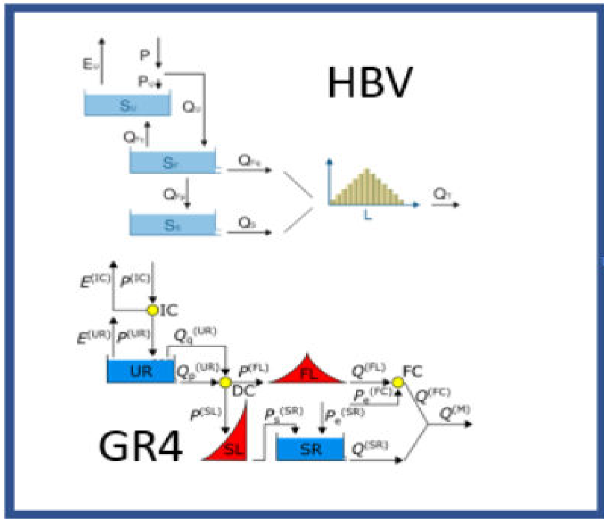
Flexible custom model structures

In order to improve modeling accuracy under diverse and heterogeneous situation

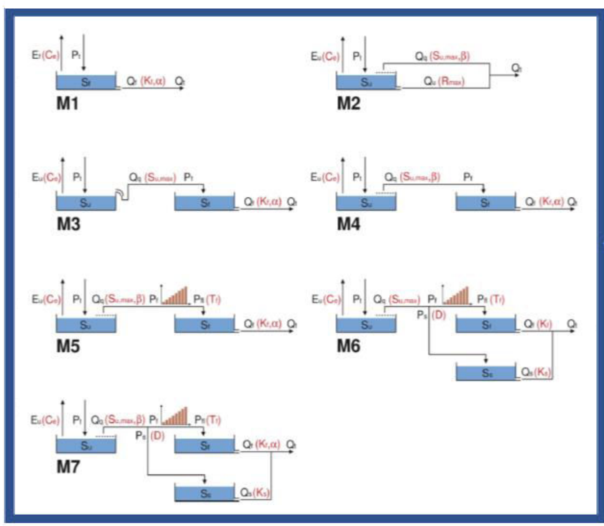
John Burkhart, 2018

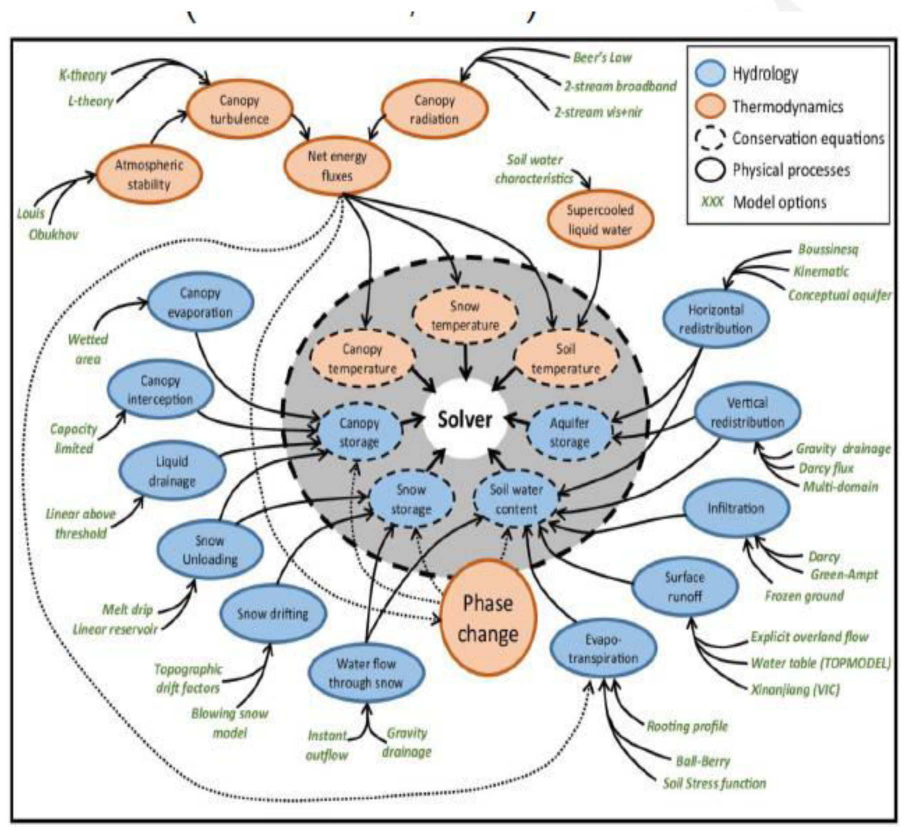
Development of flexible model types

a) Fixed model structures



b) Flexible model structures





WRR, VOL. 47, W11511, doi:10.1029/2011WR010748

Strength and limitations of data-driven models

- **Strength of Data-driven models:**
  - **Technical perspective**
    - Flexible learns a wide range of functions
    - Gains efficiency, generalizability. And accuracy with big data,
  - **Scientific perspective**
    - Discovers new functions from data
    - Accommodates large knowledge gaps
  - **Outcome perspective**
    - Generates highly accurate predictions

- **Limitations of data-driven models:**
  - Intrinsic black-box nature,
  - Large data requirements,
  - Inability to produce physically consistent results,
  - Lack of generalizability to out-of-sample scenarios

https://doi.org/10.1038/s43017-023-00450-9

Necessity of Hybrid model types

- Hybrid models that
  - combine different types of models and modelling philosophies and are intended to take the best of each approach, thereby reducing their tradeoff of advantages and limitations, and benefiting the community from:
  - <u>Technical perspective:</u>
    - using mid-size search space find true function fast,
  - Scientific perspective:
    - support quick tests of competing formulations
    - Isolate specific processes to investigate
  - Outcome perspective:
    - Improve prediction accuracy
    - Aid rapid reduction of knowledge gaps

https://doi.org/10.1038/s43017-023-00450-9

Hybrid

- New methods/models

Types of Hybrid models

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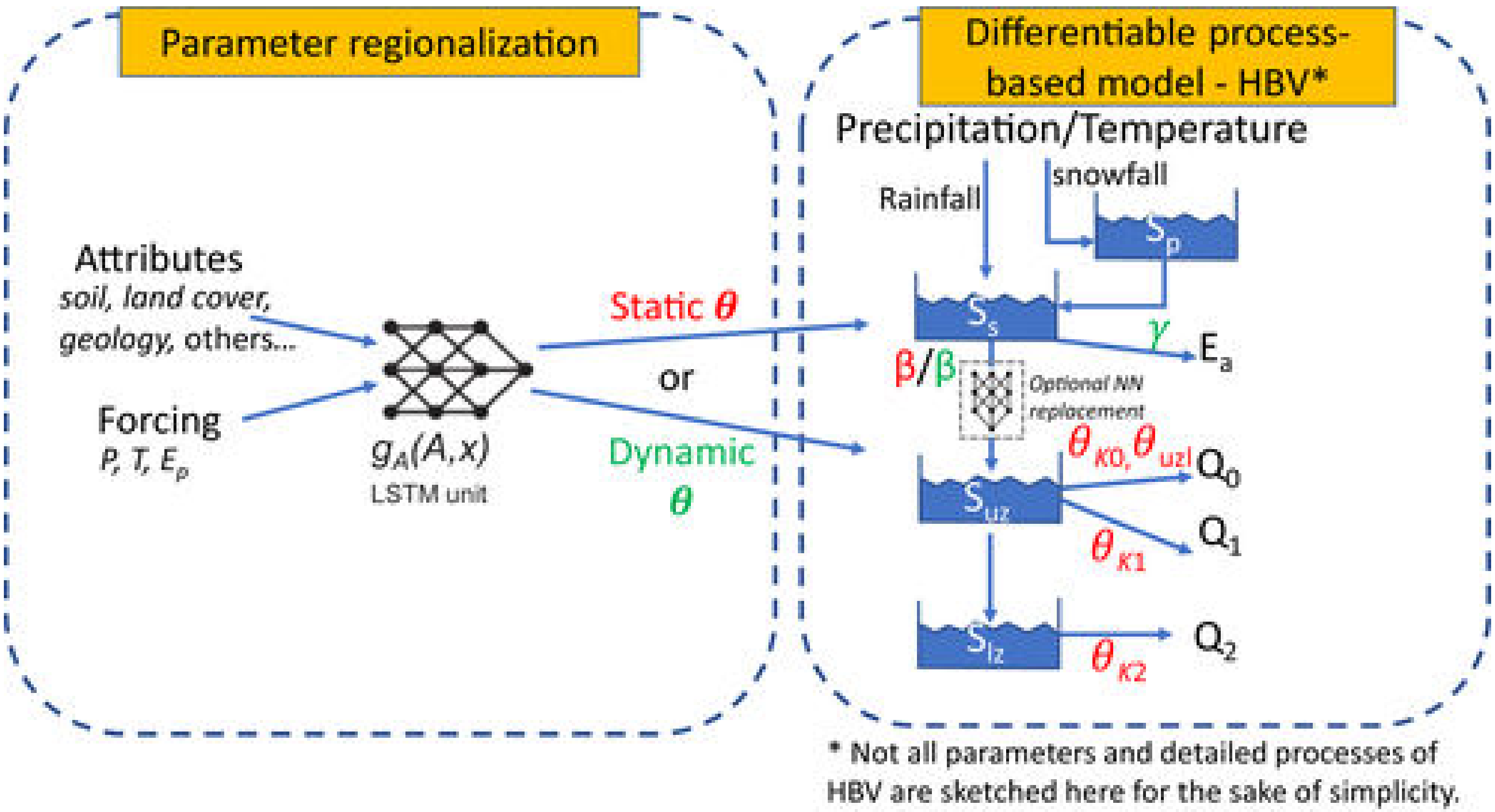
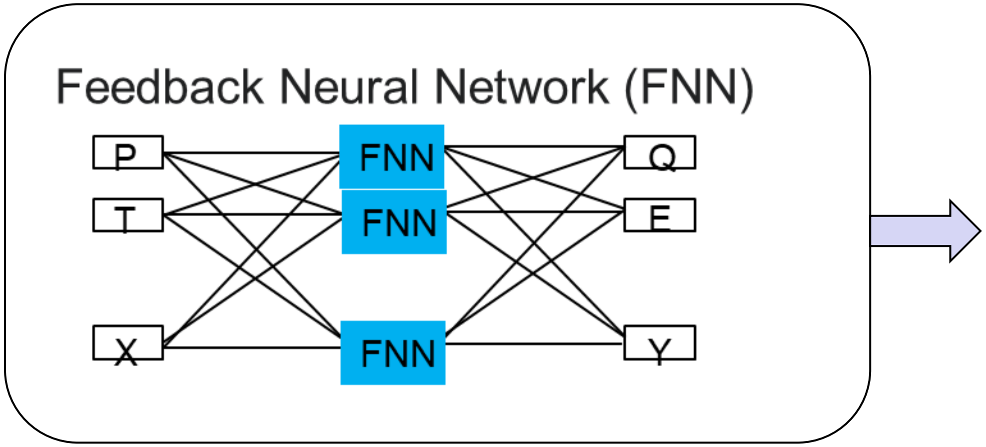
1) ML models are used as post-processors for process-based hydrological models to improve their performance by learning simulation errors
2) Utilize physical laws to generate synthetic data for training ML models
3) ML models are employed to calibrate the parameters of PHMs, particularly enhancing their performance in ungauged basins
4) PHMs are enhanced by embedding ML neural networks to replace internal modules.
5) Nodes of a deep learning architecture are substituted by the generic elements of a flexible conceptual model

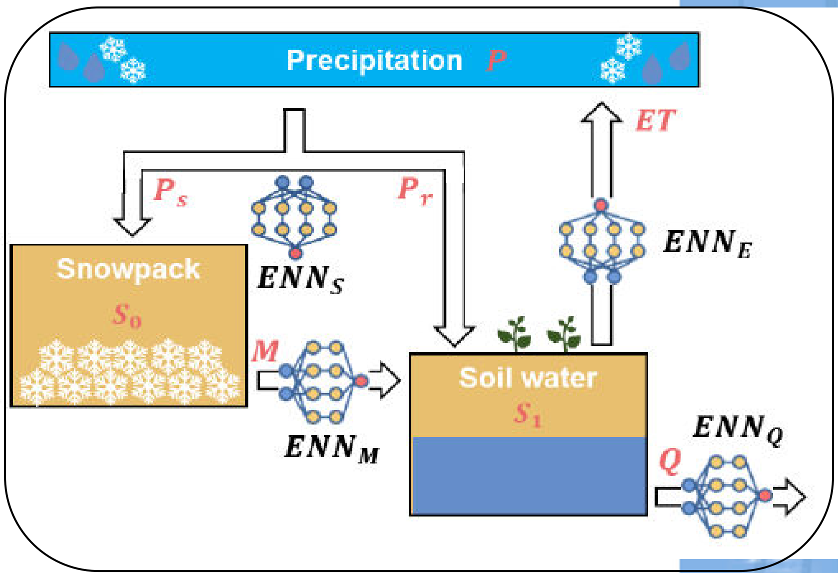
Hybrid Models – ML to calibrate the parameters of PHMs



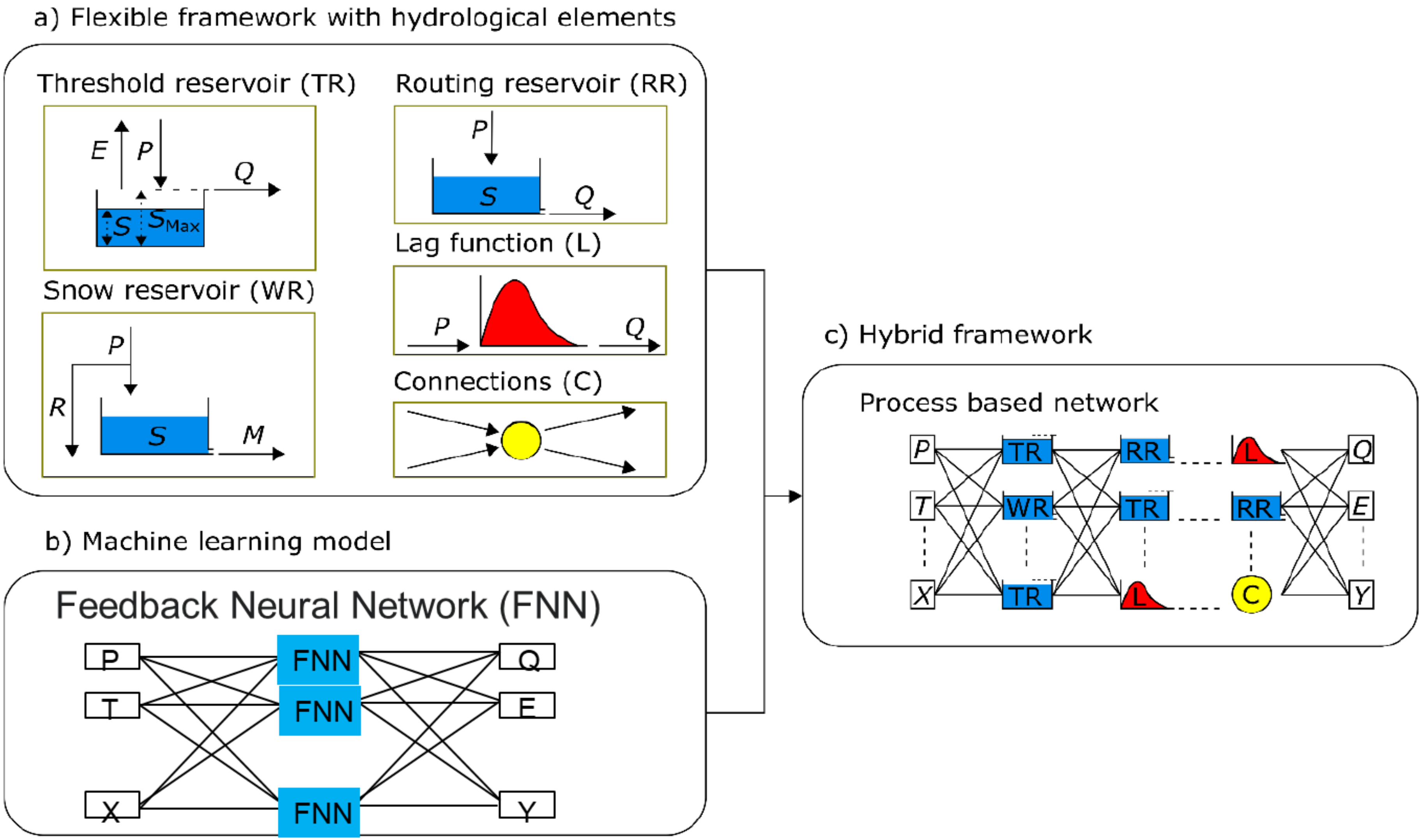
https://doi.org/10.1029/2022WR032404

Hybrid Models – ML Embedded in process-based Frameworks





Hybrid Models - Flexible PHMs Embedded in ML Frameworks



Fabrizio Fenicia, 2022


Thank you

Example of flexible models

Flexible configuration:

True flexibility is gained in evaluation of multiple configurations.

Uncertainty stems from:

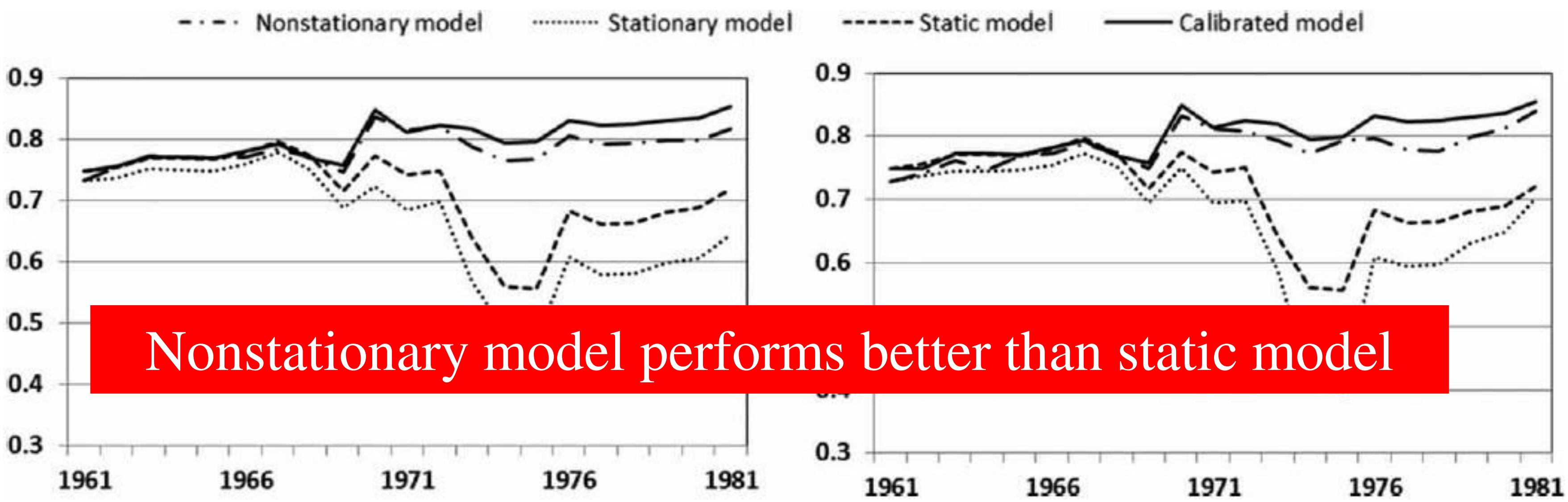
- choice of model
- forcing input
- objective function (and obs. uncertainty)

Historical Input	Forecast Input	Input Processing	Model Stack	Simulation Unit	Routing	Calibration	Updating	Forecast System
Station	AROME	IDW Interp.	PTGSK	Cell	Unit Hyd.	Min Bobyqua	None	1
AROME	EC	Kriging Interp.	PTSSK	Subcat.	Isochrone	Shuffled Complex	Substitute	2
EC Grid	GFS	Bayes TKrig	PTHSK	ElevZone	Hydraulic	DREAM	Weighting	3
ERA-Interim		GridPP	HBVSTack				Kalman Filter	4
SE-Norge		Weighting						5
		QM						6
								7
								8

- Flexible models allow for multiple working hypothesis
- Flexible models allow for testing of large number of model configurations
- Flexible models allow for fast analysis of different data sources
- Flexible models allow for analysis of uncertainty from various sources

Identifying the right model structure for a given system remains a challenging problem

Static or dynamic modeling



Nonstationary model performs better than static model

Figure 8 | Model performances (NSE) for every 10-year period from 1961–1970 to 1981–1990. Left: forward stepwise method. Right: backward stepwise method.

Kim et al. 2016