Dynamics resilience as a measure for risk assessment of the complex water systems: Project overview

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ABSTRACT: To manage impacts of natural disasters we propose the use of system approach to enhance the predictive power in resilience assessment of water system beyond the largest recorded events. The main objective of the proposed research is the development of a modelling framework for dynamic resilience assessment. The traditional risk-based approach and use of standards is replaced with a quantitative assessment of the dynamic resilience. By developing a novel framework, the research therefore makes a context introducing a dynamic resilience as a measure for risk assessment. In this context, the research will provide the generic methodology and tools for dynamic resilience assessment. This framework offers an opportunity for highlighting the role of using multi-model simulations which supports the estimation of dynamic resilience. It underpins investment decisions within the different sectors (e.g. water, hydroenergy, environmental sectors) for adaptation schemes under the uncertain changes in our environment (e.g. variable climate, natural disasters).

Key words: Dynamic resilience, System dynamics, Hydrological modelling, System element failures

ABSTRAKT: U ovom radu daje se prikaz projekta u vezi upotrebe sistemskog pristupa za unapređenje prediktivne sposobnosti pri proceni dinamičke rezilijentnosti kompleksnih vodoprivrednih sistema van dosada zabeleženih događaja. Cilj predloženog istraživanja je razvoj pristupa za procenu dinamičke rezilijentnosti vodoprivrednih sistema kao nove mere za procenu rizika. Korišćenjem predloženog pristupa, tradicionalni pristup u proceni rizika i upotreba standarda biće zamenjeni kvantitativnom procenom dinamične rezilijentnosti. Istraživanjem se predlaže generička metodologija i alati za kvantitativnu ocenu dinamičke hidroenergetske i infrastrukturne rezilijentnosti. Ovaj predlog naglašava mogućnost korišćenja lanca simulacionih modela koje će pomoći u proceni kvantitativne dinamičke rezilijentnosti. Predloženo istraživanje podržaće investicione odluke u različitim sektorima (sektor voda, hidroenergetski sektor, sektor zaštite životne sredine) kako bi se vodoprivredni sistemi adaptirali na promena u njihovoj okolini (npr. variabilna klima, prirodne katastrofe).

Ključne reči: Dinamička rezilijentnosti, sistemska dinamika, hidrološko modeliranje, otkazi elemenata sistema

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1 Introduction

The world today faces enormous challenges in redesigning and rebuilding water systems, wastewater plants and infrastructure in general. Major investment is required to renew and upgrade these aging systems to adopt for rapidly growing population, whose future is affected by uncertain changing climate and natural disasters (e.g. earthquakes). Over the last few decades we have been witnessing many catastrophic hazardous events (e.g. floods, droughts) that have considerably exceeded the largest foreseen events and caused billions in damage. For example, floods in Europe have affected more than 1,100 fatalities and 3 million people in the period 1998-2009, with direct lost estimated as EUR 60 billion (EEA a, 2019). The European Commission has estimated that, at least 17 % of its territory have been affected by water scarcity to date and put the cost of droughts in Europe over the past thirty years at EUR 100 billion (EEA b, 2019). In addition, it has been estimated that earthquakes are responsible for about 35% of the economic losses generated by natural disasters (ECSKS, 2019).

To manage impacts of natural disasters we propose the use of system approach to enhance the predictive power in resilience assessment of water system beyond the largest recorded events. We provide an overview of the project "Dynamics resilience as a measure for risk assessment of the complex water, infrastructure and ecological systems: Making a context" (2020-2022). The proposed project is a part of the program for excellent projects of young researchers (PROMIS) launched by the Science Fund of the Republic of Serbia.

The main objective of the proposed research is the development of a modelling framework for dynamic resilience assessment. The traditional risk-based approach and use of standards is replaced with a quantitative assessment of the dynamic resilience. This framework offers an opportunity for highlighting the role of using multi-model simulations which supports the estimation of dynamic resilience as well as processing of big data from multi-model simulations to extracting high-level knowledge. It underpins investment decisions within the different sectors (e.g. water, hydroenergy, environmental sectors) for adaptation schemes under the uncertain changes in our environment (e.g. variable climate, natural disasters).

Project team is consisted of the team members from Jaroslav Černi Water Institute, Faculty of Civil Engineering University of Belgrade, Faculty of Engineering and Faculty of Science University of Kragujevac. Dr Milan Stojković (Jaroslav Černi Water Institute) is a principal investigator and works alongside team members: dr Damjan Ivetić (, Faculty of Civil Engineering University of Belgrade), dr Dragan Rakić (Faculty of Engineering University of Kragujevac), dr Višnja Simić (Faculty of Science University of Kragujevac), Lazar Ignjatović (Jaroslav Černi Water Institute), and Luka Stojadinović (Jaroslav Černi Water Institute).

2 Main goals

The upper basin of the Nišava river is selected for the proposed methodology application as a flood-prone area in southeast Serbia. In this region, the Pirot water system is located, having catchment an area of around 571 km^2. It represents a multipurpose complex system including the Zavoj reservoir at the Visočica river, hydraulically connected by a pressure tunnel equipped with hydropower plant (HPP) Pirot with the Nišava river. The scheme of the Pirot water system and its location in Serbia is given in Figure 1.

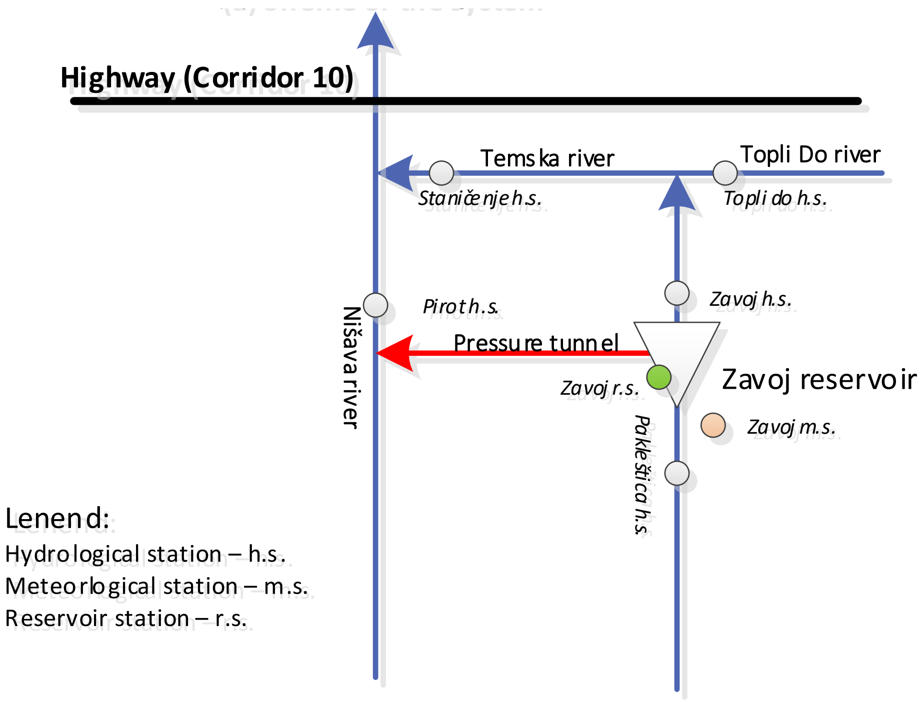
The primary purpose of the Pirot water system is hydropower generation. In addition, this water system is used for mitigation of floods at the Nišava river and downstream water quality control at the Temska river by regulation of the outflows over the low-flow season. The management of the Pirot water system depends on the actual volume of water stored in the reservoirs, inflows and energy demand. The Pirot HPP operates regularly over 4.5-5 hours per day to satisfy demands for the energy during the peak hours. The total annual hydropower generation is estimated at 120 GWh with 1400 average working hours. Through bottom outlet, the Zavoj reservoir releases the environmental flow (0.7 m^3/s) in the downstream section of the Visočica river.

Table 1. The characteristics of the Zavoj reservoir in the Pirot water system.

Reservoir	Year Built	Drainage Area (km^2)	Annual Inflows (m^3/s)	Active Volume (10^{6}m^3)	Flood Storage Volume (10^{6}m^3)	Minimal Operational Level (m.a.s.l.)	Spillway Capacity (m^3/s)	Spillway Crest Elevation (m.a.s.l.)
Zavoj	1990	571	6.2	140	5.5	568	1820	606

The earthen dam of the Zavoj reservoir is 86 m in height and 250 m in length. The power plant has two turbines (40 MW) for power generation, with the installed discharges of 45 m^3/s. Active storage of the Zavoj reservoir is 140 × 10^6 m^3. Three gated spillways are located at the left part of the dam with the capacity of 1820 m^3/s. The Zavoj reservoir is hydraulically connected with diversion-type turbines at the HPP Pirot by the 9 km pressure tunnel with 4.5 m radius. The pressure tunnel conveys the water from the Visočica river to the Nišava river providing a significant contribution to the total annual flow at the downstream river.

(a) Horizontal view



(b) Vertical view

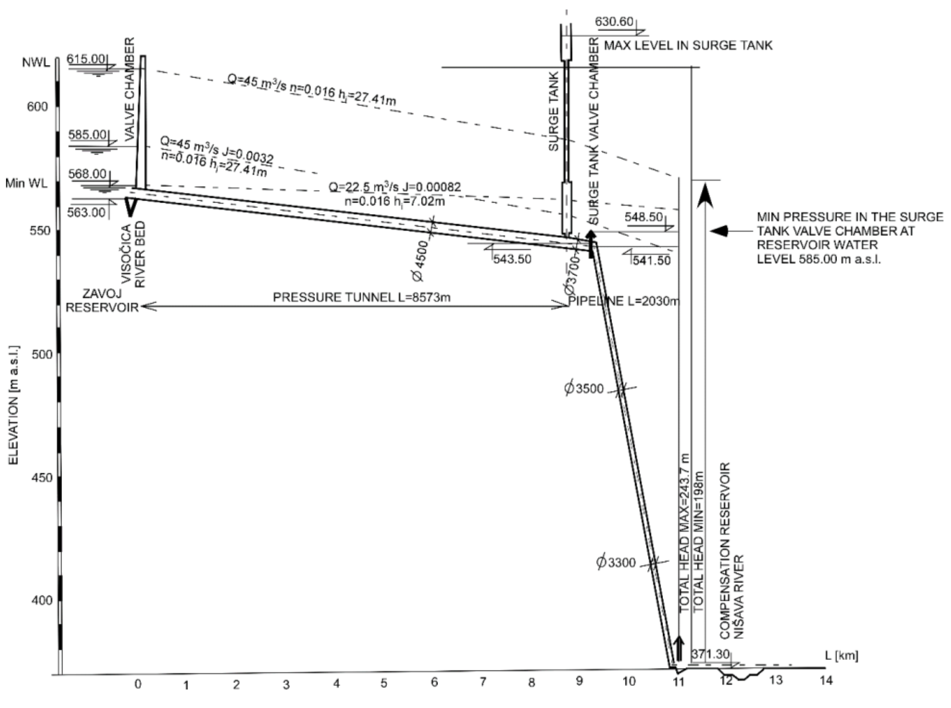


Figure 1. Schematic representation of the Pirot water system: horizonal (a) and vertical view (b)

There are major issues related to the reservoir operation of the Pirot water system which is addressed by the proposed research:

1. Assessment of hydroenergy generation resilience under an extraordinary disturbance - caused by an earthquake or extreme hydrological event. For example, failure of spillways gates, pressure tunnel, data acquisition system, damage caused by floods or similar.
2. Assessment of the flood resilience within the flood prone area alongside the Nišava river stream, by controlling the outflows from the Zavoj reservoir.

3 Methodology

A novel approach for assessment of the dynamic resilience, using the systems analysis and integration of various modelling tools (Figure 2), is proposed for considering the major issues of the Pirot water system.

The proposed research is conducted in the following phases:

1. Stochastic generation of climate data to include “black-swan” events, i.e. simulated climate beyond the observed levels.
2. Introduction of system disturbances to simulate the different system failure scenarios which are complex and not necessarily related to a single extreme event.
3. Integration of various modelling tools using a systems approach: hydrological model, system dynamics simulation model, and dam safety management model.
4. Estimation of system dynamic resilience - the dynamic resilience of the water system has four characteristics: redundancy, resourcefulness, and rapidity. It is tailored to capture consequence of various feedbacks within the complex water, infrastructure and ecological system, future unknown system states, and importance of spatial and temporal scale.
5. Big data analysis - using the data sets derived from monitoring systems, multi-models and extracting high-level knowledge by the different techniques.

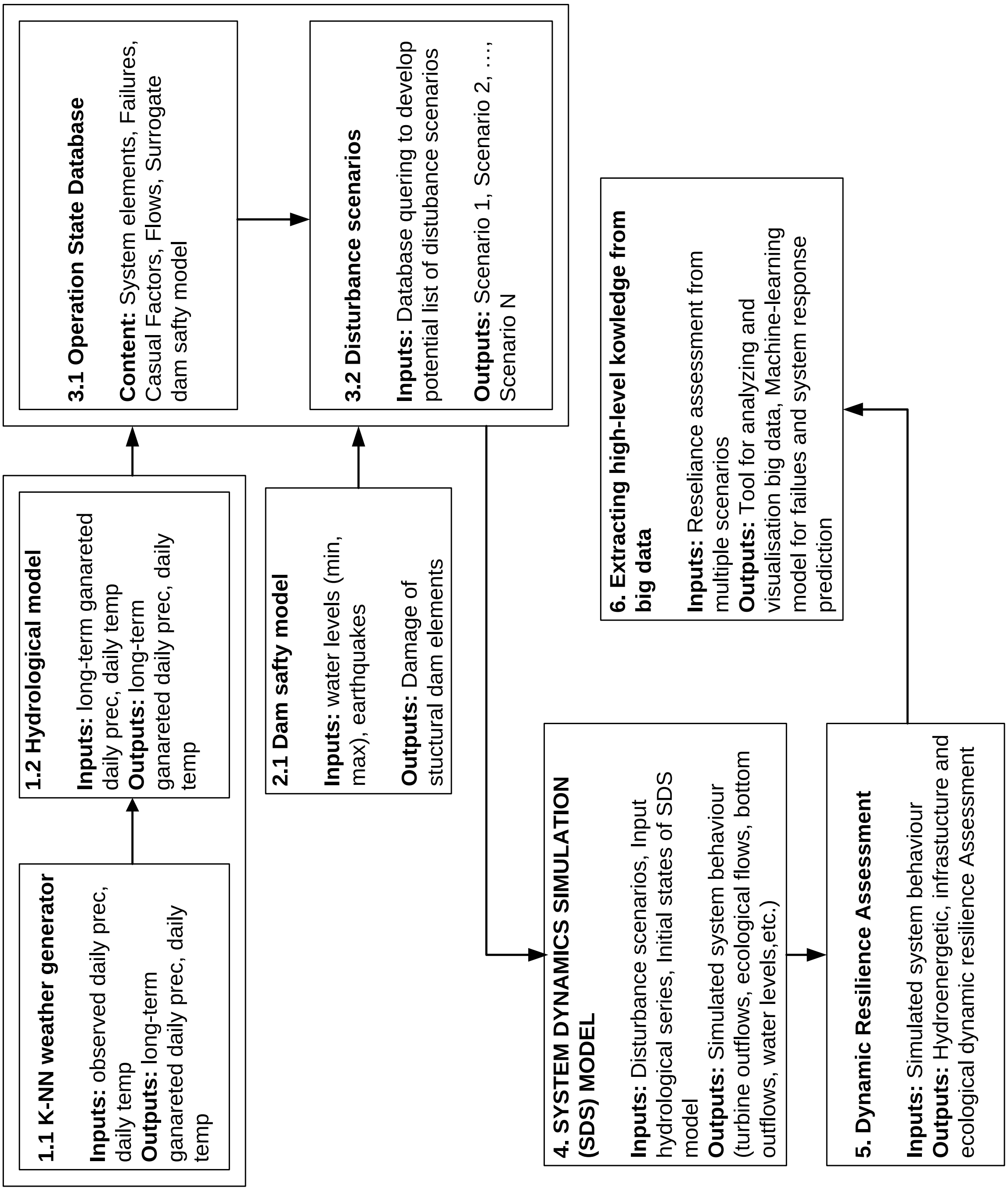


Figure 2. Graphical presentation of the proposed framework for assessment of the dynamic resilience of a complex system.

Therefore, the proposed research will result in a generic methodology for resilience assessment by achieving the following research goals:

1. Using the existing approach for climate data generation which contain members beyond the observed level;
2. Developing of disturbance method for failure scenarios (collapse of the dam, and/or collapse of any of its structural, mechanical or electric components);
3. Integration of the well-known models in the new framework by using systems analysis;
4. First-time implementation of a surrogate dam safety model within the system performance analyses;

5. Making a context by introducing an original framework for quantitative assessment of the dynamic resilience of the system; the traditional risk-based approach will be shifted to the state-of-the-art dynamic resilience;
6. Development of a novel method for processing big data from the multi-models driven by multi-scenarios analyses using artificial intelligence; and
7. Application of the proposed approach for the first time in Serbia using the Pirot water system as a case study.

The proposed framework for dynamic resilience assessment of a complex system is conducted throughout five phases illustrated in Figure 2.

Phase 1. Observed climate (daily precipitation, maximal and minimal temperature) is served as the basis for generation of additional long sequences of replicates. The K-nearest neighbour weather generator (K-NN_WG) is used to reshuffle the historical data, with replacement (King et al. 2015). Each of the resampled values will then be perturbed to ensure unique values are generated that do not occur in the historical record. Please note that the assumption of non-stationarity of climate is incorporated within K-NN_WG.

Phase 2. The disturbances can affect each variable within the multiple models (Figure 2) used to assess system performance (King et al. 2017). Various disturbance scenarios will be simulated to assess the performance of a large number of interacting components, both physical (e.g. dam, gates, turbines, highroads) and nonphysical (e.g. operator, information relays). Physical failures include collapse of the dam, and/or collapse of any of its structural, mechanical or electric components that may be caused by a system disturbance. Moreover, failures occur due to ageing of infrastructure, lack of maintenance, improper design or construction errors. Nonphysical failures happen when the system components and reservoir are not able to serve the intended purpose. These failures can be caused by improper operation and unexpected extreme natural conditions (e.g. floods, droughts).

Phase 3. The implementation of the systems approach will use the outputs from multiple models (Phase 2): hydrological model, system dynamics simulation model and dam safety management model.

The outputs (daily precipitation, maximal and minimal temperature) from the K-NN-WG (Phase 1) is used to simulate system response under variable climate scenarios satisfying the assumption of non-stationarity. Long sequences of daily flows will be derived by the last version of PRMS 5.0 (Precipitation Runoff Modeling System) hydrological model (Markstrom et al. 2015). It represents physically-based hydrological model and will be applied to the selected river basin on a semi-distributed basis. The PRMS model can consider different processes, such as evaporation, transpiration, runoff, infiltration, and interflow as determined by the energy and water budgets of the plant canopy, snowpack, and soil zone on the basis of climate information. The meteorological module is used to simulate a complex behavior of snowmelt processes. The PRMS model offers flexibility in choosing an appropriate method for the direct runoff, baseflow components, precipitation loss, and river routing. These features enable evaluation of the hydrologic response of different river basins, especially those where the snowmelt plays an important role in runoff generation.

The systems analysis (Simonovic, 2009) is used to develop the system dynamics simulation model (SDM) of the complex Pirot water system in the Python environment. The structure of the SDM is designed using a stock and flow diagram to capture the system structure. The stock and flow diagrams use four graphical objects to represent a complex system structure (Stojkovic and Simonovic, 2019): stocks, flows, auxiliary variables and arrows. The reservoirs of the Pirot water system is represented as stocks because they represent state variables accumulating over time. Inflows and outflows from the reservoirs are modelled as flows. They are attached to stocks and change the state of the accumulated water in the reservoirs. Other variables in the SDM model are represented by auxiliaries. Arrows connect stocks, flows and auxiliary variables to close the system structure. The SDM utilizes the release policy described in the operational rule book. Based on the simulated hydropower releases, the standard equation is used for the hydropower calculation.

Dams and associated facilities (e.g. pressure tunnel, spillway) are critical infrastructure elements whose failure could lead to severe social consequences and high economic losses. Therefore, dam safety management has become an indispensable component of all dam engineering projects worldwide (Hariri-Ardebili, 2018). For the purpose of the proposed research, the previously developed physical based-model (Rakić et al. 2015) of dam safety is used within the system dynamics simulation approach.

Phase 4. The resilience of the system is defined as "the ability of a system and its component parts to absorb, accommodate or recover from the effects of a system disruption in a timely and efficient manner, including through the preservation, restoration or improvement of its essential basic structures and functions (Kong and Simonovic 2018)". In the proposed research, a quantitative dynamic resilience model is estimated the recovery of the system under combinations of various disruptive events which possess a serious threat to reservoirs and dam. The quantitative assessment of resilience captures four characteristics of resilience called robustness, redundancy, resourcefulness, and rapidity. This novel measure provides insight into the dynamics of the system performance based on its characteristics and adaptive capacity.

Phase 5. The important part of the proposed research is the extraction of interpretable knowledge from a large amount of data gathered through the simulation of multiple scenarios by the multiple system models. Extracting high-level knowledge from low-level data contained in large data sets is a complex process that involves methods and techniques from multiple fields, namely: machine learning, statistics, distributed databases, data visualization and high-performance computing.

4 Conclusions

The proposed framework brings great predictive power to assess the resilience of a complex water systems to hazardous events (e.g. floods, droughts) beyond the largest records and natural disasters. Using the generated flows, it can significantly reduce the uncertainty stemming from the hydrological modelling and short records, which typically lead to the poor representations of extreme hydrological events. It is expected that the proposed research will significantly advance the understanding of (1) how complex infrastructure systems perform under disturbance; and (2) what will be the best adaptation option under the changing conditions. Therefore, this research will contribute to the development of new (1) research methodology and (2) its application to a real case study system.

Water systems are designed to withstand demands imposed by their service requirements and by hazardous events (Simonovic 2018). However, their facilities are designed by existing standards. In respect to the ageing process and rapid changes in the environment (e.g. variable change, natural disasters), they do not necessarily guaranty an adequate level of service and safety. Therefore, the proposed research introduces performance-based engineering approach as the replacement of traditional use of standards. This approach offers an opportunity for highlighting the role of using multi-model simulations for the estimation of dynamic resilience. It should be stressed out that, within the scope of the proposed research, observed data (e.g. climate, hydrological, hydraulic and exploitation data) serve both as the input for the multi-model simulations and calibration of the selected models. By proceeding in this manner, additional valuable information will be incorporated in the final results. It is also expected that, by analyzing the propagation of the measured data uncertainty through the multi-model simulations, weak points in the monitoring system are detected. Thus, providing guidance to operators and system stake-holders in prioritizing future investments in these vital elements of the complex water systems.

The systems analysis will be implemented in the proposed framework as a rigorous method for system description. It allows feedback analysis via simulation of the effects of different disturbance/failure scenarios. The systems analysis is also be incorporated into control policy behavior, in order to derive an effective strategy for the system adaptation to changing conditions. This approach can outperform the classical simulation procedures since it can deal with change in system structure and dynamic interactions of the system elements over time. It should be noted that the proposed research will be the first attempt of incorporating a surrogate dam safety model, within the system dynamics simulation analysis, which connects directly failures of the system (movements of the dam and pressure tunnel caused by external forces) with the response of other system elements (e.g. spillway gates).

Hydro-environment research and practice has already benefited from the application of artificial intelligence techniques (Savić, 2019). Application of artificial intelligence in the water management world opens a wealth of opportunities and benefits for water management practitioners. Implementation of the proposed methodology requires a state-of-the-art technique based on machine learning, statistics, distributed databases, data visualization and high-performance computing. The availability of big data generated by multi-model simulations provides further opportunities for the investigation of the utility of various artificial intelligence methods. In this manner, the proposed research develops a novel method capable of extracting knowledge from a large amount of data (obtained from simulations) which will advance contemporary hydro-environmental knowledge.

The proposed methodology is applied to the Pirot water system (Figure 1), which lies within the flood-prone region and plays an important role in the Serbian energy and water sectors. The results from this research is used to derive the dynamic plan for the renewal of the ageing elements of the Pirot water system infrastructure.

Acknowledgement

The authors express the gratitude to the Science fund of the Republic of Serbia for the support through the project of the PROMIS call: "Dynamics resilience as a measure for risk assessment of the complex water, infrastructure and ecological systems: Making a context”.

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