ML APPROACH FOR INFLOW PREDICTION AND RESILIENCE ASSESSMENT IN MULTIPURPOSE WATER MANAGEMENT SYSTEMS: LIM HYDROPOWER PLANTS AND PIROT HYDROPOWER PLANT

24.09.2024

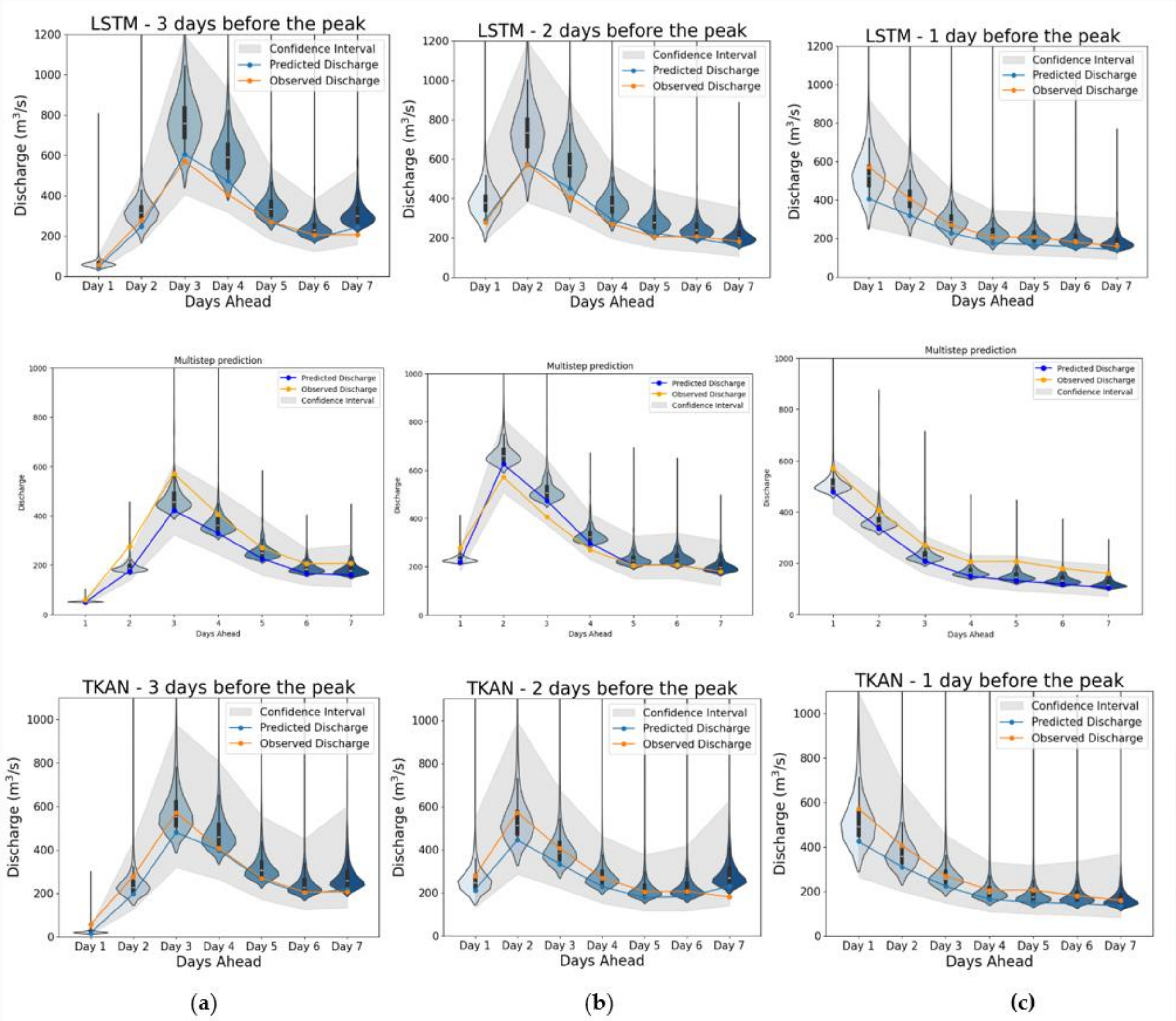
17th International Forum on Clean Energy Technologies:
STRATEGIC CHANGES IN NATIONAL ENERGY POLICY
Novi Sad

MOTIVATION

Flow prediction is crucial for hydroelectric energy production.

It enables **reservoir operation rules** to respond to demand.

It decreases the **negative effects of flood events** on hydroelectric production and the environment.



Multi-step forecast at three different time-steps for LSTM, TCN and TKAN with error probability plots.

Luka Vinokić, Milan Dotlić, Slobodan Kolaković, Veljko Prodanović, Milan Stojković. 2024. Water Research X (in preparation).

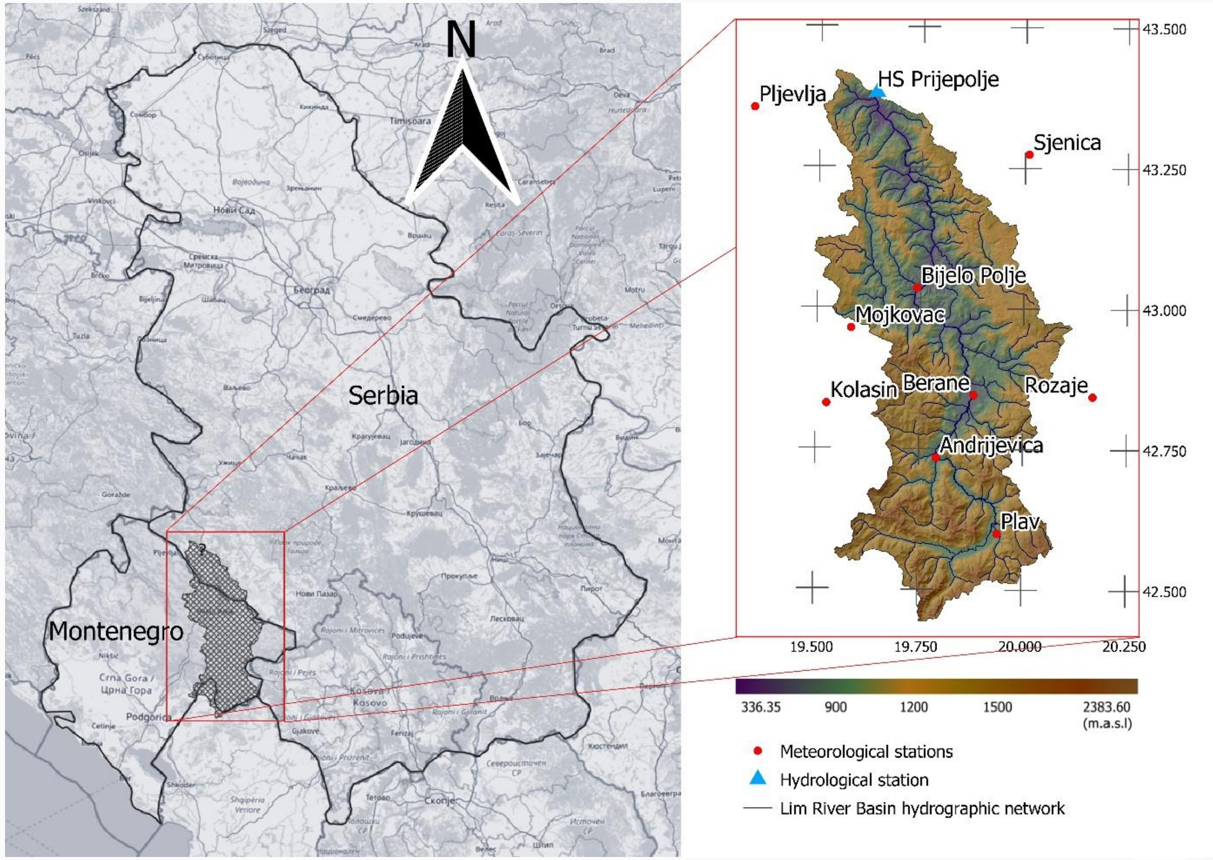
CASE STUDY

The case study was conducted on the part of the Lim River basin, positioned upstream of the Prijepolje hydrological station.

The Lim River is the largest tributary of the Drina River, stretching over 201.6 kilometers.

The Lim River basin involves the Lim water system, a multipurpose system, primarily used for hydropower generation, making the tributary significant.

The catchment area of the Lim River basin is approximately 3160 square kilometers and is mostly mountainous.



A map of the (a) regional and (b) local scale of the Lim River basin.

GENERAL METHODOLOGY

The general methodology is structured around three primary phases:

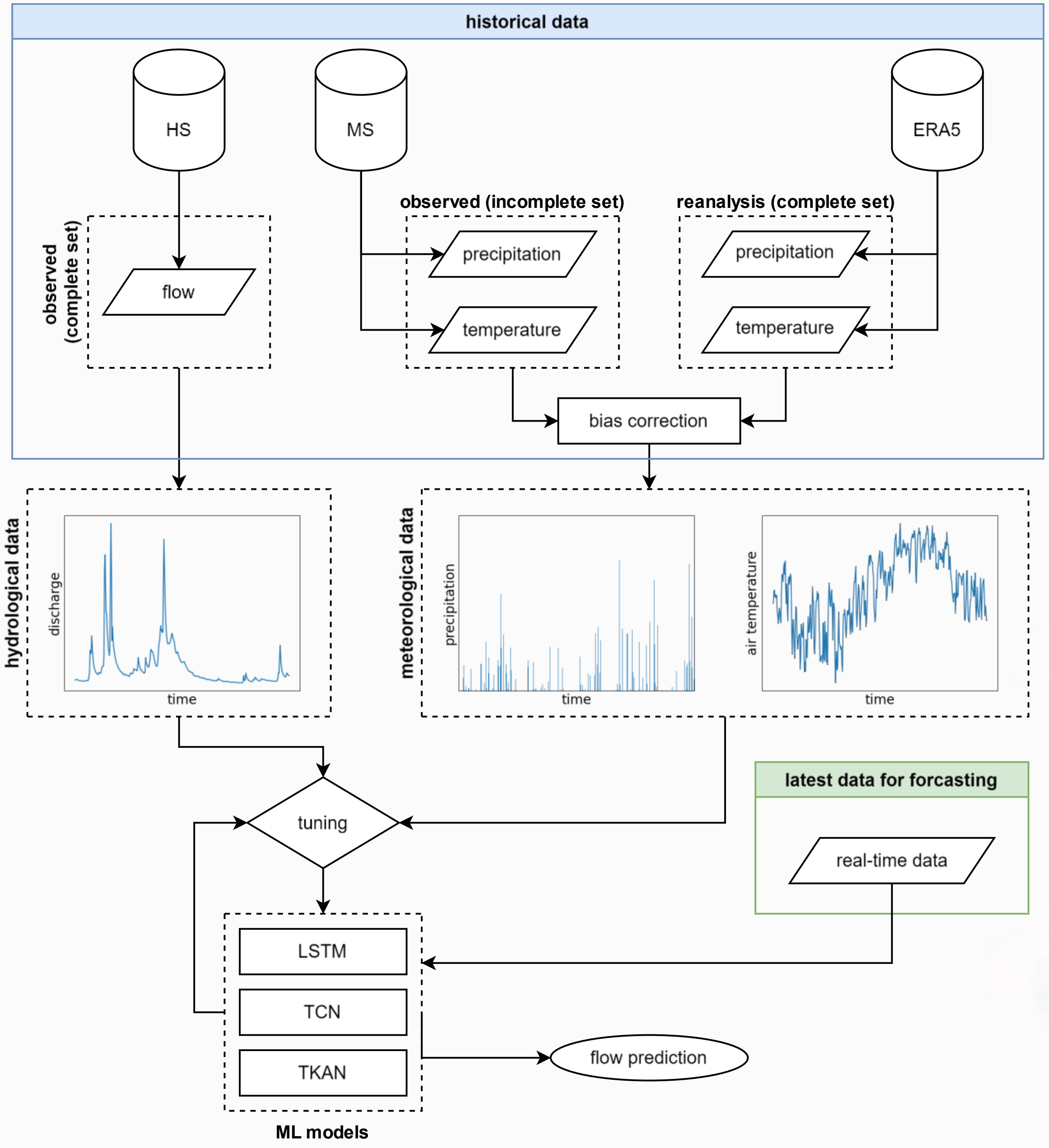
(1) dataset preparation;

(2) developing and applying machine learning (ML) models and

(3) prediction uncertainty estimation.

In the first phase, ECMWF ReAnalysis v5 (ERA 5) dataset from European Centre for Medium-range Weather Forecast (ECMWF) is debiased to align with historical data.

This complete dataset is then divided into subsets for training, validation, and testing the ML models for streamflow prediction.



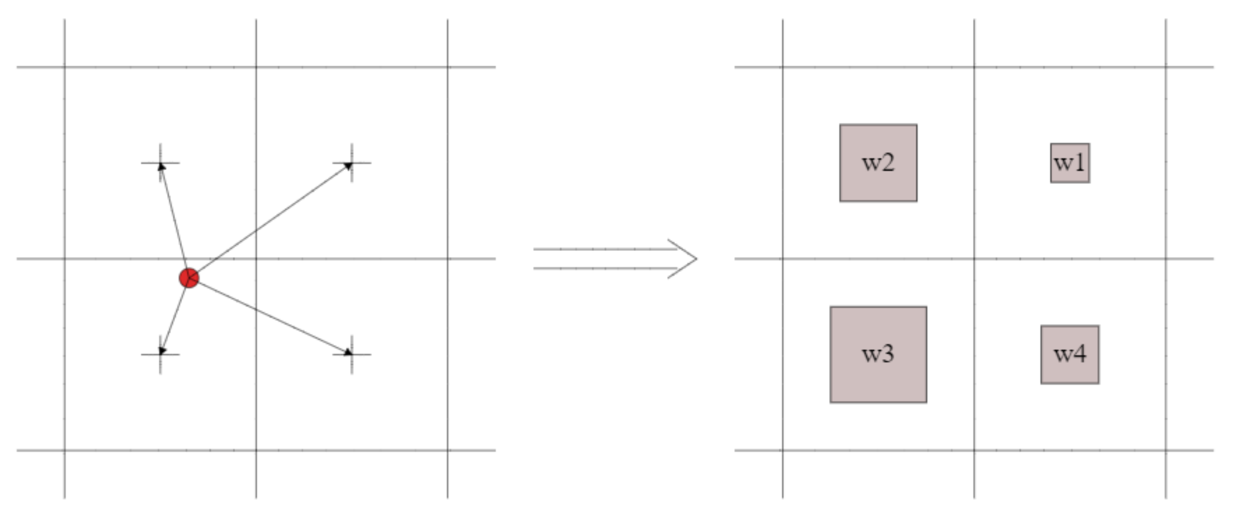
General methodology: Streamflow forecasting.

DATA PREPARATION

Reanalysis systems operate by merging the irregular observations and models that involve physical processes in order to create an integrated estimate of climate variable data.

ERA5 reanalysis is the fifth generation ECMWF reanalysis with available hourly data from 1940, and spatial resolution 0.25° x 0.25°, which is approximately 28km x 28km.

From this reanalysis, total precipitation and 2-meter dewpoint temperature are re-gridded onto the coordinates of the aforementioned meteorological stations.



Inverse distance weighting scheme.

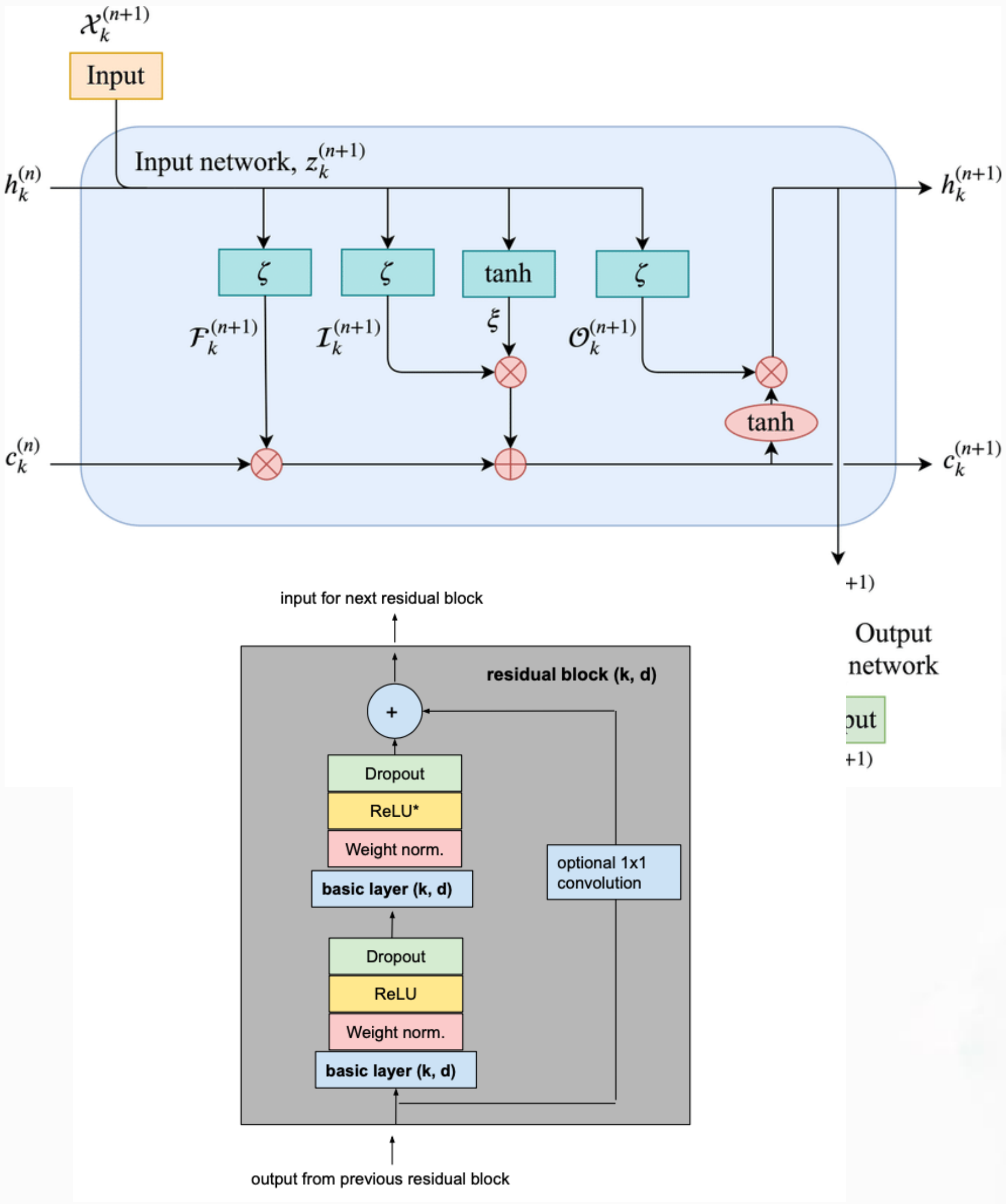
ML MODELS

LSTM (Long Short-Term Memory) Gating mechanism system

TCN (Temporal Convolutional Networks) Feature extraction through convolutional layers

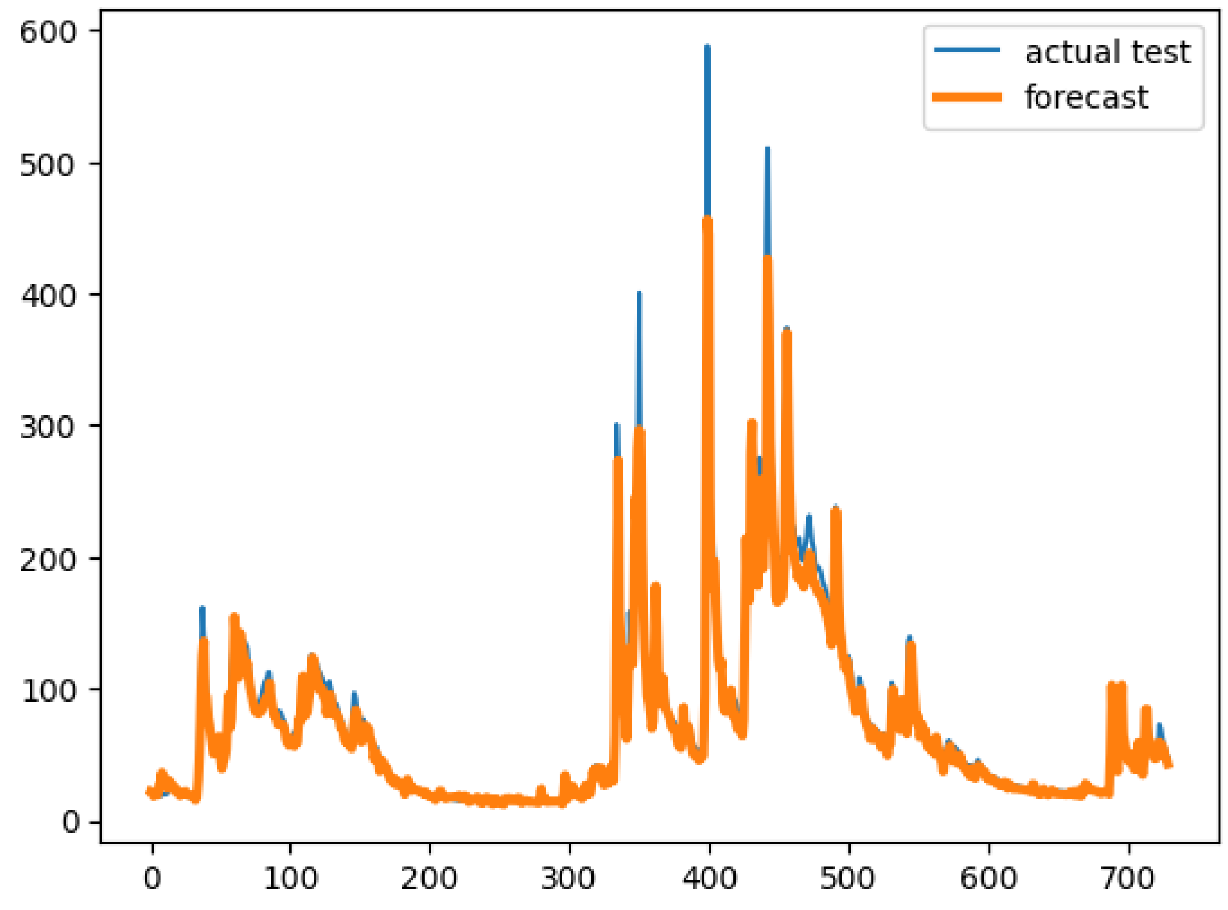
TKAN (Temporal Kolmogorov-Arnold Network) Learning activation function (spline)

GNN (Graph-oriented neural networks) using information from neighboring nodes observation of both spatial and temporal domains

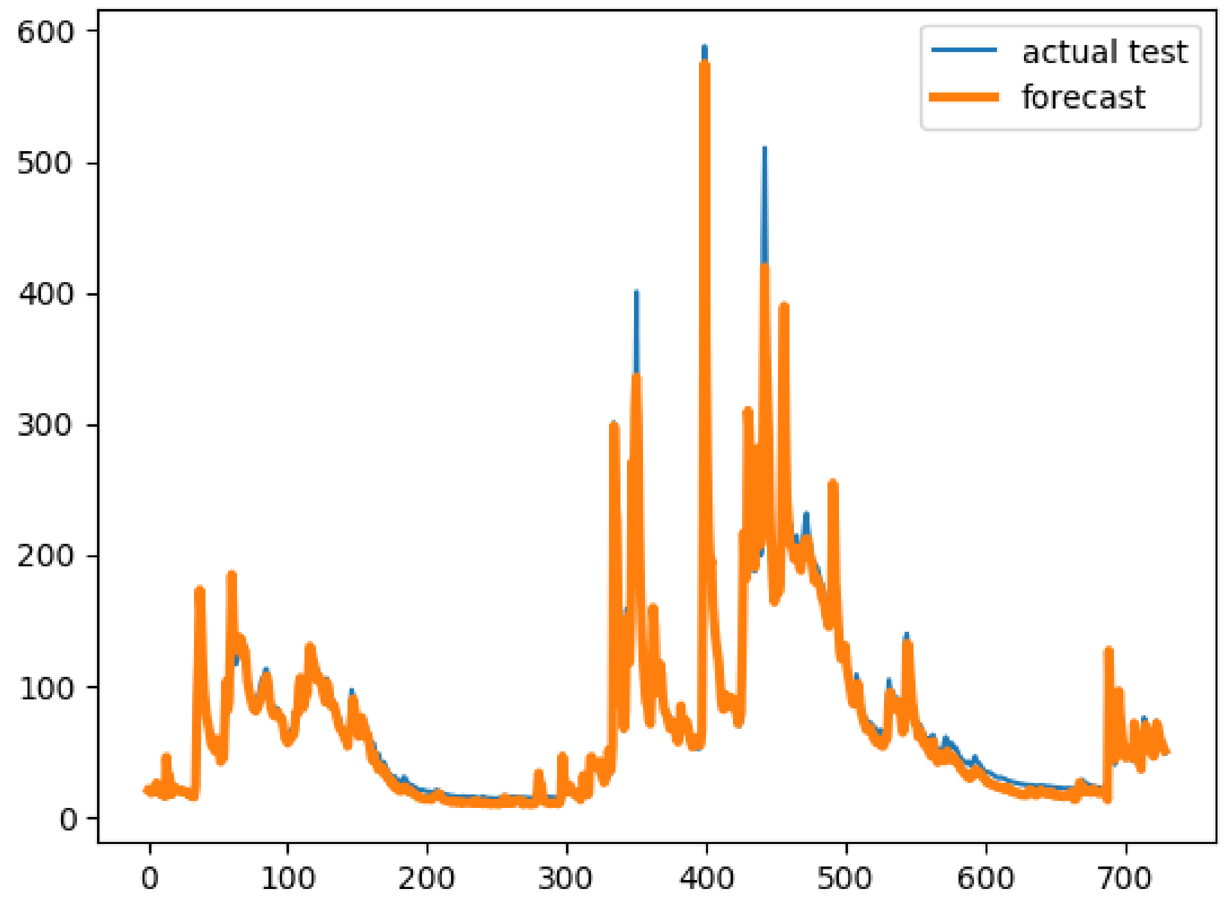


ML models used in the study.

RESULTS

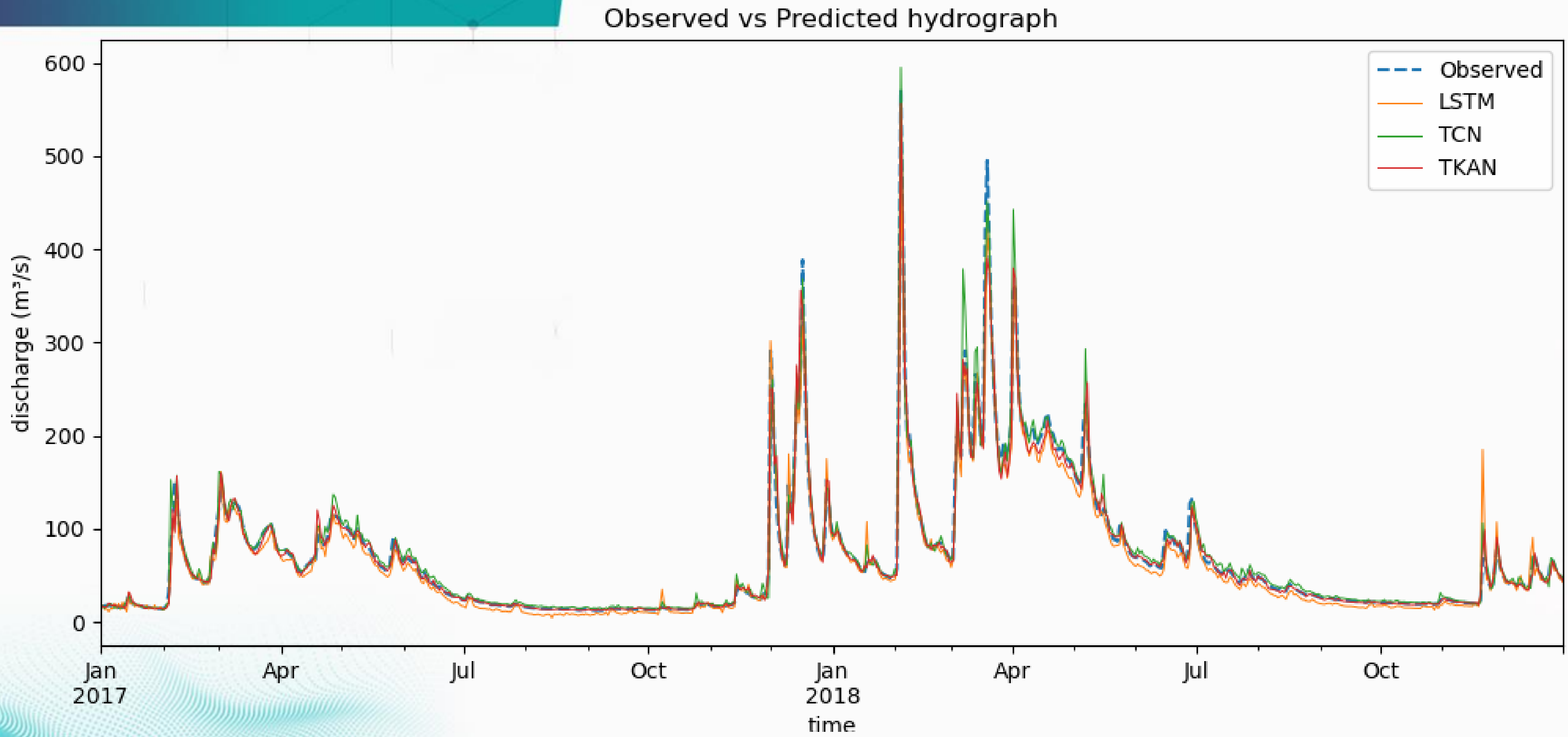


HPP Potpeć: LSTM



HPP Potpeć: TCN

RESULTS



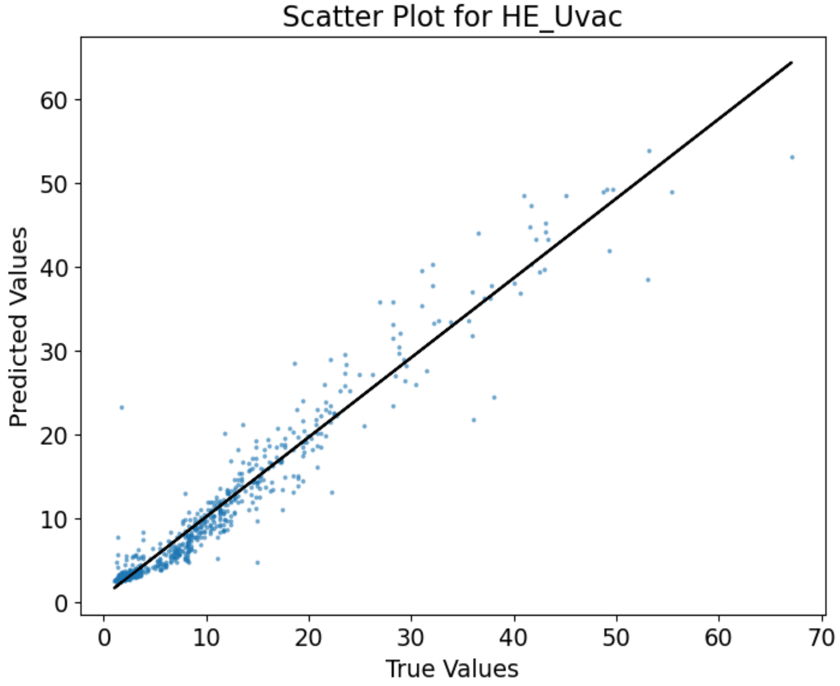
HPP Potpeć: LSTM, TKAN, TCN.

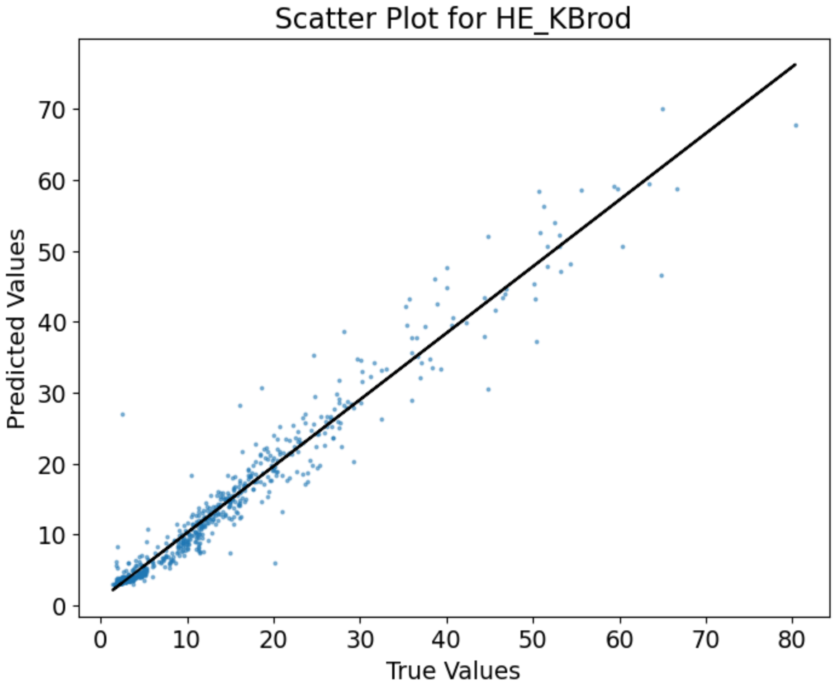
RESULTS

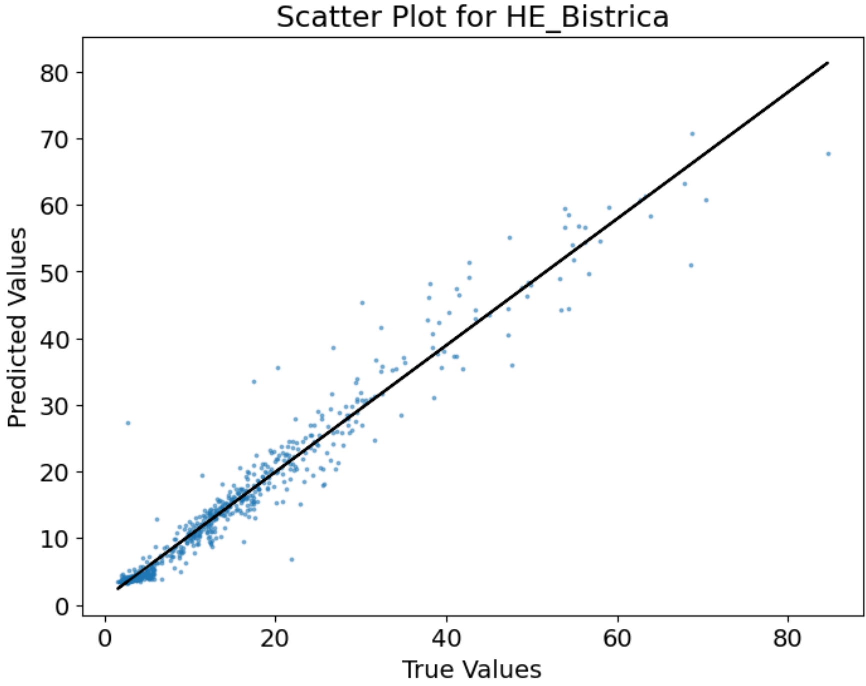
MAE	1.529 m^3/s
MAPE	0.326
RMSE	2.4103 m^3/s
NSE	0.942

MAE	1.568 m^3/s
MAPE	0.21
RMSE	2.678 m^3/s
NSE	0.953

MAE	1.605 m^3/s
MAPE	0.189
RMSE	2.8 m^3/s
NSE	0.955







Lim HPP : GNN.

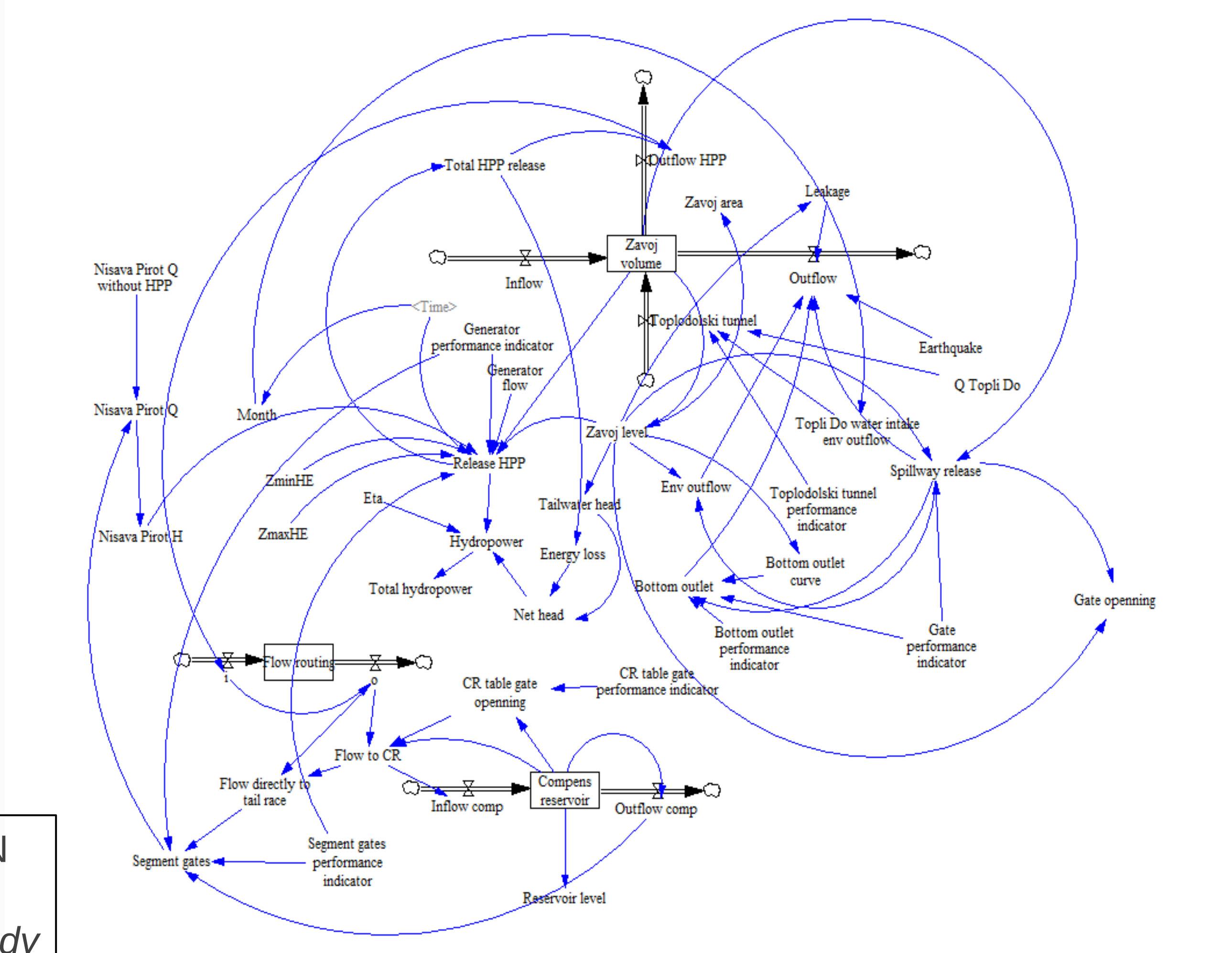
MOTIVATION

Water resources systems are designed to withstand demands imposed by their service requirements.

Their **flood-protection facilities** are designed by **existing standards and present climate**.

Considering the aging process and rapid changes in the environment (e.g., climate variability, climate change, natural hazards), **they do not necessarily guarantee an adequate level of service and safety.**

Ignjatović, L., Stojkovic, M., Ivetic D., Milašinovic, M., Milivojevic N (2021) *Quantifying Multi-Parameter Dynamic Resilience for Complex Reservoir Systems Using Failure Simulations: Case Study of the Pirot Reservoir System*. Water 13(22)



An example: System dynamics model of the Pirot water resources system

PROBLEM STATEMENT

Challenges for the complex water resouces systems:

- Catastrophic disasters:
  - *Floods* (2011, 2014)
  - *Droughts* (2017, 2018)
  - Earthquakes

~~Use of Standards~~

~~Risk-based approach~~

Proposed:

Dynamic resilience assessment

System modelling approach

Assessing risks beyond largest recorded events

Adaptation schemes under the variable climate conditions

Disturbance modelling

DYNAMIC RESILIENCE

RESILIENCE

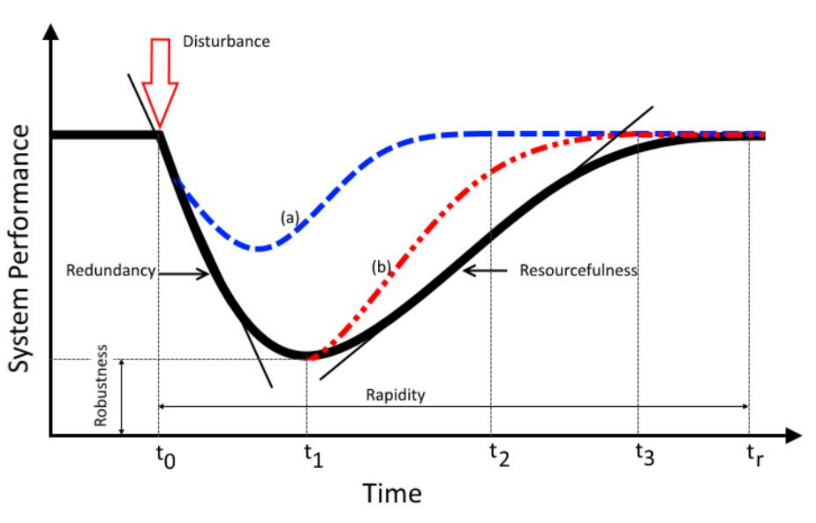
Definition of resilience:

System capacity to respond, withstand, and recover from failure

Generic representation of system performance:

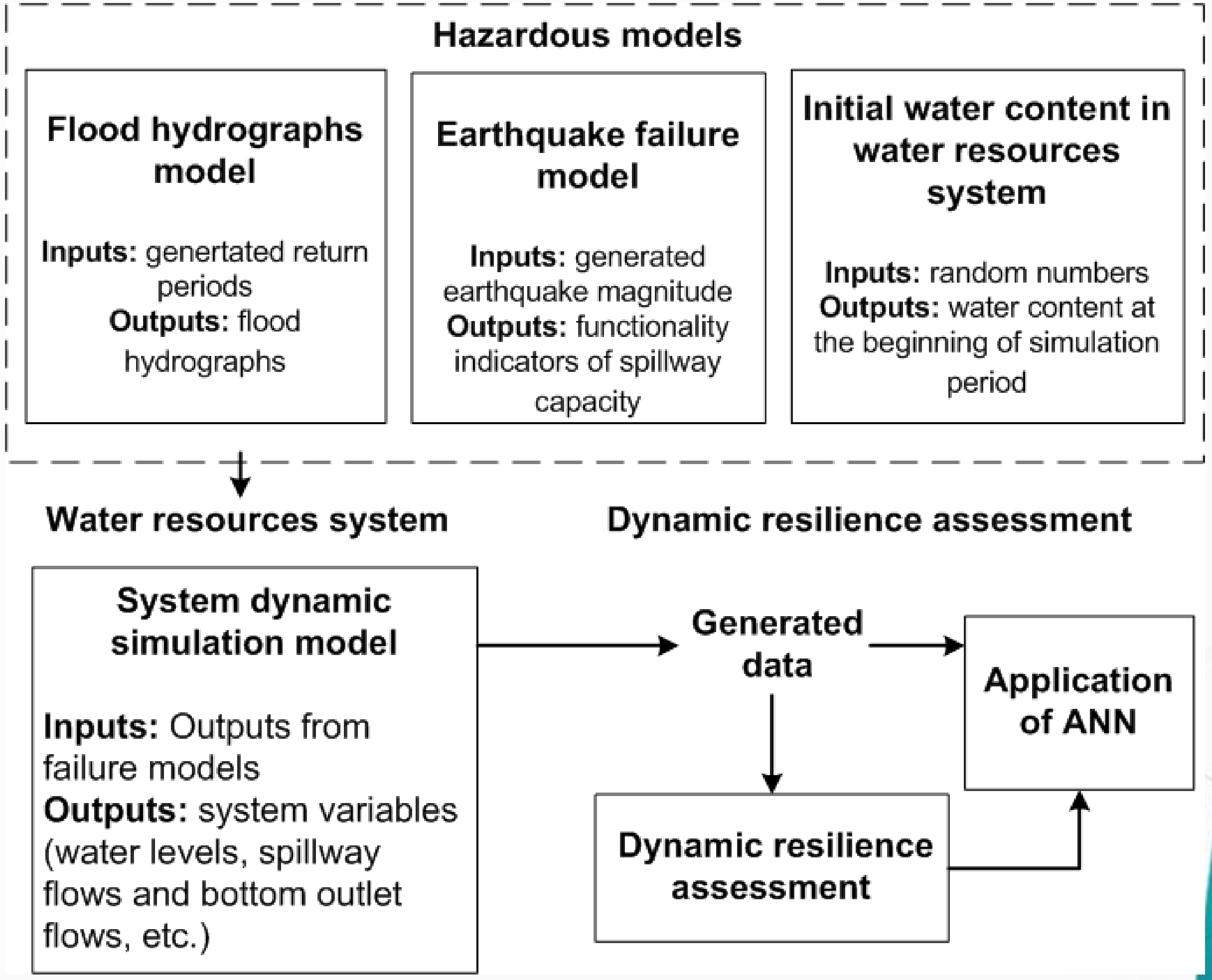
- Redundancy, Resourcefulness, Robustness, Rapidity

- Implementation of various adaptation measures
- Proactive measure – curve (a)
- Reactive measure – curve (b)



METHODOLOGY

- System dynamic (SD) model is developed **to mimic non-linear behavior of the water resources system.**
- The SD model is supported **by hazardous models which introduce the time coincidence of several unexpected hazardous events** (earthquakes, floods, and changeable water content in reservoir).
- A number of the generated hazardous events and estimated dynamic resilience is used **for extraction of the knowledge from the generated data via application of ANNs**.
- **The ANNs capture the important characteristics of dynamic resilience and enables its application for real-time decision making in a water resources system.**

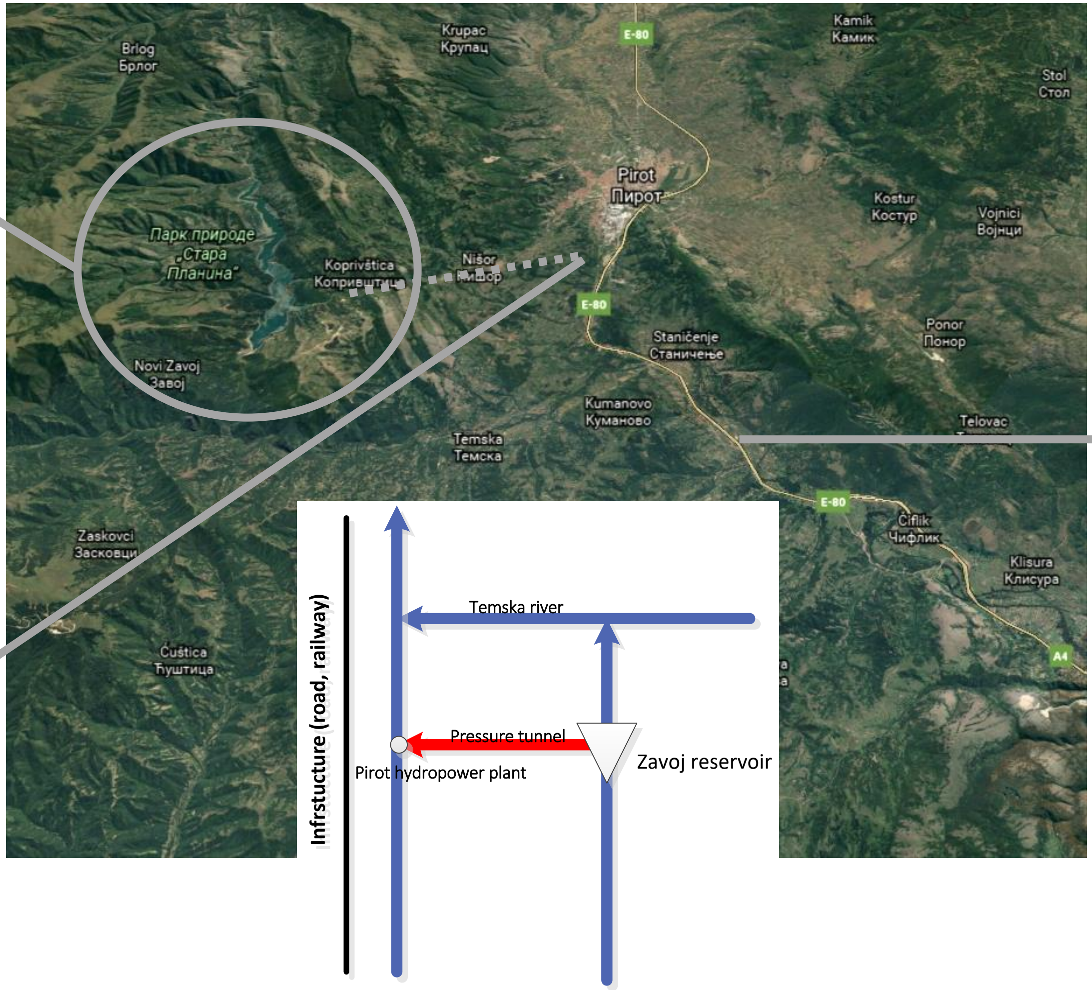


A general approach for evaluation of flood dynamic resilience for the water resources system under hazardous events.

THE PIROT WATER SYSTEM

Zavoj dam and reservoir

Hydropower plant (HE Pirot)



Crucial transportation infrastructure (Corridor 10)

A multipurpose complex system including the Zavoj reservoir at the Visočica river which is hydraulically connected by a pressure tunnel equipped with hydropower.

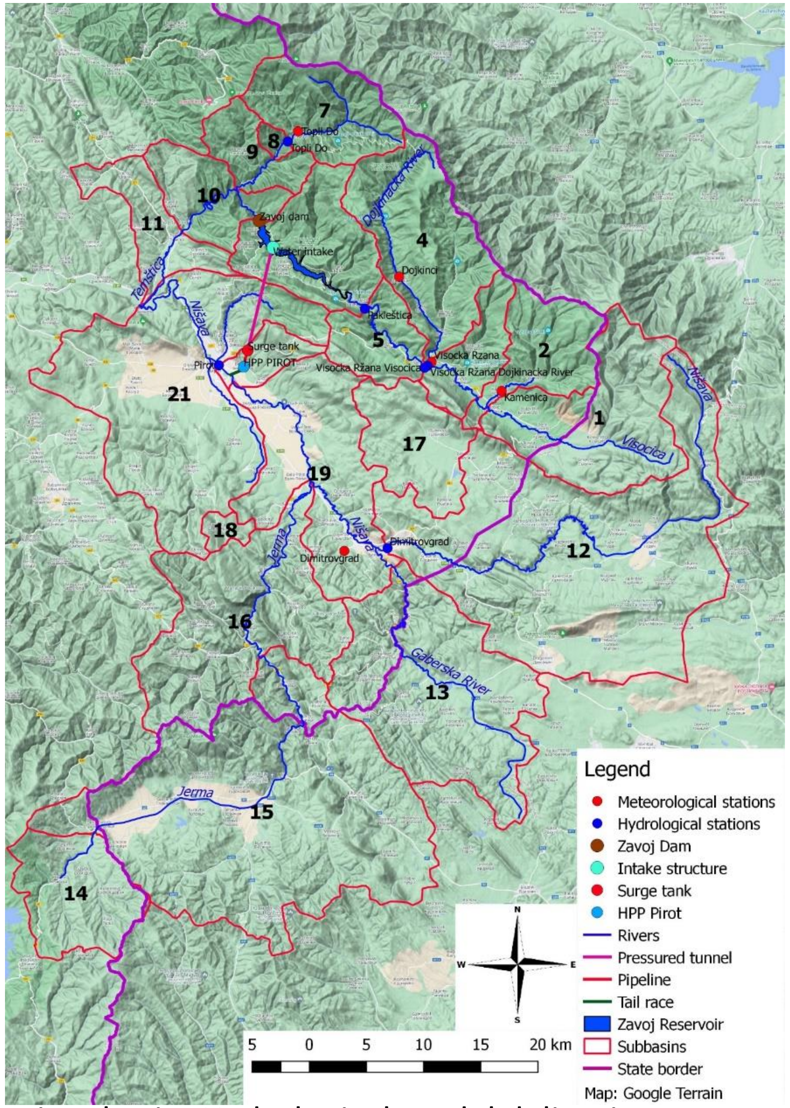
Flood hydrograph model

A deterministic, distributed-parameter, physically based hydrologic model (Precipitation-Runoff Modeling System) is used to generate the long-term flow sequences (Ignjatović et al. 2021).

It enables the evaluation of the hydrological response based on various climate combinations.

As the inputs for the hydrological model, the stochastically generated climate data by weather generator is utilized.

The non-parametric K-nearest neighbor (K-NN) weather generator is employed by reshuffling the recorded value of precipitation as well as minimal and maximal air temperature as a basis for daily streamflow assessment (King et al. 2015).



Nišava river basin: Hydrological model delination

Ignjatović, L., Stojković, M., Ivetić, D., Milašinović, M., & Milivojević, N. (2021). Quantifying Multi-Parameter Dynamic Resilience for Complex Reservoir Systems Using Failure Simulations: Case Study of the Pirot Reservoir System. Water, 13(22), 3157.

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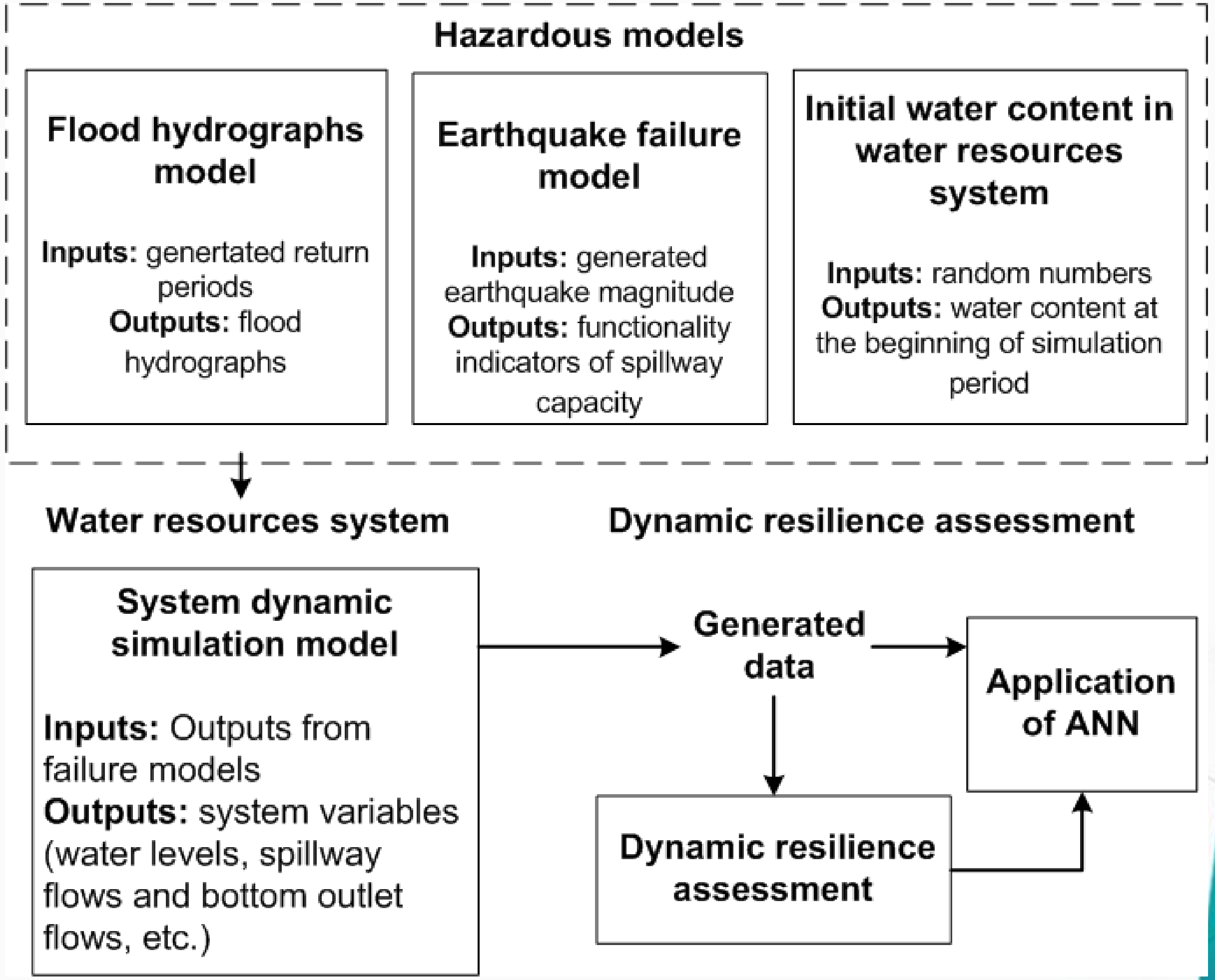


A general approach for evaluation of flood dynamic resilience for the water resources system under hazardous events.

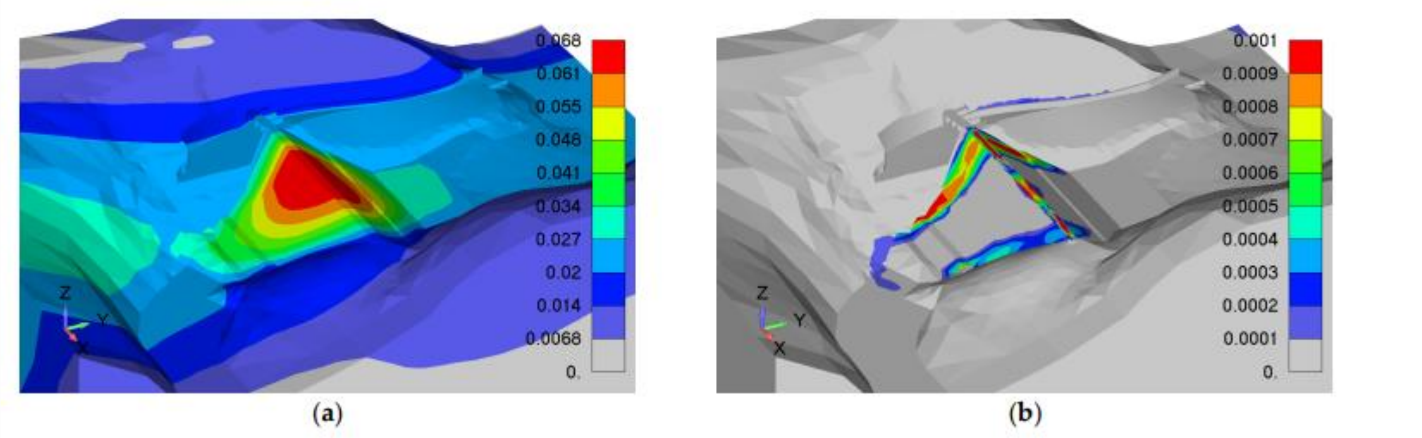
Earthquake model

The varying earthquake events are generated as a stress test of the water resources system addressing the adverse impacts on the system elements.

A numerical analysis of the system elements is performed using the finite element method (Rakić et al. 2022).

The result of the numerical analysis identifies **key structural elements with potential influence on water system performance**.

A simplified analytical form of the earthqake impact model is used witin the implemented flood-risk methodology.



Seismic celeration of the Pirto water system: (a) total translation and (b) eqvivalent plastic deformation

Rakić, D., Stojković, M., Ivetić, D., Živković, M., & Milivojević, N. (2022). Failure Assessment of Embankment Dam Elements: Case Study of the Pirot Reservoir System. Applied Sciences, 12(2), 558.

Initial water state model

Fluctuations of the water state in the system range from **the states at minimal operation level to the corresponding state at maximal operation level**.

It is more likely that operators keep the water level in the reservoir around **the normal water level** which enables the water resource system **to mitigate and attenuate flood hydrograph**.

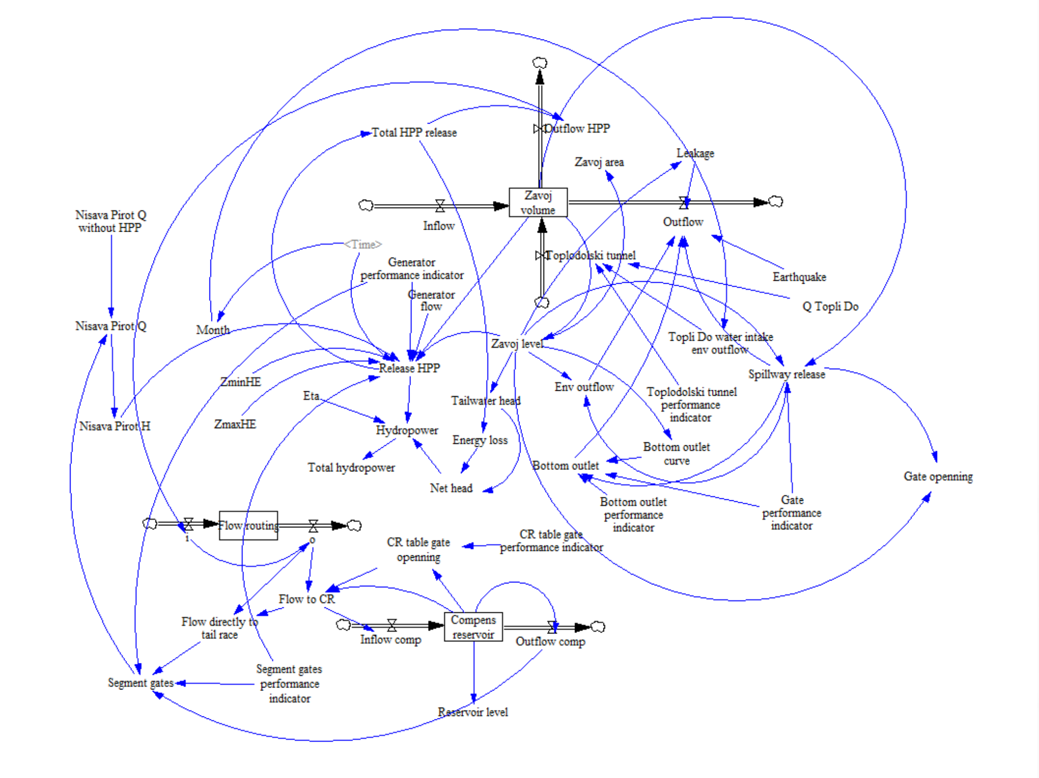
The triangular distribution is used to simulate the initial water states in the system (Stojković et al. 2022):

$$V_{start} = MCS\left\{\begin{matrix} Lower\ bound = water\ state\ at\ minimal\ operational\ level \\ Most\ likely\ value\ = water\ state\ at\ normal\ operational\ level \\ Upper\ bound = water\ state\ at\ maximal\ operational\ level \end{matrix}\right\}$$

Stojković, M., Marjanović, D., Rakić, D., Ivetić, D., Simić, V., Milivojević, N., & Trajković, S. (2023). Assessment of water resources system resilience under hazardous events using system dynamic approach and artificial neural networks. Journal of Hydroinformatics.

System dynamic (SD) model of the Pirot water system

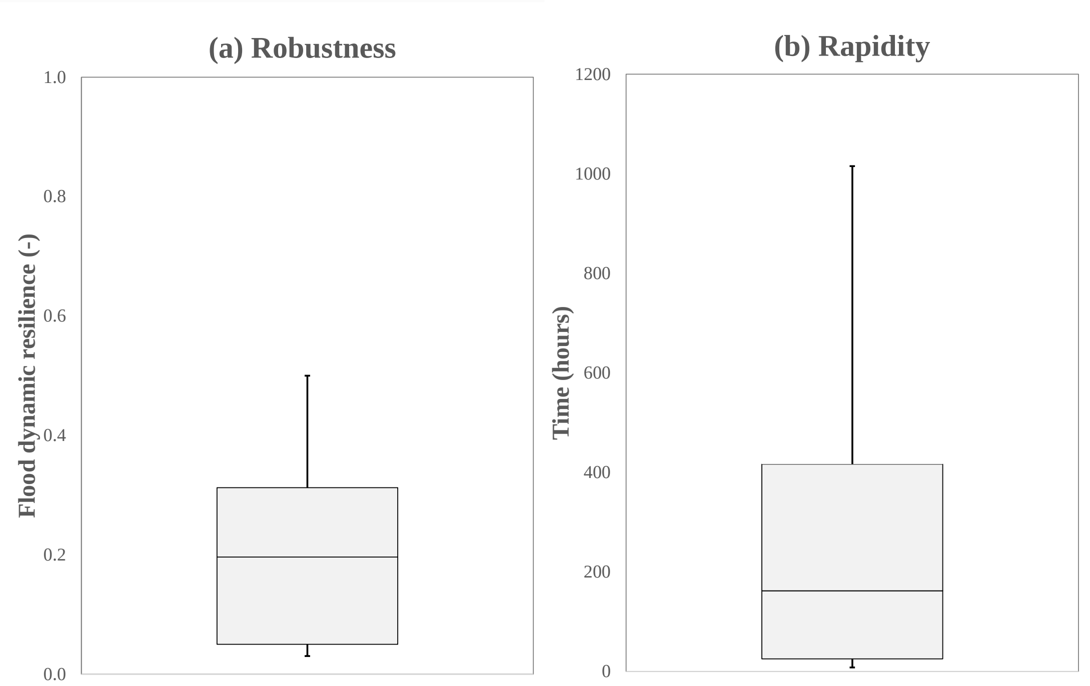
- System dynamic (SD) model of the multi-purpose Pirot water resources system includes: **spillway and bottom outflow facilities, hydropower plant, and leakage from the dam**.
- **Spillway and bottom outflow** serve to control and reduce a devastating impact of the flood events at the downstream river sections.
- **Operators of the Pirot water system control the hydropower generation releases** considering the **physical and environmental limitations** to supply the energy market over peak demand hours.



System dynamic model of the Pirot water resources system (a) alongside hazardous models (b).

RESULTS

- **The total set of the generated data (1000 simulations) is used to envelop hazardous events with low joint probability distributions.**
- For each simulation, the SD model generates random hazardous model outputs and, a functional dependence in the ANN model can be written as:
- Relative error is used as a metric to quantify the efficacy of the ANN approximation.
- The **average relative error** equals to 2.1% and to 1.8% for robustness and rapidity, respectively.



Flood dynamic resilience of the Pirot water resources system using the generated dataset of 1000 simulations: robustness (a) and rapidity (b).

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