DyRes System

JAROSLAV ČERNI
WATER INSTITUTE

WSDAC

GUIDELINES FOR DYNAMIC RESILIENCE ASSESSMENT

Dynamics resilience as a measure for risk assessment of the complex water, infrastructure and ecological systems: Making a context (DyRes_System)

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WSDAC Category 2 Centre
under the auspices of UNESCO

Guidelines for dynamic resilience assessment

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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[1]. 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[2]. In addition, it has been estimated that earthquakes are responsible for about 35% of the economic losses generated by natural disasters[3] (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, environment, and infrastructure systems beyond the largest recorded events. The main objective of the presented research is the development of a modeling framework for dynamic resilience assessment [4]. 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 provides the generic methodology and tools for hydroenergy, flood, and environmental dynamic resilience assessment. This framework offers an opportunity for highlighting the role of using multi-model simulations which will support 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).

In guidelines for the dynamic resilience assessment an overview of the project results titled "*Dynamics resilience as a measure for risk assessment of the complex water, infrastructure and ecological systems: Making a context*" is provided. The 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 Science Fund of the Republic of Serbia allocated 199,532.93 EUR to cover the research and other activities during the project realization (2020-2022).

Project team 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.

1 EEA a. 2019. European Environment Agency. Mapping the impacts of recent natural disasters and technological accidents in Europe https://www.eea.europa.eu/publications/mapping-the-impacts-of-natural
2 EA b. 2019. European Environment Agency. Water Scarcity & Droughts in the European. https://ec.europa.eu/environment/water/quantity/scarcity_en.htm
3 ECSKS. 2019. The European Commission's science and knowledge service. https://ec.europa.eu/jrc/en/research-topic/earthquakes-and-tsunamis
4 Simonovic, S.P., Arunkumar, R. 2016. Comparison of static and dynamic resilience for multipurpose reservoir operation. Water Resource Research, 52, 8630-8649, DOI; 10.1002/2016WR019551

Dissemination activities

Jaroslav Černi Water Institute has a long tradition in UNESCO Water Family. Institute hosts Water for Sustainable Development and Adaptation to Climate Change (WSDAC), 2nd Category Centre under the auspices of UNESCO, and has also a strong relationship with Intergovernmental Hydrology Programme (IHP), especially with IHP Danube Countries.The IHP is an intergovernmental cooperation programme aimed at addressing national, regional and global water challenges and building a sustainable and resilient society by expanding the scientific understanding of water, improving technical capabilities, and enhancing education.

A major challenge confronting Members States is meeting the Sustainable Development Goals (SDGs) that comprise the UN Agenda 2030 for Sustainable Development. Certainly, the majority of the global agenda are directly related to water while others are connected indirectly and any improvement in the achievement of SDG6 results in having secondary effects on them. The on-going process of UN reform with SDGs country-oriented support provides a greater opportunity for IHP through its national committees, Chairs and Centres for more engagement at country and regional levels.

It makes a great opportunity to connect the "Dynamics resilience as a measure for risk assessment of the complex water, infrastructure and ecological systems: Making a context" project outputs directly with the new launched IHP-IX phase-Strategy Science for a Water Secure World in a Changing Environment and developed Strategic Plan. The Strategic Plan for the ninth phase of the Intergovernmental Hydrological Programme (IHP-IX) covering 2022-2029 identifies key water priority areas to support Members States to achieve Agenda 2030 and the Sustainable Development Goals (SDGs), especially water-related SDGs and other water-related global agendas. One of the priority areas defined in IHP-IX Strategy is Scientific research and innovation. According to the Strategy "*By 2029, the Member States have the knowledge, sound scientific and research capacity, new and improved technologies, and the management skills that allow them to secure water resources for human development and healthy of ecosystems within a sustainable development context*." Activity 1.3 of this Priority area is focused on Research on uncertainty in climatic scenarios, hydrological projections and water use scenarios conducted and recommendations communicated to decision makers and the general public to elaborate adaptive water management strategies.

Guidelines for dynamic resilience assessment will serve to broader society, especially the research community, to improve their knowledge and better understand the dynamic resilience of complex water systems to hazardous events (e.g. floods, droughts) beyond the largest records and natural disasters.

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 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 the 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.

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

- Assessment of hydroenergy dynamic resilience under an extraordinary disturbance caused by an earthquake and extreme hydrological event. For instance, failure of spillways gates, pressure tunnel, data acquisition system, damage caused by floods or similar.
- Assessment of the flood dynamic resilience within the flood prone at the Nišava river stream and reservoir Zavoj, by controlling the outflows from the Zavoj reservoir.
- Assessment of the environmental resilience using the simulated water quantity and quality of the water system under the present and future climate conditions.

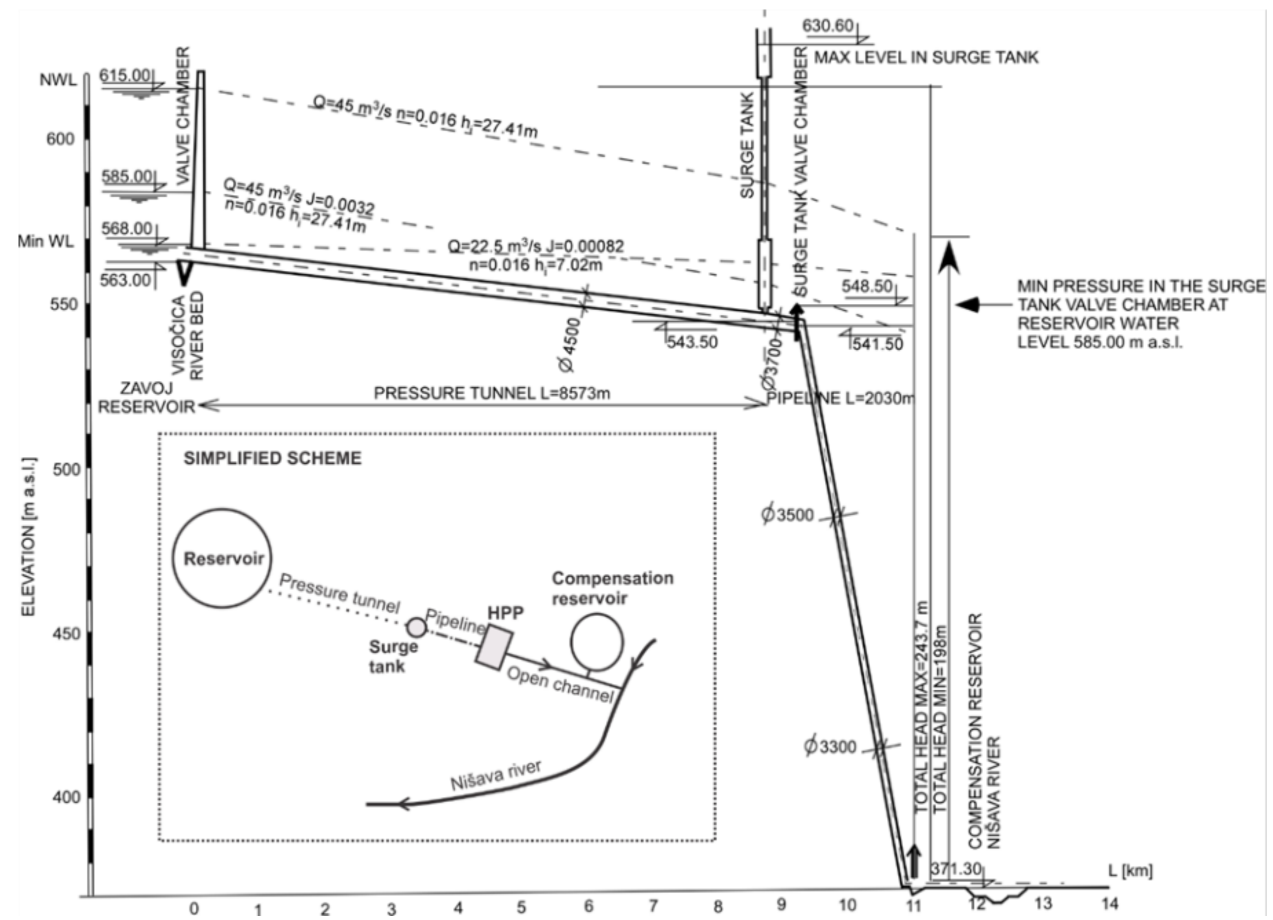

Figure 1. Schematic representation of the Pirot water system.

General methodological framework for the dynamic resilience assessment

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

The proposed research is conducted in the following phases:

- Stochastic generation of climate data to include "black-swan" events, i.e. simulated climate beyond the observed levels.
- Introduction of system disturbances to simulate the different system failure scenarios which are complex and not necessarily related to a single extreme event.
- Integration of various modeling tools using a systems approach: hydrological model, system dynamics simulation model, and dam safety management model.
- 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.
- Big data analysis - using the data sets derived from monitoring systems, multi-models and extracting high-level knowledge by the different techniques.

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

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

- Development of a novel method for processing big data from the multi-models driven by multi-scenarios analyses using artificial intelligence; and
- Application of the proposed approach for the first time in Serbia using the Pirot water system as a case study.

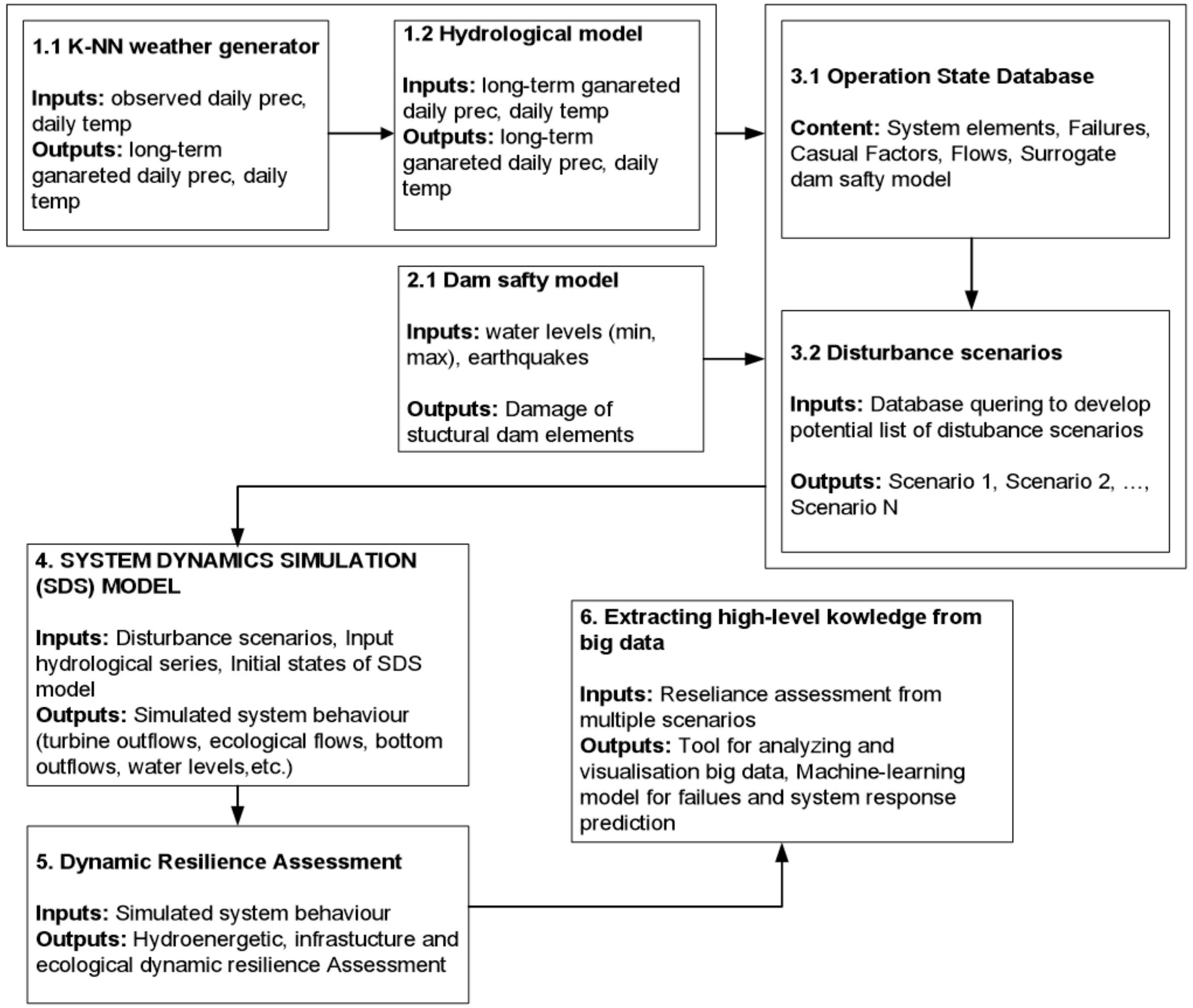

Figure 2. Graphical presentation of the proposed framework for assessment of the dynamic resilience of a complex system.

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 neighbor weather generator (K-NN_WG) is used to reshuffle the historical data, with replacement[5]. 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[6] . 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 electronic components that may be caused by a system disturbance. Moreover, failures occur due to aging 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).

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)[7] hydrological model. It represents a 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 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

5 King, L.M, McLeod, M.A., Simonovic, S.P. (2015) Improved weather generator algorithm for multisite simulation of precipitation and temperature. Journal of the American water resources association. 51(5): 1305-1320 DOI: 10.1111/1752-1688.12307

6 King, L.M. , Simonovic, S. P., Hartford, D.N.D (2017) Using system dynamics simulation for assessment of hydropower system safety. Water Resource Research, 53, DOI:10.1002/2017WR020834

7 Markstrom, S.L., Regan, R.S., Hay, L.E., Viger, R.J., Webb, R.M.T., Payn, R.A., LaFontaine, J.H., (2015) PRMS-IV, the precipitation-runoff modeling system, version 4: U.S. Geological Survey Techniques and Methods, book 6, chap. B7, 158 p., http://dx.doi.org/10.3133/tm6B7

graphical objects to represent a complex system structure[8]: 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 modeled 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. For the purpose of the proposed research, the previously developed physical based-model 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"[9]. 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, data visualization and high-performance computing.

8 Stojkovic M., Simonovic S.P. (2019) System Dynamics Approach for Assessing the Behaviour of the Lim Reservoir System (Serbia) under Changing Climate Conditions. Water. 11, 1620; doi:10.3390/w11081620

9 Kong, J., and S.P. Simonovic. (2018) A Model of Infrastructure System Resilience", International Journal of Safety and Security Engineering. 8(3):377-389 DOI: 10.2495/SAFE-V8-N3-377-389

Dynamic Modeling of the Dam and Reservoir System Reduced Functionality in Adverse Operating Conditions

Dam and reservoir systems (DRS) are the crucial infrastructure for reliable water resources management. Nowadays, they are being increasingly affected by numerous natural and anthropogenic impacts (aging and outdated infrastructure, climate change, natural hazards, global crisis etc.).

System dynamics approach has been proved as a perspective concept for long-term DRS operation simulation and analysis. To assess system performance in different undesired scenarios and its capability to recover or bounce back after disturbance event (dynamic resilience), system component failure model must be embedded in a system dynamic model. Even though there are research addressing this issue, there is still necessity for systematic, generic procedure. Therefore, in this research, generic, straight forward framework for modelling DRS dynamics and implementing component and system failures into the model, with a great degree of flexibility, is proposed[10]. The framework defines eleven steps (Figure 3). Steps (1-6) define the system model design: (1) System decomposition into the subsystems where crucial components and processes have to be identified, (2) Subsystems' interdependence linking where input/output for each subsystem has to be assigned, (3) Subsystems' mathematical representation, where the transformation of the inputs to the outputs has to be emulated using equation (e.g. balance equation, dynamic equation) of appropriate complexity, (4) Definition of the system operating rules, describing how the monitored information is used to make operating decisions (e.g. the relations between the process and control variables) (5) Failure-indicative parameters identification where variables indicating the reduced functionality of each subsystem prone to failure, have to be detected, (6) Failure rate implementation in mathematical model where the relation between failure-indicative parameter and a generic functionality indicator is defined, through which the functionality indicator can affect the value of failure-indicative parameter and emulate the subsystems' reduced functionality (partial failure). It is assumed that the used SD models have at least a minimal level of details needed for the execution of the steps 1-6. Over-simplified and fully stochastic models cannot be used, as they will fall short in the definition of the non-linear component interaction.

10 Ivetić, D., Milašinović, M., Stojković, M., Šotić, A., Charbonnier, N., & Milivojević, N. (2022). Framework for Dynamic Modelling of the Dam and Reservoir System Reduced Functionality in Adverse Operating Conditions. Water, 14(10), 1549.

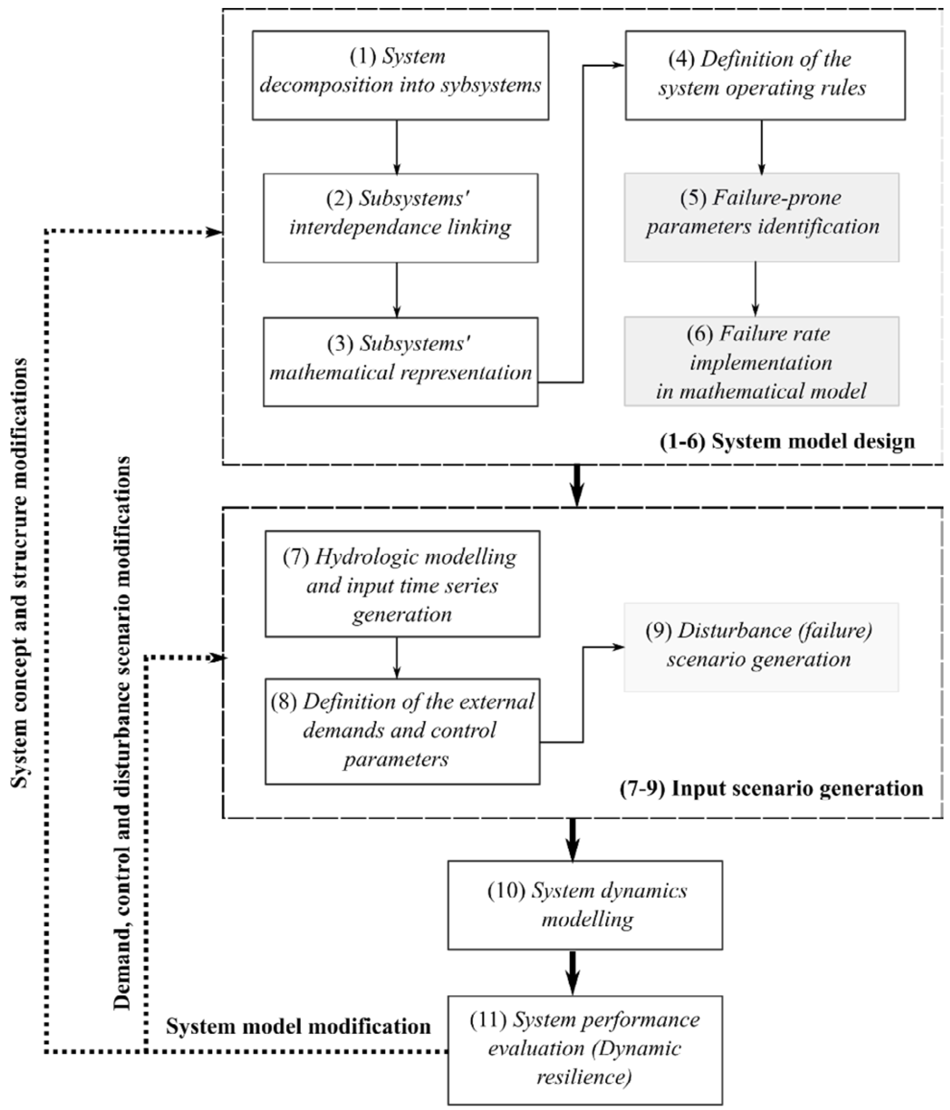

Figure 3. Schematic framework overview: Dam and Reservoir System Reduced Functionality in Adverse Operating Conditions.

Steps (7-9) cover the input scenario generation: (7) Hydrologic modelling of the water shed and the long inflow time series generation or inflow forecasting, (8) Definition of external demands and characteristic control trigger values (e.g. maximum and minimum reservoir level for power production), (9) Disturbance (failure) scenario generation, where the wide range of operating scenarios including single or a combination of system disturbances, varying in magnitude and time, and affecting the system performance, are generated. SD modelling (10) is next, where simulation model is used to emulate system behavior under different hydrological and failure inputs. Using the output results from step (10), system performance evaluation should be conducted (11). Based on the performance evaluation, SD model modifications can be performed, for example to investigate the effects of the increase in the external demands, or to analyze the behavior of the upgraded DRS with new or modified system components and operating rules. If the structural modifications are needed all the previous procedure steps should revisited, to adequately implement the modification in the existing model (e.g. new subsystem means new links, mathematical model, failure-indicative parameters etc.). Otherwise, experimentation with external demands and tuning of the control parameters of the system, for performance optimization, or increase in the number, and type of the disturbance scenarios, need only the later steps (7 – 11).

When SD modelling is used to assess system's performance for different hydrological and failure scenarios, appropriate conceptual and mathematical representation of each subsystem function, should be defined.

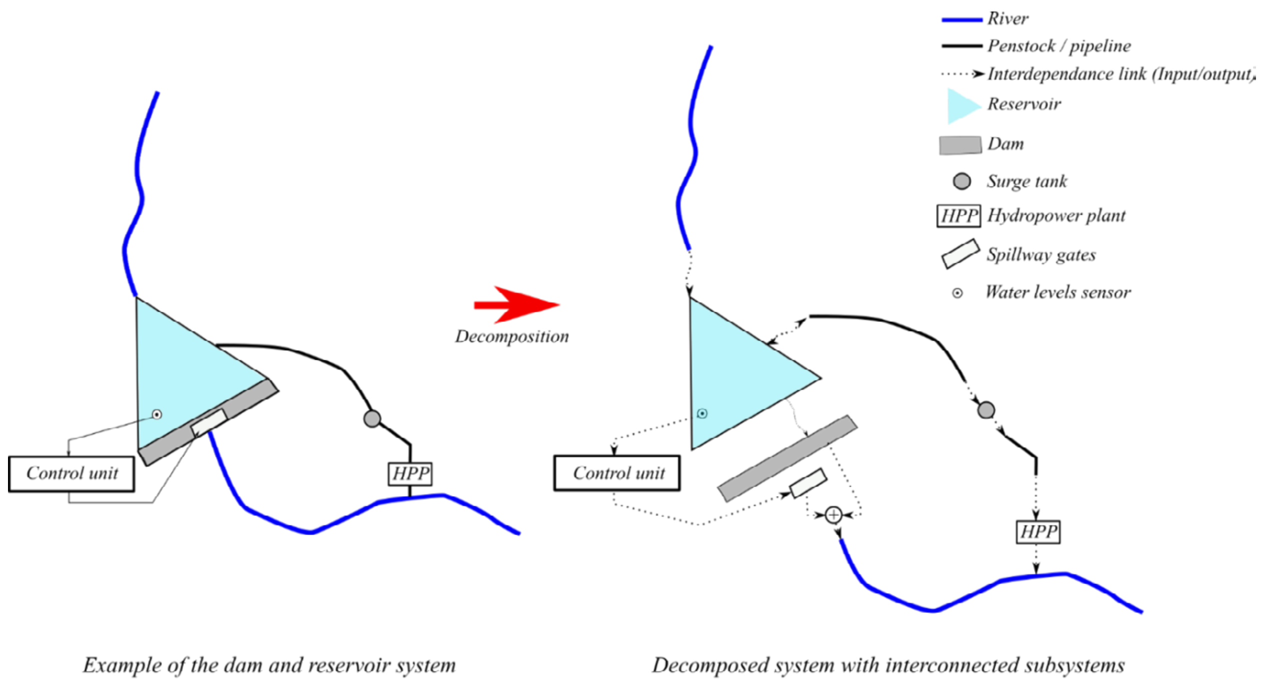

Figure 4. Example of system decomposition and definition of the interdependence links.

Firstly, system decomposition is conducted (Figure 4), where the key system subsystems, and corresponding interdependencies are identified. Subsystems are used to describe a process or a transformation of internal and/or external inputs into outputs, within the system (here DRS). A subsystem can correspond to a particular physical component/object within the system, but can also serve to describe a certain process of interest, e.g. evaporation. For each subsystem, appropriate mathematical representation must be defined to represent subsystem dynamics. Mathematical representation complexity depends on desired levels of details, simulation goals, time step and the duration (time scale) of the simulation.

One example of the SD model of the Pirot DRS is presented here to illustrate the procedure for the analysis of the DRS operation in adverse conditions (Figure 5). Depending on the timescale and time step in simulations, SD model can be simplified or more detailed. Here, one simple model is

devised for the analysis of the system functionality in adverse operating conditions, in respect to the hydropower production and flood management. Performance of the Pirot reservoir system is analyzed for a two-year period with hourly simulation time step. Thus, some of the subsystems' performance and hydraulic transformation cannot be represented (e.g. surge tank level oscillations), as their performance can be modelled only when higher time resolution is used (smaller simulation time step).

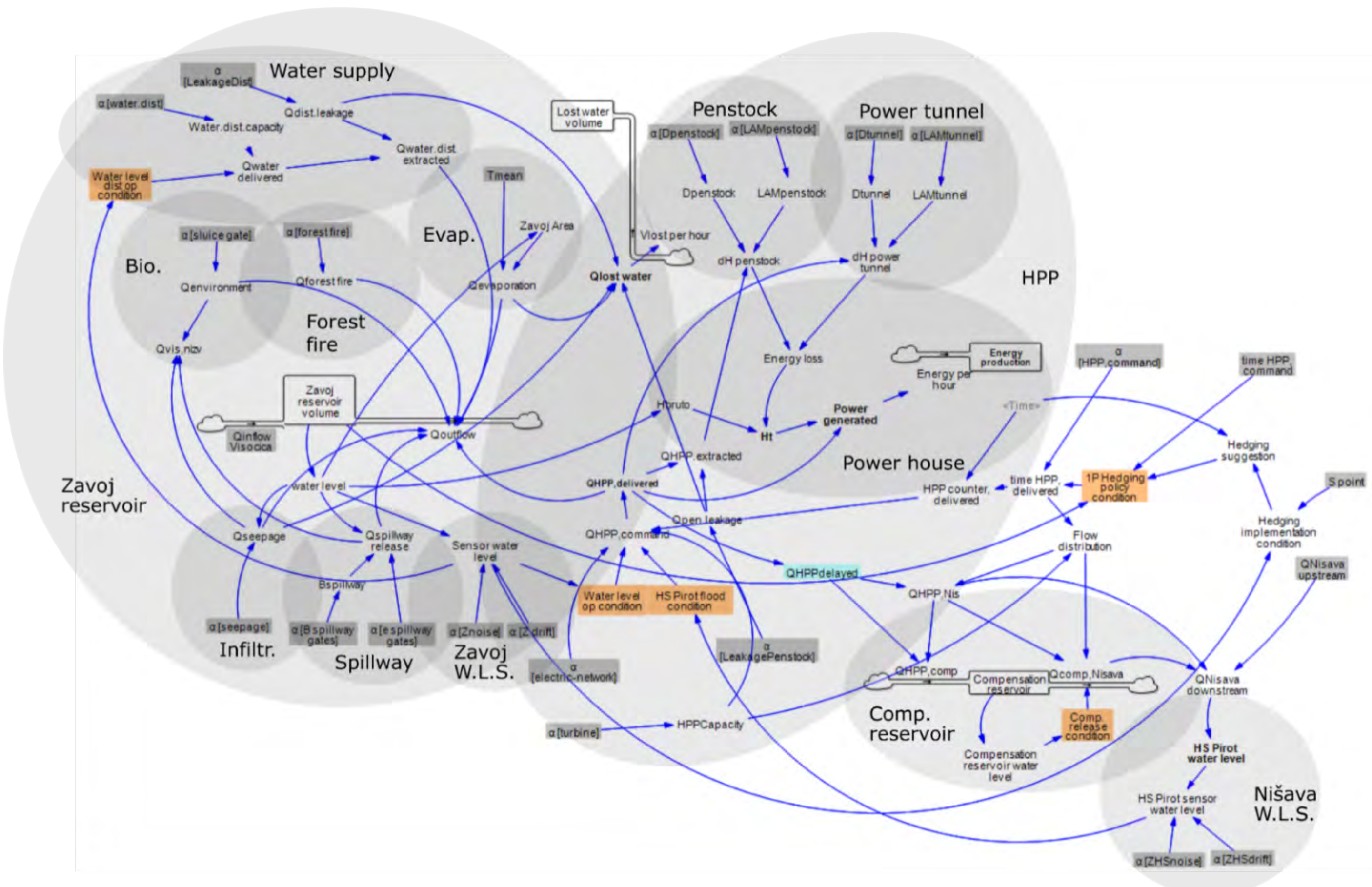

Figure 5. DRS Pirot dynamic model representation in Vensim software with reference to the subsystems.

The system operation is incorporated into the SD model through the control subsystem. This subsystem is integrated at the various points in the model and is designated to define both the external demands for power generation (e.g. how much will the HPP operate during the day), and also how will the system actuators affect the control variables in respect to the appropriate process variables. Characteristic trigger values are an important part of the control subsystem (e.g. minimum reservoir water level for hydropower operation), which can be tuned to optimize the DRS system performance. The hydropower operation is defined by the external demand for the number of operating hours during the day, the water level in the Zavoj reservoir and at the Nišava river, and the state of the turbines. Flow routing and release from hydropower plant are also determined by a control subsystem to allow for the maximal attenuation of the hydrograph entering the Nišava river, from both HPP tailrace and Compensation reservoir.

Hydroenergetic and Food Dynamic Resilience for Complex Reservoir Systems Using Failure Simulations

The objective of this research is to introduce a novel framework to quantify the risk of the reservoir system outside the design envelope, taking into account the risks related to flood-protection and hydro-energy generation under unfavourable reservoir element conditions (system element failures) and hazardous situations within the environment (flood event)[11].

To develop an adequate system for quantifying flood and hydroenergetic dynamic resilience of a multi-purpose water reservoir, needed for real-life application at the decision-making scale, a chain of models can be employed. The proposed dynamic measure involves the risks related to flood-protection and hydro-energy generation outside the design reservoir envelope. Here, an example methodology for the definition of the chain of models of a multi-purpose reservoir system is presented. Alongside the chain of models, the risk assessment methodology regarding a multi-purpose water reservoir is also depicted.

A general flow chart is shown in Figure 6 within the following four modeling steps: (1) long-term emulation of hydrological scenarios; (2) multi-failure scenarios implementation; (3) system dynamics modeling; (4) dynamic resilience quantification.

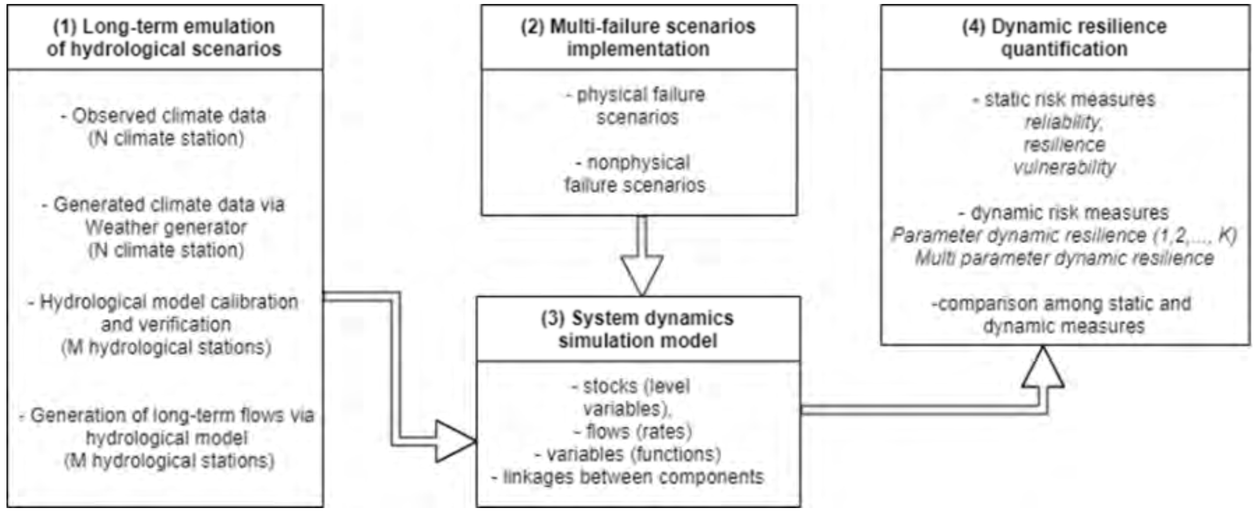

Figure 6. Chart flow diagram for quantifying multi-parameter dynamic resilience for complex reservoir systems.

A backbone for the flood and hydroenergetic dynamic resilience evaluation is the system dynamic model of the Pirot water system with an inner control loop (Figure 7). The inner control loop provides the relation between the hydropower generation and flood-protection.

11 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)

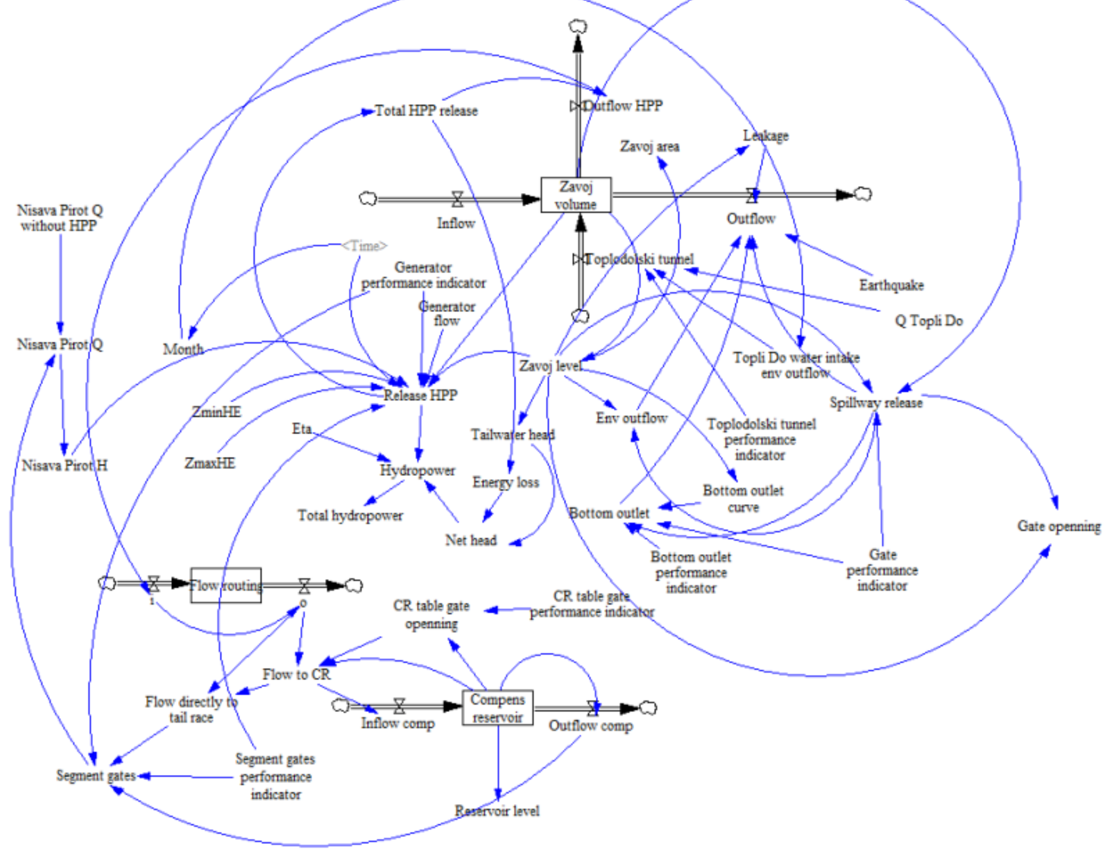

Figure 7. System dynamics simulation model of the Pirot reservoir System.

To assess the risk of a multi-purpose reservoir system, multi-failure scenarios as the input for the system dynamics simulation model are generated. Multi-failure scenarios assume that the disturbances can affect each system element. The scenarios represent physical failures of the structural, mechanical, and electric system components of the Pirot reservoir system (Table 2). During these failures, the performance measures of the system elements are reduced, and therefore functionality indicators for each system element are employed in the range from 0 to 1.

Table 2. Description of failure scenario events.

Number of Failure Event	Element:	Disturbance Scenario	Active/Passive Element	Number of Elements	Functionality Indicator Values	Failure Start and End Time (h)	Failure Duration (h)
1	HPP generators	Generator failure	active	2	α_{HPP} = {0, 0.5, 1}	7129–15,889	8761 (1 year)
2	Spillway segment gates	Gate failure	active	3	α_{SWI} = {0, 0.33, 0.67, 1}	7129–11,509	4381 (6 months)
3	Dam leakage	Earthquake/ leakage	passive	1	$\alpha_{EARTHQUAKE}$ ∈{0, 15}	7129–24,649	17,521 (2 years)
4	Toplodolski Tunnel	Water intake gate failure	passive	1	α_{TUN_TD} = {0, 0.5, 1}	7129–10,009	2881 (4 months)
5	Compensation reservoir segment gates to Nišava River	Gate failure	active	2	α_{CRSG} = {0, 0.5, 1}	7129–9289	2161 (3 months)

Based on the outputs from the system dynamics model and failure scenarios generated, system performance is determined and, later, hydropower and flood protection resilience. An example of the multi-parameter dynamic resilience estimation (hydroenergetic and flood) is provided as follows (Figure 8).

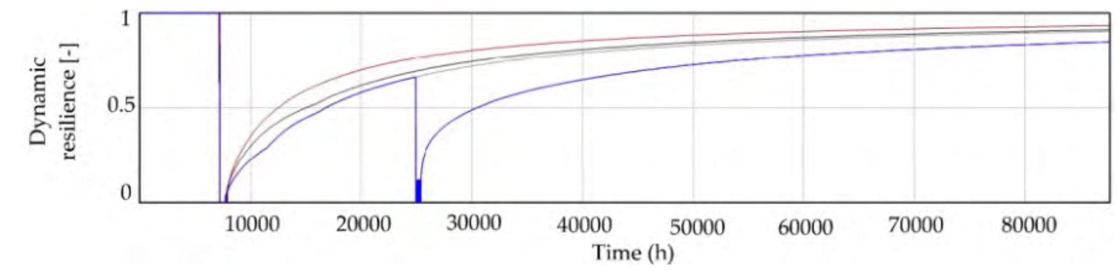

Figure 8. Dynamic resilience assessment of the Pirot reservoir system: multi-parameter resilience envelopes hydroenergetic and flood resilience.

The values of multi-parameter (flood and hydroenergetic dynamic) dynamic resilience are summarized from the start to the end of the simulations and normalized in the way that final values are ranged between 0 to 1. The result suggests a general increase in the risk assessment following the severity of the failure scenarios (Figure 9). The most resilient scenario (SC0) considers only the extreme flood event without any additional failure of the system element. However, it decreases the functionality of the system significantly (0.935). The multi-parameter resilience is in the range from 0.913 to 0.851 under the failure of the hydropower plant, spillway gates and leaking from the reservoir (SC1, SC2, SC3). Moreover, additional stresses on the reservoir system (SC4 and SC5) do not increase the risk since dynamic resilience keeps the value at the same level as for SC3.

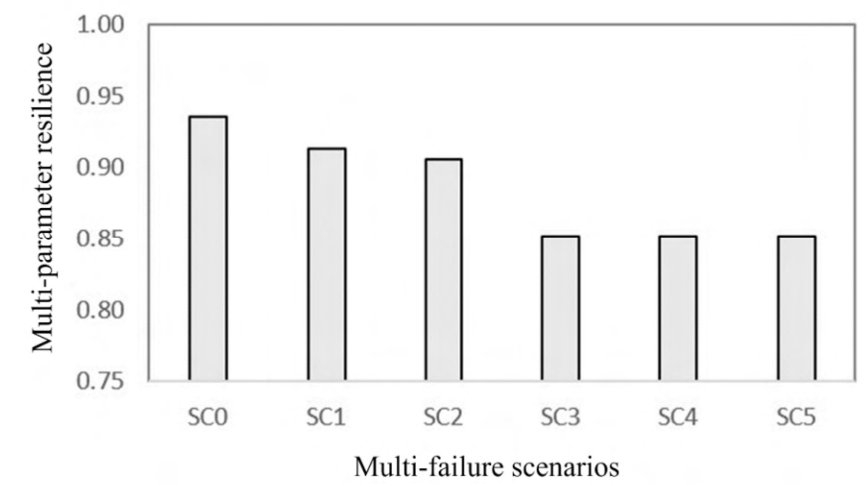

Figure 9. Multi-parameter dynamic resilience within the multi-failure scenarios.

The estimated multi-parameter dynamic resilience of the Pirot reservoir system is compared with the traditional static measures (reliability). Discrepancy between the drop between multi-parameter resilience (from 0.851 to 0.935) and reliability (from 0.993 to 1) shows that static measure underestimates the risk to the water system. Static risk measures do not provide variability in the risk assessment during the failure scenarios causing insufficient insight into the ability of the system to respond and recover from the failure scenarios. For instance, the system reliability does not recognize the risks related to the multi-failure scenarios or underestimate them. Another point is that multi-parametric dynamic resilience is not time-independent and defines the risk at each simulation step. Therefore, multi-parameter (flood and hydroenergetic dynamic) resilience can be used for proposing or updating reservoir operation strategy or forecasting system performance after hazardous events like major floods or earthquakes.

Failure Assessment of Embankment Dam Elements

Within this activity, an analysis of the functionality of key elements of the dam was conducted based on the finite element method results. A detailed analysis of filtration processes and strength of the dam and the surrounding rock mass was conducted. Dam elements whose potential damage could jeopardize the normal functioning of the embankment dam have been identified. A particular emphasis was placed on the analysis of dam elements that have been identified as weak points. To analyze the partial stability of individual structural elements, a new measure of local stability was introduced named the remaining load-bearing capacity. Investigation revealed that local damage to the grout curtain will not significantly increase leakage under the dam body, the overflow section is one of the most robust elements of the dam, but the slope above the spillway can compromise the functioning of the overflow, and thus the safety of the entire dam. Based on the analysis results of the remaining load-bearing capacity, the dependence of the spillway capacity on the earthquake intensity has been defined. The established relationship represents a surrogate model for further assessment of dynamic resilience of the complex multipurpose reservoir system, within the scope of the advanced reservoir system management.

The concept of global stability of geotechnical structures is commonly used in the analysis of the safety of complex structures by determining the global safety factor. However, the conclusion that the structure is stable under the acting of the loads considered does not always mean that the structure is safe, especially when it comes to complex systems, such as dams and reservoirs with accompanying elements. For this reason, in addition to the analysis of the global safety factor, it is necessary to conduct analyzes of the impact of damage that in the short term does not endanger the stability of the structure, but in the long term can affect its stability. In order to overcome this shortcoming in the stability analysis of complex multipurpose systems, in addition to the analysis of the global safety factor, the concept of the functionality analysis of individual structural parts exposed to loads whose intensity is lower than the loads endangering short-term stability is proposed. To conduct this analysis, it is necessary to identify the weak points of the system, and then to analyze their impact on the functionality of the system for hypothetical scenarios, and thus on the long-term safety and operation of the system. The analysis used the case study of the Zavoj dam and accumulation near the city of Pirot in the Republic of Serbia. For the purpose of analyzing the impact of damage to the identified critical dam elements on the functionality of the system, a new measure of local stability of the structure named remaining load-bearing capacity was introduced. This quantity provides a measure of the available load-bearing capacity of the material in relation to the initial load-bearing capacity of the material that is not exposed to the load. The remaining load-bearing capacity of the material is presented as a field of physical size. This new vector represents a measure of the distance of the stress point from the failure surface for the same value of the first stress invariant (Figure 10). The remaining load-bearing capacity of the material is expressed in relation to the limit value of the stress at which fracture occurs.

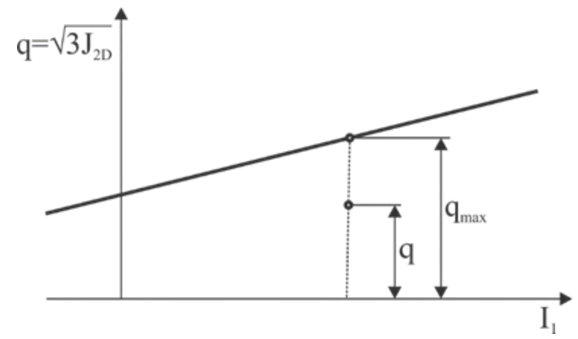

Figure 10. Remaining load-bearing capacity.

The residual load-bearing capacity can be calculated at each finite element integration point, independent of the constitutive model, according to the following equation:

$$RP = \left(1 - \frac{q}{q_{max}}\right) \cdot 100\ \%$$

In the previous equation, the quantity qmax represents the distance of the failure surface for a specific stress state. The quantity q represents the distance of the stress point for the same stress state.
The effect of the earthquake is modelled by applying the maximum value of seismic acceleration at the dam site in two orthogonal directions, for 1000 years return period. Occurrence of earthquakes in the southeast Europe yields a growing concern to the operators of the large complex reservoir systems, as in last decade multiple significant earthquakes have been recorded: Serbia 2010-5.5 MMS, Albania 2019-6.4 MMS, Croatia 2020-6.9 MMS, etc. Apart from the apparent risk to the safety of the structures, significant risks related to the reduced functionality of these systems need to be addressed and analyzed in detail. Particularly, for the complex reservoir systems like Pirot, nowadays special attention is being allocated to hydro energy harvesting, flood defense, and

drinking water distribution. In the case of the Pirot reservoir, three key elements whose damage, induced by earthquake, affects the functionality of the system have been identified: the grout curtain, the overflow and the spillway. The results of the functionality analysis of the individual elements of this system represent the input data in the analysis of system dynamics, the realization of which is carried out, by applying the concept of dynamic resilience.
The 3D model of the dam and surrounding rock mass (Figure 11) was developed on the basis of geometry, engineering-geological structure of the terrain and exploitation conditions in accordance with the requirements of numerical solvers. Numerical analysis of filtration processes and strength analysis were performed using the software package PAK.

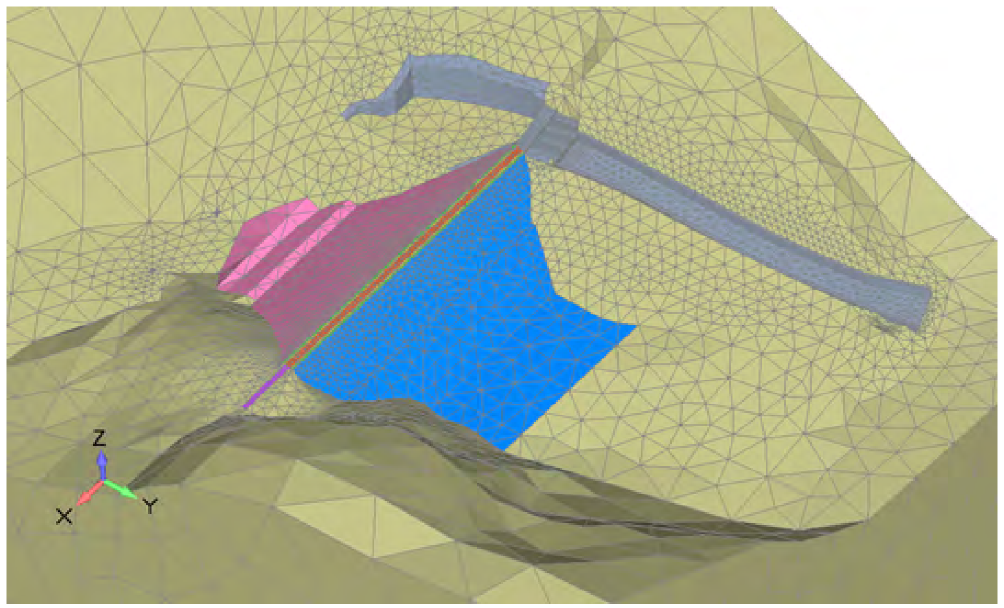

Figure 11. Finite element model of the Zavoj dam.

In order to conduct a numerical analysis of the impact of damage to individual dam elements on the functioning of a complex multi-purpose reservoir system, the identification of the potentially weak structure elements was performed. As structure elements whose potential loss of functionality would affect the operation of this multipurpose system, the impact of damage to the grout curtain on leakage under the dam, damage to the overflow zone, as well as damage to the rapids was analyzed. By changing the coefficients of filtration, it is possible to establish the dependence of the amount of water that leaks under the dam body as a function of reservoir water levels and the damaged zone of the grout curtain. The strength analysis of the overflow gates zone should provide an answer as to whether these parts of the structure can be damaged by the seismic loads and jeopardize the functioning of segment gates. If there is a possibility of such damage, their impact on the function of the elements for water evacuation will be analyzed. In addition to exceeding the strength of the concrete overflow under the acting of seismic load, the functioning of these elements may be endangered by the total or partial loss of stability of the slope above the spillway. Loss of stability of this part of the structure could cause a reduction in the overflow capacity, which would jeopardize the normal functioning of the dam and lead to compromising its stability.

For all conducted analysis of stability, the remaining load-bearing capacity was calculated. In the conducted analysis, it was adopted that in all finite elements in which the bearing capacity is less than 2.5%, there is a high possibility of local loss of stability and their collapse. This is especially important in areas where the loss of local stability would jeopardize the functioning of other elements of the system. One of such elements is spillway. The spillway was divided lengthwise into ten parts, so that the length of one segment approximately corresponds to the width of the spillway section. The volume of the slope above the spillway was divided in the same way. The volume of rock mass elements in which the remaining load-bearing capacity is below the adopted limit is compared with the volume of the corresponding spillway segment. The ratio of the volume of the spillway segment and the volume of the finite elements of the slope that have lost load-bearing capacity is presented as the degree of functionality reduction of the spillway segment, accordingly, the spillway functionality of the segment was calculated as:

$$C_i = \left(1-\frac{V_{i,sl}}{V_{i,sw}}\right)100\%$$

where Ci represents the capacity of the i-th segment of the spillway, Vi,sl is the volume of finite elements of the i-th segment with remaining load-bearing capacity less than 2.5%, and Vi,sw is the volume of the i-th segment of the spillway.

The analysis of the influence of seismic load intensity on the spillway capacity reduction was performed for different values of seismic acceleration. The results of this analysis are presented as the dependence of the spillway capacity on the magnitude of the seismic acceleration (Figure 12).

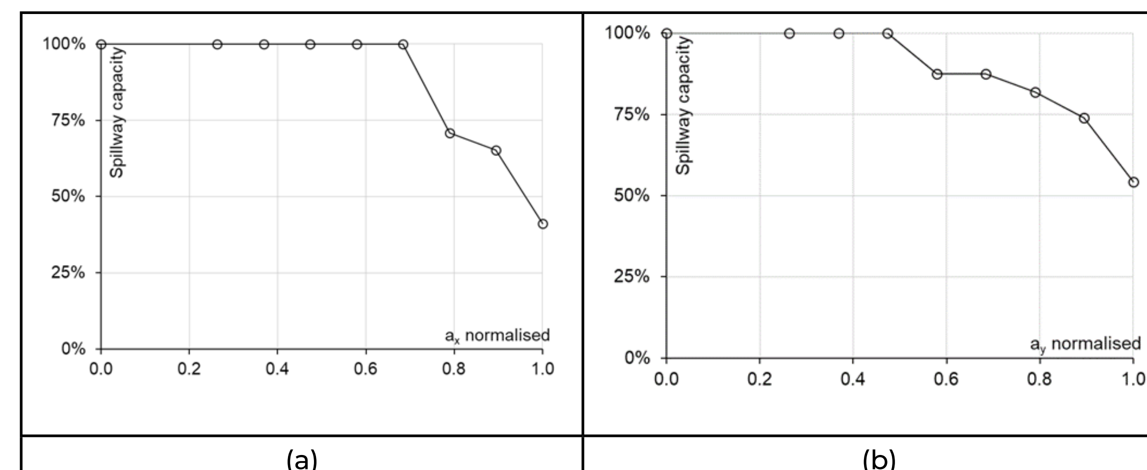

Figure 12. Spillway capacity vs. seismic acceleration in: (a) x direction, (b) y direction.

Based on the dependence of the spillway capacity on the value of seismic acceleration in two orthogonal directions, the effective capacity was calculated, so the capacity for the worst case was used. The dependence of the effective spillway capacity on the seismic acceleration value is shown in the next Figure.

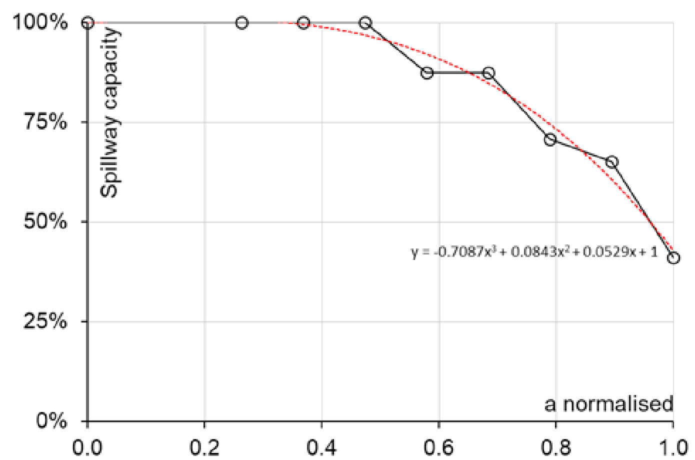

Figure 13. Effective spillway capacity vs. seismic acceleration.

The dependence formed in this way can be approximated by a third-degree nonlinear equation:

$$C = 1 + 0.0529a + 0.0843a^2 - 0.7087a^3$$

where "C" represents the spillway capacity, while the quantity "a" represents the normalized value of the maximum seismic acceleration (from 0 to 1). This approximation represents a surrogate model of the FEM model behavior, which can be used in the assessment of dynamic resilience of the analyzed multipurpose reservoir system.

Assessing Dynamic Resilience Under Hazardous Events using Digital twin of the water system, Artificial Neural Networks, and Data generated

A general increase in available data and computing capacity attracts large interest in digital twins, especially in the water resources sector[12]. The term "digital twin" refers to a digital replica of a physical system providing a digital representation of a specific part of the water system (e.g. water facilities, hydropower plant, spillways). It uses real-time measure data to simulate expected or critical physical water system behavior beyond the design water system envelope.

Our research utilizes a digital representation of the Pirot water system, based on a chain of models, to assess the dynamic resilience during hazardous events. The chain of models consists of the hydrograph model describing the flood dynamics over the simulation time, earthquake failure model to simulate the impact of earthquakes on the element of the system reservoir and system dynamics (SD) simulation model to mimic the non-linear behavior of the reservoir system[13].

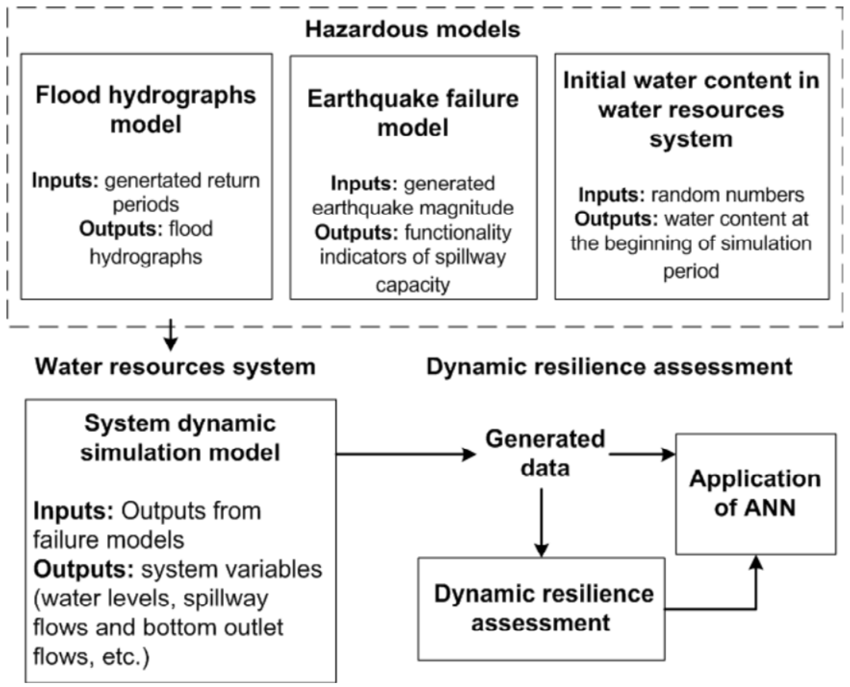

Figure 14. A general approach for evaluation of flood dynamic resilience for the water resources system under hazardous events.

12 Borja Valverde-Pérez et al. 2021. Digital Water: Operational digital twins in the urban water sector: case studies. International water association. London E14 2BE, United Kingdom.

13 M. Stojkovic, D. Marjanović, Dragan Rakić, D. Ivetić, Višnja Simić, N. Milivojević, S. Trajković. 2022. Assessing Water Resources System Dynamic Resilience Under Hazardous Events using Artificial Neural Networks (submitted to the Journal of Hydroinfromatics)

Then, the dynamic resilience model is used to estimate the risk of the water system related to flood events with varying return periods followed by a decreased capacity of water system elements brought about by earthquakes. Finally, an artificial neural network (ANN) is employed to determine the related risks enabling a real-life application at the decision-making scale.

The hydrograph model generates a flood hydrograph that is used as an input into the SD model. Flood hydrograph generation consists of three steps; First, a flood magnitude (expressed as a return period) is generated from existing hydrological data. Secondly, a theoretical flood hydrograph shape is approximated by the Gumbel distribution. Finally, using the flood magnitude and shape of the flood hydrograph, flood hydrographs are generated using Monte Carlo simulations with predefined upper and lower bounds.

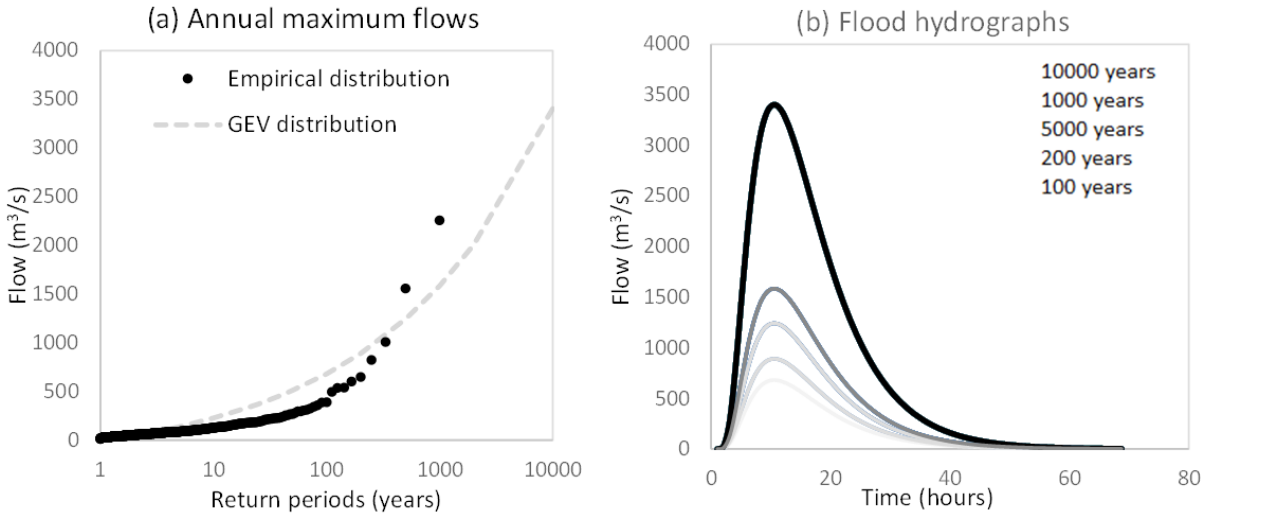

Figure 15. Annual maximum flows (a) and flood hydrographs for different return periods (b) at the Zavoj reservoir (Pirot water resources system).

The earthquake failure model generates varying earthquake events in order to thoroughly assess adverse effects on the reservoir system. The model itself is used to determine the dependence between the magnitude of the earthquake and the functionality of the system, as expressed by a functionality indicator, which describes a physical drop and corresponding effects in the system operation.

The SD model with a causal loop is developed to mimic the behavior of the water resources system representing the digital twin of the Pirot water system. The digital twin mimics a multipurpose water resources system with a focus on flood management reservoir roles. Additional water management roles are also incorporated within the digital twin allowing for the control of the discharge to suit the demand for hydropower generation, ecological flow improvements during low-flow periods, and losses from the water resources system.

The dynamic resilience model is utilized in order to capture several significant numerical characteristics during a disruptive event that poses a serious threat to the water resources system and its belonging elements. The most important of those characteristics are robustness and rapidity. Robustness represents the system's ability to resist disturbance, whereas rapidity is the system's

ability to return to a pre-disturbance level of functionality. Once a water system is unable to provide the required services under a hazardous event, its dynamic resilience starts to decrease, the minimal value to which the dynamic resilience of a system drops represents the system's robustness. Upon the conclusion of a hazardous event, its dynamic resilience begins to increase, and a system with a higher adaptive capacity will take less time to return to its pre-disturbance state of functionality. This adaptive capacity is represented through rapidity, which is measured from the initial drop in dynamic resilience to a complete return in functionality.

Using a randomly generated set of hazardous events with different impacts on the element system, an ANN is employed to extract the information about the flood dynamic resilience of the system. Accounting for the fact that the flood dynamic resilience depends on hazards with variable magnitude, time of occurrence, and duration, there is a need to generalize the assessment of dynamic resilience using an ANN. The biggest advantage of the NARX ANN is its ability to provide the information on the dynamic resilience of a system in a timely manner, enabling the prediction needed to perform adequate strategies aimed at reducing the adverse effects of the hazardous events. The utilized NARX ANN architecture has its advantages in its ability to account for the temporality of hazardous events, thus giving a more accurate representation of the dynamic resilience of a system following hazardous events. The ANN takes the maximum value of the flood hydrograph, the functionality indicator (which represents the earthquake) and the initial water state in the reservoir as inputs and attempts to reconstruct the robustness and rapidity of the water resources system. The optimization algorithm used is Levenberg-Marquardt, along with the sigmoid activation function.

The digital twin of the Pirot water resources system is implemented on an hourly basis, using system dynamics software (Vensim), to provide an adequate response to dynamic hazardous events. The data used for ANN training encompasses 1000 independent simulations of coinciding hazardous events with low joint probability distributions, as well as the system response to those hazardous events. The choice of 1000 simulations was influenced by the need to cover a large span of hazard magnitudes.

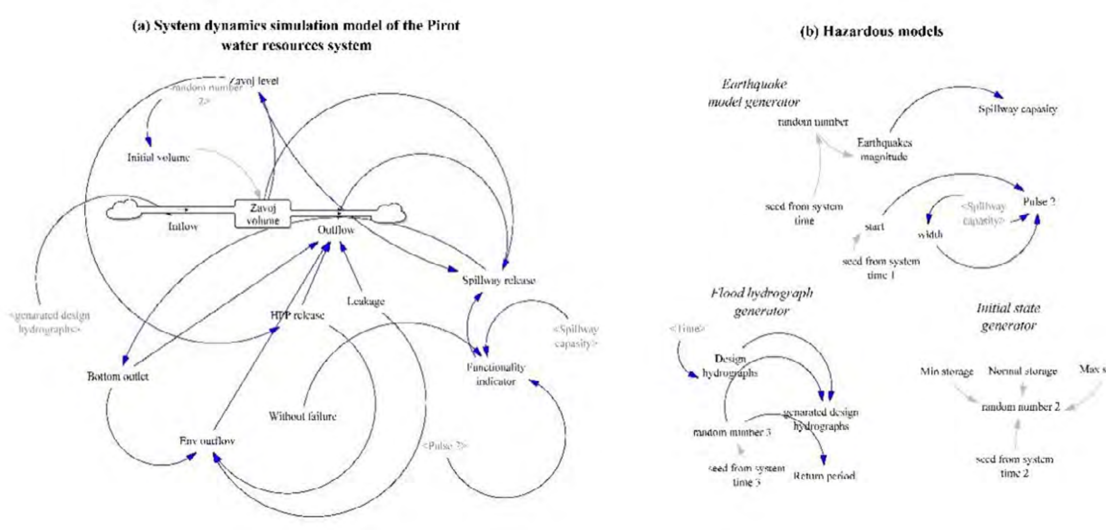

Figure 16. System dynamics model of the Pirot water resources system (a) alongside hazardous models (b).

From the 1000 simulations, the most extreme hazard combination consists of a hydrograph peak value of 3233 m3/s, corresponding to a return period of 6183 years, with a significant earthquake magnitude. This combination corresponds to a flood dynamic resilience decrease to roughly zero (the minimum value of robustness equaling to 0.03 given in Figure 1a) As expected, considering the magnitude of this flood event, the water levels in the Zavoj reservoir and spillway outflows reached the highest possible values. During these extreme flood events, the bottom outflow facility also reaches the highest possible value of discharge. Please note that the total capacity of the bottom outflow (80 m3/s) is substantially lower than the spillway capacity (1820 m3/s). For this extreme case, to retrieve system functionality under such severe hazards the rapidity of the Pirot water resources system reached 1000 hours (Figure 1b). In the case of moderate hazards, system robustness has a median of 0.2 (Figure 1a), while the median rapidity was equal to 162 hours (Figure 1b).

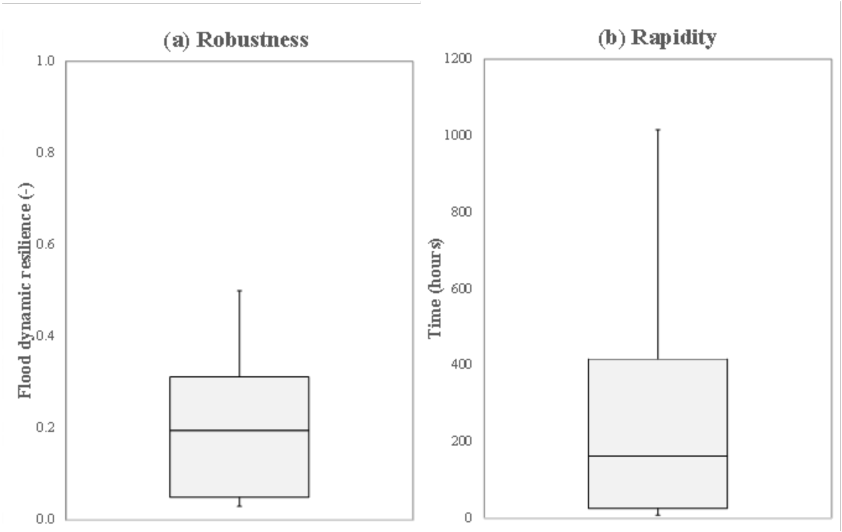

Figure 17. Flood dynamic resilience of the Pirot water resources system using the generated dataset of 1000 simulations: robustness (a) and rapidity (b).

The ANN employed to model the dependencies between hazardous events with different impacts on the system elements and flood-risk metrics (robustness and rapidity) contains 3 hidden layers of 4 nodes each, and 2 output nodes. The network is fully connected, and the hidden, as well as the output layers activation functions, were all sigmoid. The Levenberg-Marquardt optimization algorithm consisted of 1000 epochs. The ANN's inputs are: The maximum value of the generated flood hydrograph, (2) the reduction of the functionality indicator (), and (3) the initial state in the Zavoj reservoir. The dataset was split into 3 subsets: the training set, validation set and test set using a 70%-15%-15% split, respectively.

The metric used to quantify the efficacy of the ANN approximation is the relative error of the approximation. For robustness, that relative error is equal to 2.14%, whereas for rapidity that relative error was equal to 1.77%. Moreover, the RMSE values for robustness and rapidity are equal to 0.004 (-) and 12.7 hours, respectively. While the RMSE for rapidity may seem significant, considering the timespan in which rapidity fluctuates, such an error is not substantial.

The results of the training suggest that it is possible to train a network to approximate the rapidity and robustness of a system. Especially in the case of rapidity, where the approximation highly matches the target values. While the real system is susceptible to measurement errors, the timescale of rapidity allows for such errors to occur without significantly affecting resilience predictions. The same cannot be said for robustness, which the network cannot capture as efficiently due to the rapid changes in flood dynamic resilience after a disturbance is introduced.

Explainable genetic fuzzy rule-based system for resilience assessment

Assessing the resilience of a complex water resources system to hazards can be achieved using a prediction metamodel, obtained by learning from the data collected through the numerous simulations of the system's dynamics (SD) model and hazard models. Despite the remarkable advancement of the most popular Machine Learning (ML) algorithms, their resulting predictive models often lack transparency and interpretability. Techniques such as artificial neural networks and random forests generate black box models which do not provide an explanation for the decisions they will take and cannot help in understanding the dependencies between adverse events and the system's resilience. For Artificial Intelligence (AI) to be trusted, greater transparency can be provided by the means of explainable AI (XAI) systems. Explainability can be ensured via Fuzzy Rule-based systems (FRBSs) that are intrinsically understandable and comprehensible. FRBS consists of a set of IF-THEN rules expressed in natural language which serve as a part of Knowledge Base (KB) for Fuzzy Logic-based inferencing. KB can be generated using expert knowledge or learned from the data. The process of learning an FRBS can be viewed as finding the set of linguistic rules that, based on the data, best represents a relationship between input and output. Searching for the best set of rules is guided by the optimization of a given performance metric. Having the optimization task in mind, the automatic learning of an FRBS can be performed by the means of a Genetic Algorithm (GA) which is a powerful evolutionary global search technique.

The aim of our research was to enable the user to easily understand the cause-and-effect relationships of hazardous events, their timing, and intensity that can lead to a water resource system failure. To achieve this, an XAI general framework was developed for assessing the resilience of water systems to hazards and system element failures. The simulation data of the system's dynamics (SD) model and hazard models which introduce the temporal coincidence of unfortunate events (earthquakes, floods, and changeable water content in reservoir) was used to learn the FRBS via GA. Hence, the FRBS became a metamodel of the original system's model and its behavior under the hazard. The advantage of using a metamodel comes from the fact that once it has been trained, it can be used independently of the original SD model and hazard models, avoiding costly simulations to reason about the resilience of the water resource system. It is important to point out that the data-driven generation of FRBS does not rule out further

refinements using experts' opinions, but rather allows expertise to be incorporated into the FRBS in a natural and transparent way, by translating it into fuzzy IF-THEN rules.
A general workflow of developing and using the explainable FRBS for assessing the resilience of a complex water resources system to hazards is depicted in Figure 18.

The workflow includes the following four phases:

Phase 1.
The dataset is split into the training set and the test set using a 70%-30% split, respectively. The data for these subsets are selected randomly to preserve generality.

Phase 2.
The training data are used for fuzzy partitioning of input and output space, that is creating the database of the membership functions (MFs) which model the linguistic terms for each numerical feature of all inputs and all outputs. For example, a numerical (crisp) value of flood hydrograph peak (Q_{max}) can be described in linguistic terms as *low*, *medium*, or *high*, using a corresponding fuzzy set for each term. A fuzzy set is defined by its membership function, with the membership gradually transiting from 0 to 1 to describe vagueness and ambiguity common in natural language. MFs for each feature are created using the algorithm for learning MFs from data presented in the paper by Bhatt et al[14]. Obtained MFs are used for determining the membership degree of the crisp feature values of the training data to each fuzzy partition. For example, according to the MFs for the aforementioned fuzzy sets *low*, *medium*, and *high*, a crisp Q_{max} value of 2500 m^3/s could, at the same time, belong to the fuzzy set *medium* and to the fuzzy set *high* to a degree of 0.4, and 0.7 respectively.

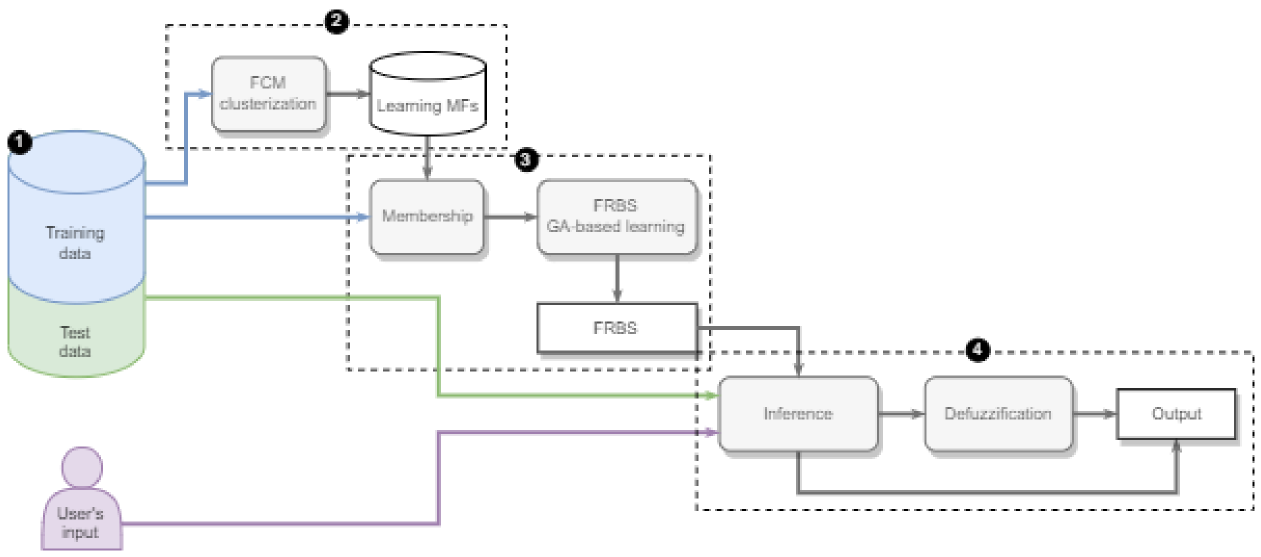

Figure 18. A general workflow of developing and using the FRBS for assessing the resilience of a complex water resources system.

14 Bhatt, R. B., Narayanan, S. J., Paramasivam, I. and Khalid, M. (2012, December). Approximating fuzzy membership functions from clustered raw data. In 2012 Annual IEEE India Conference (INDICON) (pp. 487-492). IEEE.

Phase 3.
The membership values of the training data are utilized for learning the FRBS through the evolutionary learning procedure based on GA[15]. The process results in the complete FRBS knowledge base which includes MF database and a rule base.

Phase 4.
The FRBS created in Phase 3 is tested using test data as an input to the fuzzy inference system. The max-min Mamdani inference method is employed. Crisp test data values intersect the antecedent membership functions of certain rules at some membership level. The minimum of all membership values determines the consequents' membership functions of matched rules. Aggregation (union) of all membership functions from each matched rule yields the overall conclusion in the form of a fuzzy set, which can be defuzzified to a crisp value to produce a final output. Once the FRBS is learned and tested, it can be used for inferencing with new, user-provided data, for predicting the system's resilience.

For the testing purposes of the proposed framework, we used the simulation data of the Pirot water system SD model. The data contains 220 input-output pairs where each input is a vector of 6 numerical values measuring the flood hydrograph peak value (Q_{max}), the corresponding return period (T), the initial water volume in the reservoir (V_{init}), the temporal distance between the flood peak and the earthquake start time (t_{dist}), the earthquake duration (t_e), and the normalized value of the maximum seismic acceleration (). The output is a vector of two numerical values: robustness and rapidity. The data were randomly split into training and test data. In phase 2 of the abovementioned procedure, we obtained the MFs for all inputs and outputs, and in phase 3 the rule base comprising 24 rules was created. An example of the fuzzy IF-THEN rules for the prediction of robustness and rapidity is given in Figure 19. It can be noticed that the interpretability degree of FRBS is very high and that linguistically described fuzzy partition of the input and the output space correspond to the intuitive idea of those linguistic terms.

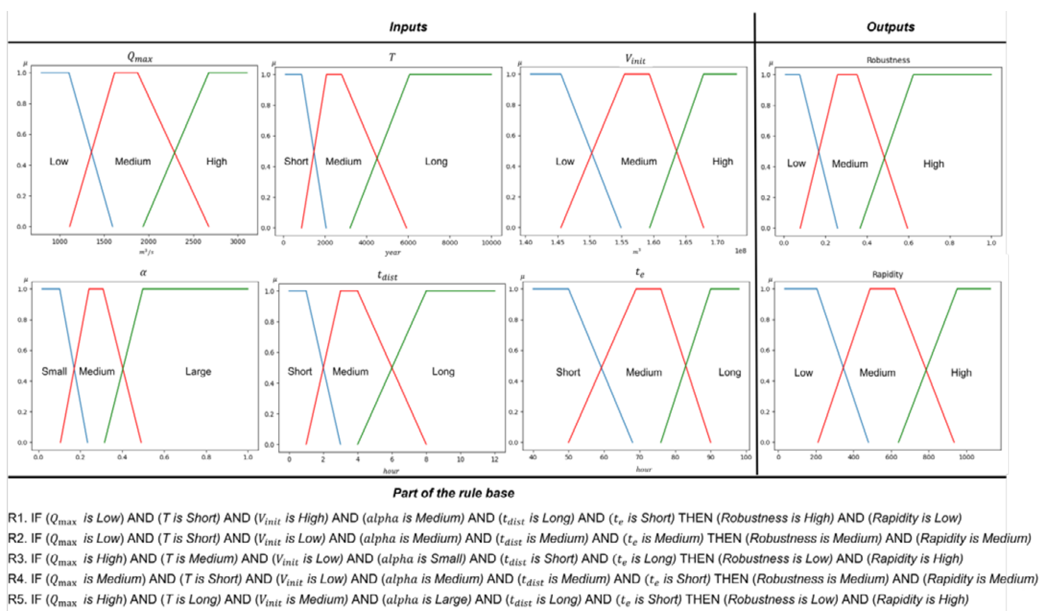

Figure 19. Membership functions for fuzzy sets that correspond to linguistic terms for describing input and output values. Part of the rule base generated from the training data using GA-based learning.

15 Yuan, Y. and Zhuang, H. (1996). A genetic algorithm for generating fuzzy classification rules. Fuzzy sets and systems, 84(1), 1-19.

Python Scikit-Fuzzy fuzzy logic toolbox was used to implement the obtained FRBS and enable inferencing with the test data. The performance of FBRS was analyzed in terms of system accuracy when it comes to assigning the output values of the test data to the correct fuzzy set. The achieved accuracy was 95%. This is a favorable result that showed that it is possible to develop a successful decision support tool with XIA fuzzy metamodel by GA-based learning from the simulation data. Hence this approach constitutes a very promising contribution toward bringing great predictive power to assess the resilience of complex water and infrastructure systems to hazardous events and benefits water management practitioners.

Environmental resilience under climate change

To assess the environmental resilience of the urban water systems, the chain of models (Figure 20) is used consisting of the weather@home2 climate modeling framework, DECIPHeR hydrological modeling framework as well as the CityWat urban system water model[16]. First, the performance measures from the CityWat model are selected to assess the sub-system and overall environment resilience. Next, the same performance measures are used to estimate reliability of an urban water system aiming to benchmark the proposed approach for the environmental resilience assessment against the traditional risk-based approach.

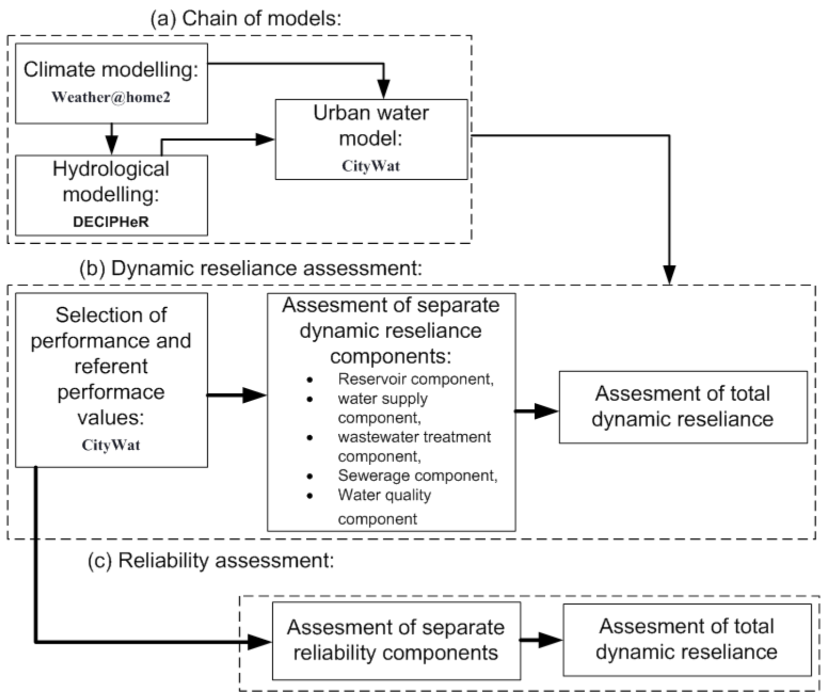

Figure 20. Assessment of environmental resilience using the chain of the models: (a) chain of models, (b) Environmental resilience assessment, (c) Environmental reliability assessment.

16 Dobson, B., Mijic, A. (2020). Protecting rivers by integrating supply-wastewater infrastructure planning and coordinating operational decisions. Environmental Research Letters, 15(11), 114025.

A framework for the environmental resilience of the urban water system is implemented within the Vensim software (Vensim, 2022). This software enables effective climate-related risk framework development by cause-and-effect diagramming as well as graphical and textual model construction of the interconnected variables (Ignjatović et al. 2021). A scheme of the developed framework is provided on Figure 21.

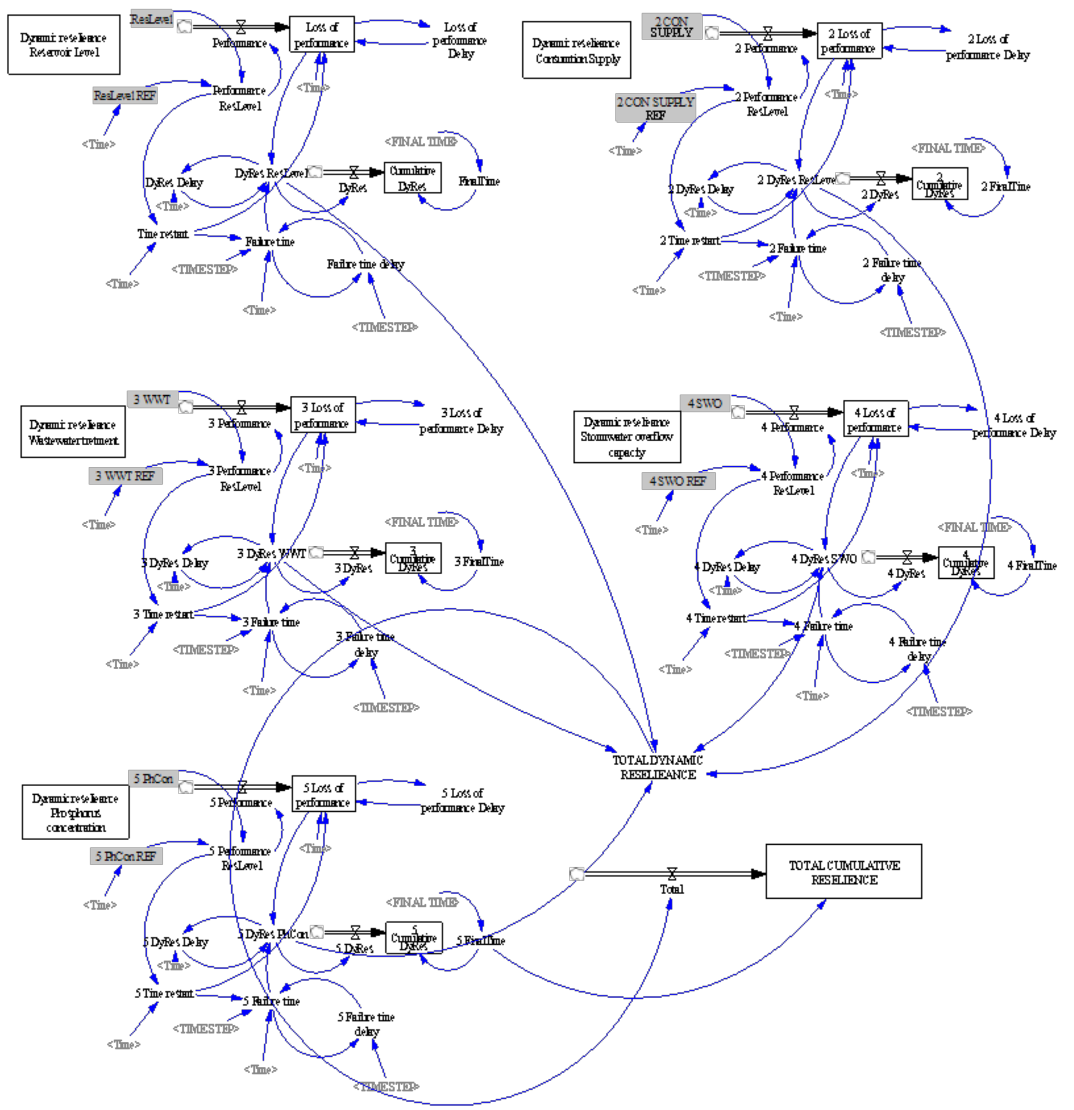

Figure 21. Implemented framework for sub-system and total dynamic resilience assessment of the urban water system.

As the input for dynamic resilience assessment, the proposed framework uses variables simulated by the CityWat model. Considering the selected variables from the CityWat model, it simulates the sub-system and overall environmental resilience for the baseline (1975-2004) and near future time frames (2020-2049) by respecting the performance measures defined for each system part. To select the performance measures, the urban water sub-system components are linked with the simulated variables. For instance, the reservoir sub-system component considers the water content in the reservoir, while the phosphorus concentration represents the water quality sub-component. Overall outflows from the drainage system are selected to describe the behavior of the sewage system part. Moreover, the water supply sub-component is defined by the simulated consumers supply. Wastewater outflow from the wastewater treatment plants is chosen to represent the waste treatment sub-component.

The results indicate an expected reduction of 10.5% of the overall urban water system environmental resilience within the near future period (2020-2049) compared to the referent period (1975-2004). The most significant environmental resilience reduction is expected for the water quality (15.4%) and reservoir parts (13.6%) of the urban water system. On the other hand, environmental reliability follows the results obtained from the proposed concept suggesting the reliability redaction equal to 6.8%. However, reliability does not consider the recovery time needed for reaching full system functionality and consequently underestimates the climate-related risks of the urban water system.

Conclusions

The proposed framework brings great predictive power to assess the resilience of a complex water systems to hazardous events (e.g. floods) 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. The proposed research significantly advances 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 contributes 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. 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 is incorporated in the final results. 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 is 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 outperforms 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 is 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. 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, 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 advances contemporary hydro-environmental knowledge.

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

Acknowledgement

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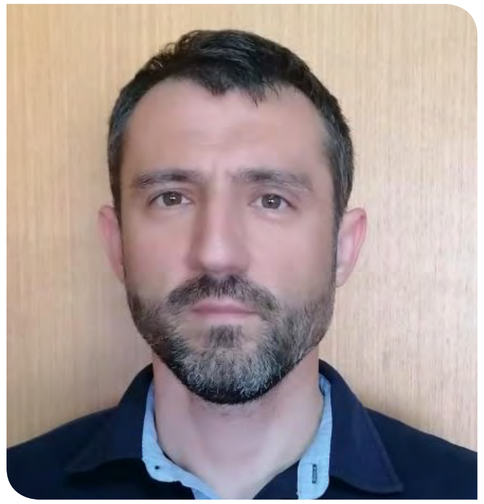
Principal investigator

Research fellow, dr MILAN STOJKOVIC, dipl. Civil Eng.

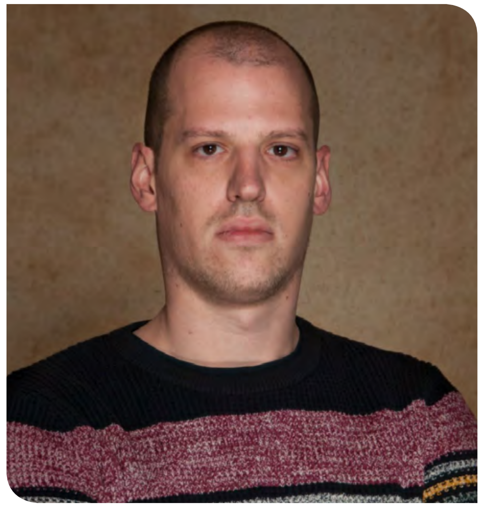
Dr Stojković has been working at the Jaroslav Černi Water Institute as a Research Fellow for the last 13 years. Prior to conducting postdoctoral research at the University of Western Ontario (Canada) in system dynamic and climate change impacts, he obtained a doctoral degree from the Faculty of Civil Engineering (University of Belgrade) in stochastic hydrology. From his research, dr Stojković published the monograph "Stochastic modeling of hydrologic time series" and 18 papers in top-ranking peer-reviewed journals.



Team member

Associate prof. DRAGAN RAKIC, dipl. Mech. Eng.

Prof. Rakic is engaged in teaching courses of applied mechanics on Faculty of Engineering University of Kragujevac. His field of research relates to the application of numerical methods in the dam and tunnel stability, and constitutive modelling of geomaterials. He has gained experience in a number of studies of stability of embankment and concrete dams, tunnel stability and stability of other geotechnical structures.



Team member

Assistant prof. DAMJAN IVETIĆ, MA Civil Eng.

Damjan is assistant professor at the Faculty of Civil Engineering, University of Belgrade. He is conducting courses in Measurements in hydraulic systems and Fluid Mechanics. Focus of his research is in the field of the measurement uncertainty assessment and hydraulic system monitoring and modelling, especially in the dam and reservoir, sewer and drinking water distribution systems. He has published 7 papers in top-ranking peer-reviewed journals

Team member

Assistant prof. VIŠNJA SIMIĆ, dip. Math.

Dr Višnja Simić is an assistant professor of artificial intelligence and machine learning at the Department of Mathematics and Informatics, Faculty of Science, University of Kragujevac. With B.Sc. in Mathematics and Informatics, she has received a Ph.D. in Computer Science in 2016. She is the co-author of several papers published in international peer-reviewed journals and conference proceedings and has participated in research projects funded nationally and by the European Union.

Team member

LAZAR IGNJATOVIĆ, MA Civil Eng.

Team member Lazar Ignjatović, MA Civil Eng. Lazar Ignjatović is working as a research engineer at the Jaroslav Černi Water Institute for five years. He has experience in hydrological and hydraulic modeling, GIS application in water management, water quality modeling, water supply and sewerage systems design, hydroinformatics and water systems resilience.

Team member

LUKA STOJADINOVIĆ, MA Civil Eng.

Luka Stojadinović is employed as a research engineer at Jaroslav Černi Water Institute, where he is involved in development of various hydroinformatic systems. His focus is on hydrologic and hydraulic modeling, modeling of complex water systems, data science, model integration etc. He is also a PhD candidate.

Project team associates

Dr NIKOLA MILIVOJEVIĆ,
dipl. Mech. Eng.

Dr Nikola Milivojevic is a president of the scientific board and executive director of the Jaroslav Černi Water Institute. He has experience in research, IT and management. His key qualifications include information system design, mathematical modeling and simulation, programming, database design, optimization, data assimilation, and project management.

Dr BRANKICA MAJKIĆ-DURSUN,
dipl. Geol. Eng.

Dr Brankica Majkić-Dursun is a water protection expert, research associate, employed in the Jaroslav Černi Water Institute. She has a multi-disciplinary background and experience in the water management and environmental engineering sector. She has experience in scientific research of new methodologies, groundwater processes in alluvial aquifers, resolving problems with groundwater exploitation and water well ageing. From 2019. she is a director of the WSDAC Category 2 Centre under the auspices of UNESCO.

DUŠAN MARJANOVIĆ,
MA Civil Eng.

Dušan Marjanović is a PhD candidate at the Faculty of Civil Engineering, (University of Belgrade) specializing in the fields of Hydroinformatics, Fluid Mechanics and Hydraulics.

Belgrade, Serbia
July, 2022