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Engineering Approach to Assessing the Vulnerability of Water Abstraction

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Abstract: Variability in stream flow/discharge results in serious problems for engineers and difficulties in characterizing water systems under future climatic conditions. The management of water security in the engineering domain requires approaches aimed at minimizing the detrimental effects of the hydrological behavior of natural systems. Abstraction facilities must be strengthened to ensure sustainable supply and water security over time and at different scales. Several approaches and methodologies have been developed to translate water security into a framework that provides information on how to improve it. In this study, a scalar range idea is used to evaluate the sensitivity of a water resource system and cause–effect linkages define the vulnerability indicator as management-relevant information to address water security. This intuitively relates the extreme deviations of a particular streamflow to the average system response related to a particular hazard indicator. This determines the current stress in the operation of the abstraction facilities based on historical hydrometeorological changes, which is the basis for assessing future operational conditions and risks. This study uses streamflow extremes and averages as hazard-relevant indicators of water supply security. The results of the two case studies show that the applied approach fully appreciates the internal properties of water resource systems that affect the sensitivity/vulnerability of streamflow, as well as the derived streamflow vulnerability index and function. The obtained results were used to assess the vulnerability of water intake as well as the choice of safety factors and design parameters in accordance with the forecasted average annual and seasonal climate factors.

Keywords: water resource systems; streamflow vulnerability; engineering approach; water abstraction performance; climate change; water security

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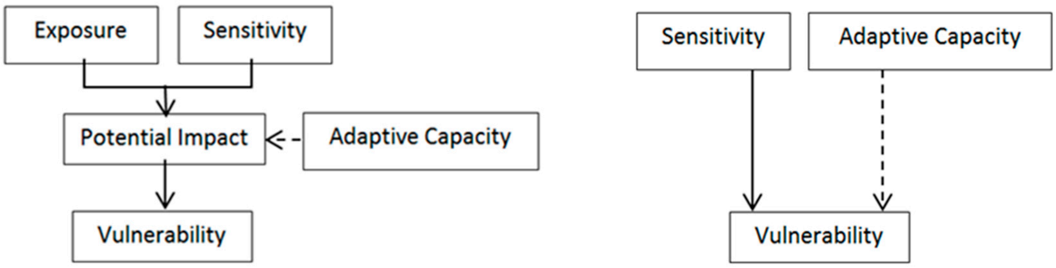
1. Introduction

In recent years, the issue of the impact of climate change on water security has become an important topic [1–4]. The great variability in natural water supply and water demand results in serious problems for engineers [5]. In the planning process for adapting or adjusting to the actual and expected climate and its effects, climate-related vulnerabilities and risk assessments are important. Such assessments are designed to identify adaptation options and measures. These approaches are generally classified into two groups: top-down modeling assessments and bottom-up threshold analyses [6]. To date, most top-down scenario-led impact assessments have been applied to select optimal solutions [7]. These approaches are based on climate projections and GCM downscaling to predict the impacts of climate change. These methods have proven to have little practical use in site-specific water resource management and water infrastructure project design decisions at the local level [8]. In contrast to the top-down approach, bottom-up climate assessments begin in the vulnerability domain and assess particular climate impacts using the best available or prescribed climate information [8]. Such approaches do not consider climate projections and are intended to assess the current sensitivity and vulnerability of a water resource system as a basis for water structure and system vulnerability. The bottom-up approach generally seeks robust strategies that perform reasonably well in a wide range of uncertain future scenarios. This approach was used in this study.

These approaches relate to the vulnerability framework proposed by the Intergovernmental Panel on Climate Change (IPCC). To date, two frameworks have been proposed, the first in the *Fourth Assessment Report* (IPCC 2007) [9] and the second in the *Fifth Assessment Report* (AR5) (IPCC 2014) (Figure 1) [10]. In the IPPC 2007 framework, vulnerability is conceived as a function of exposure, sensitivity, and adaptive capacity, while IPPC 2014 separates exposure from vulnerability, and vulnerability is therefore a function of sensitivity and the capacity to cope and adapt. Both frameworks have been widely used, depending on the risk assessment context and approach [11].



(**a**) IPPC paradigm; "top-down" approach. (**b**) IPPC 2014 paradigm; "bottom-up" approach.

Figure 1. The concept of vulnerability as presented in the IPPC 2007 and 2014 reports (solid arrows show positive functional relationships with vulnerability, while dashed arrows show negative functional relationships).

The top-down method projects future climate conditions specific to the watershed of concern, i.e., assessed exposure: "The nature and degree to which system is exposed to significant climate variations" [12]. Precipitation feed-in system Global Climate Models (GCMs) frequently provide streamflow outputs, enabling the assessment of the performance of water-supply systems in a changing climate [13–15]. This is a top-down, data-driven approach to the concept of vulnerability presented in the IPCC report (2007) (Figure 1a).

Different approaches and methods have been used, including the scenario approach, climate sensitivity methods, paleoclimate studies, historic climate observations, and theoretical models (hydrothermal-coupled equilibrium) [6]. These approaches are computationally and resource-intensive. In addition, the transformation of climate data into long sequences of runoff data and data on possible variations in runoff resulting from climate change is not possible. Therefore, the statistical distribution of future conditions is unknown or cannot be trusted. Therefore, it is necessary to apply a simplified and robust approach. This enables a bottom-up approach that generally favors robustness over optimality. This approach was used in this study.

The bottom-up approach generally integrates methods for climate risk assessment and robust decision analysis with risk management procedures. The procedure is flexible and adapts to a local problem-solving framework and the available information and knowledge. In this approach, climate change vulnerability assessments are based on the knowledge of the system itself (water resource systems, water abstraction facilities, and utilities). With this mixed-methods approach, a qualitative and semi-quantitative system assessment can be conducted to determine which system components and parameters are potentially vulnerable to change and to what degree. An engineered system has to be determined to satisfy the minimum performance criteria over a wide range of uncertain future scenarios. Therefore, it is necessary to assess the current condition, vulnerability, and sources of vulnerability to identify portfolios that address these vulnerabilities under existing and different climate change scenarios. It is important for engineers to determine the possible range of future flow extremes, average variations, and factors of safety (FOS) to be adopted in the planning period to maintain the required water system within regulated limits. This approach was used in this study. It is a specific type of decision scaling approach in which decision scaling is a systematic bottom-up approach used to align climate change adaptation designs with traditional engineering planning.

The approach used in this study is based on historical streamflow data and an assessment of the internal properties of the water resource system, which is more suitable for engineering practice (Figure 1b) [10]. This robust approach is suitable for unknown or untrusted future conditions. This approach facilitates the assessment of the vulnerability of a system because it considers vulnerability to be an internal property of a system that is independent of physical events. Hazards were anticipated by selecting hazard-relevant indicators for the sensitivity and adaptive capability of the system to be used in vulnerability and risk assessments.

Indicators are used to address the sources of vulnerability and resilience in the system. The applied approach examines natural system vulnerability independently in accordance with river system characteristics (without considering economic and human social issues) and technical system vulnerability, which considers the socioeconomic, environmental, and technical framework of the water infrastructure (Figure 2). The assessment of technical vulnerability, water security issues, and risks takes into account the vulnerability of the water resource system (streamflow), these include "the potential consequences where something of values is at stake and where outcome is uncertain, recognizing the diversity of values" [10]. This comprehensively presents the adaptation and sustainability challenges related to water management, upstream and upstream from the water extraction point and downstream, which includes water withdrawal.

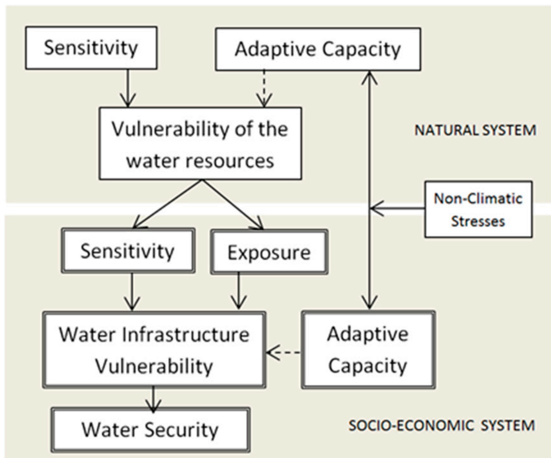


Figure 2. Conceptual framework for water supply vulnerability assessments (solid arrows show positive functional relationships with vulnerability, while dashed arrows show negative functional relationships).

Rivers and socioeconomic systems are dynamic and constantly adapting to climate and other changes. The resulting water security state is a consequence of the interaction between the water resource system (physical) and the socioeconomic system, which addresses water stress and availability, vulnerability to hazards, water demand, and sustainability dimensions, as shown in Figure 2. Key issues are the risk and uncertainty in water resource systems related to streamflow and design parameters. Risk results from the interpretation of vulnerability (a function of sensitivity and adaptive capacity), exposure, and hazard [10]. With this approach, resilience and vulnerability are considered additional engineering performance criteria in the planning process of adapting or adjusting to the actual or expected climate and its effects.

The values of the vulnerability indicators (existing weaknesses and strengths) were based on the historical performance of the water resource system instead of simulating the future performance of the system based on GCM precipitation and temperature predictions. This is the unfolding effort of progressively moving from an understanding of past trends to a projection of probable futures through the explication of present conditions. The key hazard indicators for the vulnerability assessment were the maximum, minimum, and average streamflow. Extreme flows are marginal operating conditions and the issue of risk of engineering structures (water stress and hazard), whereas average flow is an important factor for assessing the risk for the sustainability of water supply, that is, water supply and demand balance.

The three risk performance criteria for evaluating the performance of water supply systems are reliability, resilience, and vulnerability. Reliability is defined as the probability that the system will be in a satisfactory state in the planning period, resilience defines how quickly it recovers from failure, and vulnerability describes the severity of the consequences of failure. These are used for the evaluation, planning, and design of water abstraction facilities in current and future water resource systems, including the selection of safety factors to achieve appropriate safety levels and acceptable physical and economic efficiencies. Traditionally, accounting for uncertainty in engineering design has been based on FOS, followed by reliability-based design in building codes. Therefore, it is important to assess current and future sensitivities, vulnerabilities of water resource systems, and hazard-relevant indicators (extremes and averages) as accurately as possible.

When designing infrastructure for climate change issues, it is crucial to understand the impossibility of defining a hazard using probability distributions a priori. In this regard, a procedure based on the scalar range concept applied to the annual minimum, average, and maximal streamflow as the most appropriate metric for design and hazard-specific indicators was proposed. Based on existing performance metrics, it is possible to create a water resource system performance function that can be used to assess future performance metrics, as envisaged in the proposed approach.

It is a simple and robust approach that offers vulnerability assessment and risk reduction under a wide range of poorly characterized uncertainties. This is a different approach compared with those found in the literature [11,13,16–18] and is based on the relative range assessment of specific annual streamflow and the interpretation of existing and possible future streamflow vulnerability and impacts based on the physical reality and natural behavior of the system and true historical data. This technique is used within specific natural boundaries that depend on the inputs of climatic variables. The focus is on the relevant system and vulnerability indicators and not on the impacts of future climate hazards and scenario analysis. It is accepted that the average size and range of streamflow oscillations in a hydrological year faithfully reflect the historical sequence of climate change impacts, as well as the impacts of non-climatic stresses and previously applied adaptation measures on the water resource system (Figure 2). This is a mixed-methods approach that uses a combination of qualitative and quantitative approaches to determine the cumulative impact of sensitivity and autonomous adaptive response on the vulnerability of water resource systems and associated water abstraction facilities. The integration of both methods helps address and integrate the complex and diverse climate vulnerability issues of natural and local socioeconomic systems.

The resulting effects are inputs for the assessment of complex human–water systems, water security issues, and planning adaptation measures to reduce water infrastructure vulnerability (Figure 2). Normally, actual impacts are much smaller than potential impacts. Therefore, future impact assessments should integrate potential impacts and planned adaptation measures. The future adaptive capacity of a natural system is the result of autonomous adaptation, planned adaptation, and nonclimatic stress. It has been assumed that autonomous adaptation and sensitivity, that is, the flexibility between output and input variations in water resource systems (physical), will not change considerably by natural processes in the long-term planning horizon of adapted water resources (generally 50 years). When the uncertainty is not fully defined or estimated, an attempt is made to determine the future risk of an engineered water system to determine the appropriate FOS. This is an adaptive design approach that attempts to define a "robust" system suitable for the unknown realization of the future and unquantifiable conditions and risks. Priority is defined as the set of measures used to reduce vulnerability to existing climatic conditions and streamflow variability. The selected measures should perform well in future climates and weather extremes by using an appropriate FOS in engineering design. In this study, the Jadro Spring and Krka River in Croatia were used as illustrative examples for the application of the proposed methodology.

2. Materials and Methods

2.1. Assumptions

The magnitudes of the changes in and statistics of future streamflow are not known as future inputs and are subject to changes, watershed characteristics, and other non-climatic factors. Therefore, historical hydrological data are the only reliable basis for assessing the sensitivity, vulnerability, character, and range of changes in streamflow in the future and thus define the possible future range of difficulties and vulnerability of water structures. This retrospective assessment emphasized the historical data and the development of the present data.

To quantify the sensitivity of streamflow/discharge related to climate change and the predictability of given historical time-series data, a scaled range idea was proposed:

$$r = \frac{\max(response) \; - \; \min(response)}{average \; (respnse)}, \tag{1}$$

where the scaled range r is defined as the range of the specific hazard-relevant flow (Q^x) divided by the average response for a given time series. This is related to the extreme deviations of a particular streamflow from the average value, which is an intuitive concept for measuring water resource system performance. The result obtained for r is called the "cumulative sensitivity/vulnerability indicator" k^x, with sensitivity/vulnerability representing a lack of knowledge that is immeasurable and impossible to calculate.

The non-dimensional indicator k^x measures the sensitivity and robustness of hazard-relevant annual streamflow values in a particular climate framework and does not incorporate any effects of other runoff generation processes. By knowing the value of k^x, it is possible to assess future vulnerability and estimate the risk for water abstraction facilities and the order of magnitude of the FOS to be used in system design and/or operation. The indicator k^x was calculated using the following equation:

$$k^x = \frac{Q^x_{max} \; - \; Q^x_{min}}{Q^x_{average}} = \frac{\Delta Q^x}{Q^x_{average}}, \tag{2}$$

where $Q^x{}_{max}$ is the maximum/highest annual value, $Q^x{}_{min}$ is the minimum/lowest annual value, and $Q^x{}_{average}$ is the average annual value of the x discharge or streamflow sample over N years. This indicator represents the relative range/variability in a particular hazard-relevant annual streamflow (Q^x) at the reference point (i.e., the streamflow gaging station). It determines the maximal range of the deviation related to the average value that occurs and presents the cumulative sensitivity and response to past climate input changes. This makes it possible to assess the current stress and vulnerability in the operation of water facilities and to project possible future stress and vulnerability based on the climate model data forecast of $Q^x{}_{future}$. It is essentially an indicator of the magnitude of the change in "specific" outgoing energy variability (discharge sensitivity) from the water resource system related to variability in the input energy induced by net rainfall. In a natural water resource system, streamflow vulnerability is fully integrated by natural processes within the sensitivity and autonomous adaptive capacity framework of the system. That is why the name "vulnerability coefficient" (k^x) is used below.

In the proposed approach, the worst-case scenario (1/N), or the most severe outcome for the water supply from the past period, is covered because bounded extreme values of streamflow data are considered, which is an excellent starting point for developing reliability and resilience related to the impacts of climate change. It is the basis for assessing engineering preferences, including FOS, in accordance with the concept of a "worst-case scenario" for uncertain future climate variables. This information is reliable and directs engineers toward solving the problem of strengthening robustness in relation to the possible magnitude and oscillations in hazard-relevant streamflow. Any major change in the absolute range of streamflow or discharge variability in the future period was detected through the value of the relative range, that is, the change in the index k^x. Therefore, k^x can be considered as a relevant index of vulnerability that can be used to assess the operational reliability and resilience of water abstraction.

The indicator k^x is a scalar variable given by the annual maximum, average, and minimum streamflow data that define the general characteristics of the analyzed hydrological system. Therefore, these values reflect the vulnerability of the water resource system at the reference point, which can be determined and presented by a regression function, where the dependent variable is k^x and the independent variable is $Q^x{}_{average}/Q_{average}$. The fitted regression function of k^x is a continuous function that represents a general system vulnerability function suitable for decision-making under a wide range of future climates based on projected global carbon emissions. Climate change will change the variability/uncertainty in streamflow and the value of k^x; however, the form of the function and order (hierarchy) of the k^x values will be maintained because the order represents the internal system property. The fitted regression function was ultimately derived from the continuous bounded variation function of Q in the finite time interval of the streamflow data sample (N), where the total variation was bounded by extreme streamflow values [$minQ^{min}$, $maxQ^{max}$]. Such a function can be considered a generalized solution to the nonlinear problem of system vulnerability. This implies that the coefficient of determination was $R^2 = 1$.

Thus, the hierarchy of k^x defines the order of magnitude of stress and vulnerability in a water resource system at a reference point. In this way, k^x determines the hazard-specific characteristics of the system at a particular location that integrates the character and magnitude of the variability in the streamflow, and thus the sensitivity and autonomous adaptive capacity, that is, the cumulative vulnerability related to climate change and the impacts of non-climatic stresses in the system. This helps engineers design systems for future frameworks under a wide range of climate scenarios. A robust system must be developed to satisfy the minimum performance criteria for a wide range of uncertain future scenarios.

For engineers, it is crucial to determine the FOS to be adapted during the planning period to maintain the required water abstraction within the regulated limits. This simplifies the resilience design because it favors robustness over optimality. This is a decision-making process in which the main sensitive system variables are the perception of change, the risk to the user, and the desired level of water supply [19].

The statistical distribution of future conditions is unknown or not trusted, which creates a system state of "deep" uncertainty related to future climate conditions and uncertainty about regulatory, environmental, economic, and social conditions. Using forecasted changes in precipitation and temperature/evapotranspiration, the net rainfall (P-ET) can be estimated, future flow can be forecasted $Q^x{}_{future}$, and the coefficients $k^x{}_{future}$ and $D^x{}_{future}$ can be determined using the proposed methodology. This information forms the foundation for assessing the future level of vulnerability of water-abstraction facilities. Such decision-making approaches must define a robust system that satisfies the engineering performance criteria over a wide range of uncertain future scenarios.

This procedure is simple. In accordance with the forecasted changes in net rainfall (± %), the future mean values of hazard-relevant streamflow, $Q_{average}$ (annual), $Q_{min,average}$ (dry period), and $Q_{max,average}$ (wet period) are determined as follows:

$$Q^x{}_{average,future} = ((\pm\ \%)/100 + 1) \cdot Q^x{}_{average,historic} \tag{3}$$

The obtained values were used to calculate the $k^x{}_{future}$ coefficient using the correlation function $k^x{}_{future} = f\,(Q^x{}_{average,future}/Q_{average,future})$. $Q^x{}_{average,future}$ was multiplied by $k^x{}_{future}$ to determine $D^x{}_{future}$, ea. range of $Q^x{}_{future}$ and the difference between the highest and lowest values that define the level of variability and risk for engineered water systems (water abstraction facility):

$$k^{x}{}_{future} \cdot Q^{x}{}_{average,future} = D^{x}{}_{future} \tag{4}$$

The historical and calculated variables were compared and analyzed to gain insight into the level of possible changes in flows and risk. The required FOS sizes were considered for Q_{max} (flood hazard), Q_{min} (drought hazard), and $Q_{average}$ (demand risk). The selected FOS^{X} was multiplied by $D^{x}{}_{future}$ to determine the project operational range ($D^{x}{}_{design}$); that is, the designed performance of the system $D^{x}{}_{design} = FOS^{x} \cdot D^{x}{}_{future}$, and $Q^{x}{}_{average,future}$ to determine the hazard-relevant streamflow for future climate conditions to be used to design the abstraction facility; $Q^{x}{}_{design} = FOS^{x} \cdot Q^{x}{}_{average,future}$.

The FOS^{x} or suitable marginal safety of infrastructure in future water resource systems is determined by expert judgment, considering the obtained values for $Q^{x}{}_{averaage,future}$, $D^{x}{}_{future}$, and $k^{x}{}_{future}$; characteristics of the applied climate change scenario (pessimistic, optimistic, etc.); design period (usually 50 years); and vulnerability of the water abstraction facility. The expert considered several levels of FOS^{x}, as well as resilience concepts, and consulted with stakeholders to reach a consensus on the necessary characteristics and capacity, as well as the cost of the water abstraction facility.

This is a general concept of "resilience by design." The proposed approach is straightforward, flexible, and understandable to engineers and stakeholders. This is similar to the Factor Analysis method, in which a set of interdependent relationships is examined to design water infrastructure facilities for unknown or untrusted future climate conditions. The factors used were concepts that described observed phenomena.

Water security issues arise when the conditions of "deep" uncertainty are identified, but poorly described. This is a much broader and more complex natural and socioeconomic problem that includes issues and concepts of risk and uncertainty related to capacity expansion, vulnerability to hazards, development needs, and sustainability [1]. The tools presented in this study aim to facilitate the technical/engineering assessment of water supply sustainability within natural and socioeconomic system relationships and water security issues. In a broader analysis of the problem, it is necessary to consider sensitive system variables along with stakeholders to strengthen water security during existing and uncertain future periods [20]. According to Holerman and Evers (2020), knowledge about sensitive system variables is crucial to understanding the effects of different visions and, hence, action within the human–water system to cover the whole range of social responses. The human–water interaction in modern society is complex. Therefore, the application of methods and tools to strengthen resilience should be adapted to the level, time, and features of the specific problem being addressed. Flexibility and wider coverage that respects local and global issues related to human–water interactions and sustainability are needed, and this is not the topic of this work.

2.2. Rationale

An open natural system transforms the input water energy into outgoing energy through water discharge and energy loss to overcome the resistance to flow based on the principle of minimum energy expenditure in any link of the water system (surface and subsurface) and in the system as a whole [21]. Climate defines the input, whereas system structure defines the water retention capacity, potential energy transformation, and dissipation of an unregulated water system in different time periods (recharge and after recharge). It is assumed that future climate change will not considerably change the energy loss processes in the system to overcome the resistance to flow in a spatially self-organized river system because a stable structure corresponds to the minimum total energy dissipation in the system. In other words, future minor local changes in the channel properties will not considerably change the behavior of the entire river system. Thus, the system response to future energy input variations driven by climate change will be similar but will result in different discharge values (outgoing energy). The extent of these possible changes is difficult to estimate; therefore, the problem must be simplified. It is important to understand physical reality to assess the vulnerability of a system.

In the river system, the streamflow at a certain locality is composed of a groundwater contribution equal to cS_{t-1} and surface runoff equal to dx_t:

$$Q_t = cS_{t-1} + dx_t \quad (5)$$

The continuity equation for the groundwater storage is written as:

$$S_t = (1 - c)S_{t-1} + ax_t \quad (6)$$

Combining Equations (5) and (6), streamflow Q_t can be written as:

$$Q_t = (1 - c)Q_{t-1} + dx_t - (d(1- c) - ac)\, x_{t-1} \quad (7)$$

which is modeled when precipitation is an independent series, where x_t represents the precipitation in period t, ax_t infiltrates, percolates, reaches the groundwater storage, and bx_t evaporates [22]. Hence, the equation:

$$(1 - a - b)x_t = dx_t \quad (8)$$

Surface runoff is a fast flow driven by differences in gravitational potential energy caused by elevation differences. Groundwater contributes to the flow, and cS_{t-1} represents the base flow driven by differences in gravitational potential energy caused by groundwater table elevation, where c represents the aquifer coefficient and S_{t-1} is the groundwater storage at the beginning of period t. The following conditions are necessary to validate the above:

$$0 \le a, b, c, d \le 1 \text{ and } 0 \le a + b \le 1 \quad (9)$$

Equation (5) holds for a karst hydrological system [23]. The presented conceptual hydrological model (precipitation–runoff) was used to analyze hydrological processes in water systems for the qualitative analysis and justification of the proposed vulnerability model.

In a natural environment, all streams attempt to flow toward a state of dynamic equilibrium. More major changes in the stream network are the result of complex geomorphological processes over a long period (longer than 100 years). Therefore, the physical reality of the system will not change considerably in the near future. It can be concluded that the internal properties of the system and the sensitivity of the streamflow do not change substantially because the difference in gravitational potential energy in the watershed area and streams changes gradually with natural processes. However, occasional climatic extremes and the flows generated by internal properties, which occur more often, locally change the state and adjust the channel property toward the optimal state and can have a major impact on the local natural and socioeconomic system. Therefore, in the wet period (higher potential energy period), streamflow sensitivity is generally higher than that in the dry period because smaller changes in maximum inputs generate larger output oscillations than the same relative ratios of changes in the dry period. However, the overall energy balance, and thus, the state of the system due to climate change, will not change considerably in a short period (e.g., 50 years) unless human activities change the internal energy of the river system substantially. Therefore, the water resource system behaves similarly and generates streamflow as a function of bounded variation, which can be estimated in a simplified manner using the proposed methodology.

3. Method Validation

The characteristics of the proposed method are illustrated using two case studies: the Jadro Spring, which has been used for water supply for more than 2000 years, and the Krka River in the Skradinski Book, where a water abstraction facility for a regional water supply system is located. These are two different karst hydrological/river systems; therefore, they are good examples of the characteristics of this method. Only the basic features of the method are presented rather than a comprehensive engineering analysis used to select an acceptable engineered solution.

Climate models for the Dalmatian coastal region will forecast minimal changes in annual and seasonal precipitation in the near future (until 2040). For the period 2040–2100, models forecast an increase in the average annual temperature of 0.6 to 4.0 °C and in the summer temperature of 0.9 to 4.7 °C and a reduction in annual precipitation of 2 to 7%, with the majority occurring during the summer (5 to 25%), followed by the autumn (3 to 13%) and spring (3 to 8%), whereas precipitation is expected to increase by approximately 2 to 7% in the winter [24]. This is typical for direct engineering applications, water structure vulnerability assessments, and resilience strengthening. However, water engineers experience challenges when adapting supply sources and infrastructure systems to climate change.

3.1. River Jadro Spring

The Jadro Spring is situated on the hillside of Mosor Mountain at an elevation of approximately 33.00 m a.s.l., 3 km east of the Adriatic coast, in the vicinity of the city of Split, Croatia, Figure 3 [21]. According to various authors, the total area of the Jadro and Žrnovnica Spring catchments is approximately 450 km^2 [25]. According to the Köppen classification, the climate is classified as Csb/Csa, where Csa and Csb are Mediterranean climates with hot and warm summers, respectively. The total annual precipitation is approximately 1200 mm, and two-thirds of the total precipitation occurs from September to March.

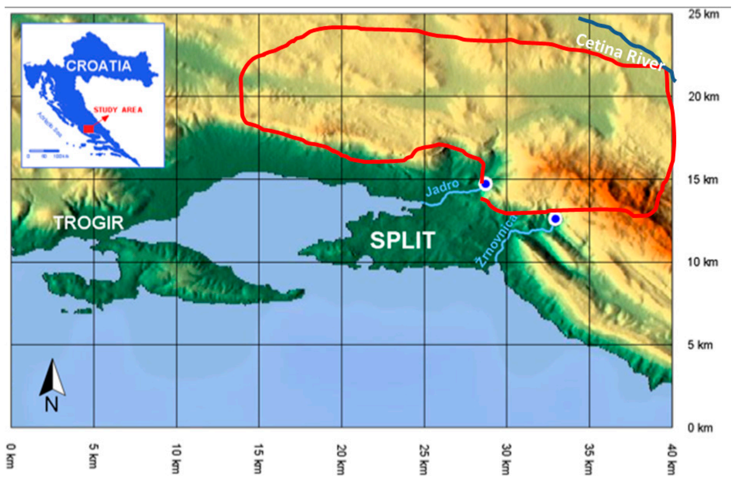


Figure 3. Location of the study area and catchment boundary.

This system has a karst aquifer as its basic unit, which is influenced by the neighboring aquifer of the Žrnovnica Spring and the Cetina River (Figure 3). The system is isolated from the sea by an extensive coastal waterproof flysch barrier; therefore, there are no significant uncontrolled discharges into the sea. It can be concluded that the main output of the system is the Jadro River Spring.

The discharge hydrograph is characterized by a highly dynamic rainy period in which the discharge rapidly increases and decreases in the wet period with each major rainfall event, and a long drought period in which the discharge steadily decreases and remains at the minimum value, as shown in Figure 4.

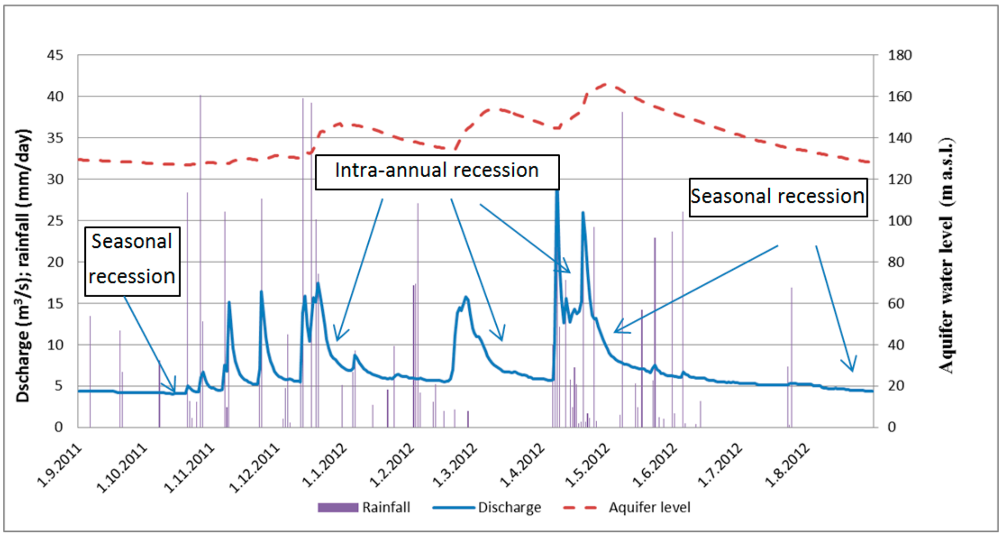


Figure 4. Discharge hydrograph, rainfall, and aquifer water level from 1 September 2011 to 31 August 2012.

The upper part of the aquifer with porous channels and karst caverns empties and draws down quickly, whereas the middle part with porous small to large fissures has a slightly slower reaction, and the lower part with porous clastic deposits discharges gradually. Such features of the discharge hygrogram and aquifer behavior define the main features of a permanent karst spring [26]. Springs have been used for water supply in the wider area of Split, the second largest city in Croatia, since 100 B.C. During the summer, the $Q_{supply}/Q_{demand} \approx 1$ ratio, where $Q_{demand} = Q_{abstraction} + Q_{environment}$, $Q_{environment}$ environmental constraints, and $Q_{abstraction}$ intake capacity; therefore, the future reliability of water intake facilities is questionable.

Table 1 shows the data and values of the indicators for the time series of the average discharge $Q^{average}$, minimal discharge Q^{min}, and maximal discharge Q^{max} groups from 1995 to 2005.

Table 1. Characteristic discharges and range of fluctuations in the discharge from 1995 to 2005.

Characteristic Values	Discharge Group		
	$Q^{average}$ (m^3/s)	Q^{max} (m^3/s)	Q^{min} (m^3/s)
Average	9.81	51.81	4.29
Max	12.02	70.06	4.85
Min	7.81	31.57	3.72
D(max − min)	4.21	38.49	1.13
Indicator k^x	0.43	0.74	0.26

The fitted regression model, that is, the vulnerability function for the Jadro Spring, is $Y = 0.1917\ ln\ (X) - 0.432$, where Y is the indicator k^x, and X is the ratio of the average value of any specific discharge of interest $Q^x{}_{average}$, between Q_{min} and Q_{max}, and the average value of the discharge dataset $Q_{average}$. This is a logarithmic function with a lower extreme at k^{min} and an upper extreme at k^{max}. The indicator used for the determination was $R^2 = 1$.

In a real hydrological system, k^x is a positive real number $R_{>0} = \{x \in R | x > 0\}$. In the Jadro case, $0 < k^x < 1$, and the discharge is characterized by $Q^x{}_{average} > D(Q^x)$, which indicates a moderate aquifer retention capacity. The obtained values of k^x ($0.25 < k^x < 0.75$) indicate that climate change variation has the greatest impact on the uncertainty value of Q^{max}, which will change the most and the least Q^{min}. The trend in the discharge variability increases with an increasing value of Q^x, which defines the k^x hierarchy, min < average < max. The deviation from the average for the annual minimum streamflow is 25%, the annual average streamflow is 45%, and the annual maximal streamflow is 75%, while the absolute range of operation of the system is 66.34 m^3/s, and in the case of annual Q_{min}, it is 1.13 m^3/s, $Q_{avearage}$ is 4.21 m^3/s, and Q_{max} is 38.49 m^3/s. The area of operation is wide, and climate change can widen it further. However, it increased the least at minimum flows and the most at maximum flows.

By applying the proposed methodology and using the forecasted seasonal changes in precipitation, the future average streamflow was estimated ($Q^x{}_{average,future}$), followed by $k^x{}_{future}$ and the expected range of streamflow ($D^x{}_{future}$). Based on the obtained results, the design range ($D^x{}_{design}$) and hazard-relevant flows ($Q^x{}_{average}$) were determined, as listed in Table 2. In this example, to simplify the calculation, it was assumed that $Q^x{}_{average}$ is proportional to the predicted change in precipitation (±%), and a unique FOS = 20% for all flows was used. If necessary, to be more accurate, the estimated amount of net precipitation (precipitation—evapotranspiration) can be used, as well as different values for the FOS.

The obtained "initial" results are in accordance with the forecasted trend in climate change related to precipitation and the assessed water resource system vulnerability. The winter and summer high flows were slightly higher and lower, respectively.

Table 2. Jadro Spring estimated variables for the year 2100, the first iteration.

$Q_{historic}$ (m^3/s)	Precipitation Change (%)	$Q^x{}_{average,future}$ (m^3/s)	$k^x{}_{future}$	$D^x{}_{future}$ (m^3/s)	FOS	$D^x{}_{design}$ (m^3/s)	$Q^x{}_{average,design}$ (m^3/s)
Maximal change scenario for the year 2100							
$Q_{average}^{average}$ (9.81)	Annual (−7)	9.12	0.43	3.86	0.8	3.09	7.30
$Q_{average}^{max}$ (51.81)	Wet period (+7)	55.44	0.77	42.63	1.2	51.15	66.53
$Q_{average}^{min}$ (4.29)	Dry period (−25)	3.22	0.22	0.72	0.8	0.58	2.57
Minimal change scenario for the year 2100							
$Q_{average}^{average}$ (9.81)	Annual (−2)	9.61	0.43	4.07	0.8	3.25	7.69
$Q_{average}^{max}$ (51.81)	Wet period (+2)	52.85	0.75	39.62	1.2	47.54	63.42
$Q_{average}^{min}$ (4.29)	Dry period (−5)	4.08	0.26	1.05	0.8	0.84	3.26

The vulnerability of the water supply (Q_{supply}) until 2100 is moderate, and adaptation measures are not demanding. However, in the critical summer months, $Q_{supply} < Q_{demand}$, the standard solution for the redistribution of water over time can provide the necessary capacity (surface water storage reservoirs, manipulation of groundwater storage, etc.) supported by demand management [27].

In a real case study, the decision-making process will continue with a more comprehensive analysis of the input–output process in the system considering different climate change scenarios and water demands. Risk, sustainability, and impact were assessed. Based on the results, the process of selecting an acceptable solution continues with the application of relevant FOS^x values or stops if a compromise solution is defined. Generally, water supply security considers trade-offs among expected benefits, reliability, resiliency, and vulnerability.

3.2. River Krka

The Krka River is located on the central Adriatic coast of Croatia (Figure 5) [28]. It is known for its attractive karst lakes, waterfalls, and long estuaries. The river system is comprised of several tributaries, cascading lakes, waterfalls, and long karstic estuaries.

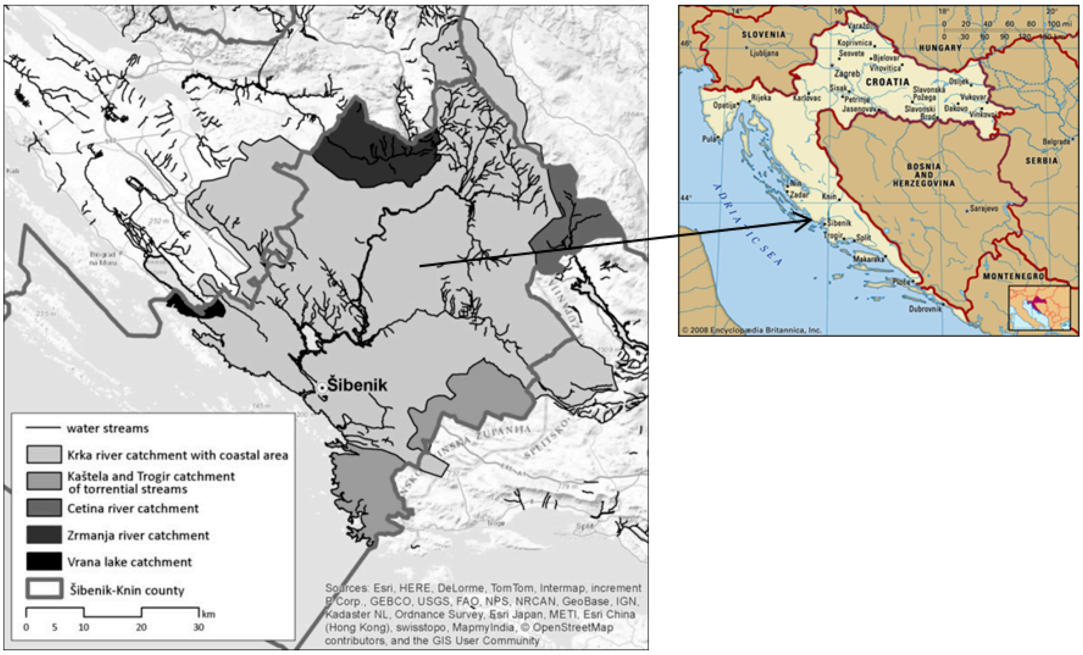


Figure 5. Overview of the coastal zone of the Šibenik-Knin County and Krka River catchment boundaries.

The catchment area of the Krka River is 2500 km^2 and is located in the coastal and mountain karst dinaride areas. According to the Köppen climate classification, the wider area of the Krka River is classified as Cfb/Cfa, where Cfa = moderately warm humid climate with hot summers and Cfb = moderately warm humid climate with warm summers. The total annual precipitation is approximately 900 mm, and the maximum precipitation (two-thirds of the total precipitation) is most likely to occur from September to March.

The main Krka River spring near Knin is Krčić, at an elevation of 224 m a.s.l. There are several smaller springs that create temporary tributaries and karst lakes, of which Lake Visovac is the largest, with a series of waterfalls between them. Its long and attractive estuary begins downstream from the last waterfall, the Skradinski Buk, and continues through Šibenik Bay to Sv. Ante the channel to the sea (Figure 5). The river is 72.5 km long, and the estuary area is 23.5 km. The river has a large fall on the riverbed (average slope of approximately 0.3%) and seven waterfalls that have distinct landscape values (more than one million visitors in 2019). The river's large gross head and winter flows make it productive for hydropower generation; hence, five hydropower plants were built with small relative reservoirs. The landscape value of the river and its biodiversity are the main barriers to a more complete utilization of its hydropower potential. The river is the main source of drinking water for the two regional water supply systems, and there is a constant problem with the capacity of the water supply system during the peak tourist season because of the environmental streamflow restrictions at waterfalls. With the development of tourism, this problem will become increasingly complex and demanding.

It is a karst hydrological system with a large catchment area and relatively open boundary in contact with the sea. It does not have a large retention capacity, and the transformation from input to output is fast. The river has a huge drop in its bed, which increases the flow energy of the streamflow, allowing the water to move fast through the river network. Specific hydrogeological settings are responsible for the dynamic recharge system manifested in river flow, which is highly responsive to rainfall (Figure 6).

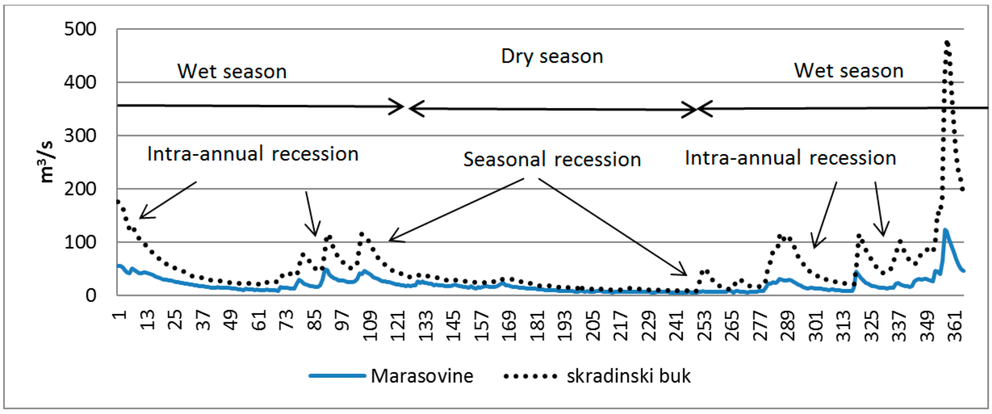


Figure 6. Hydrograph of the Krka River at Marasovine station (41 km from estuary) and Skradinski Buk station (5 km from estuary), calendar year 2002.

The data and values of the indicators for the time series for the average discharge $Q^{average}$, minimal discharge Q^{min}, and maximal discharge Q^{max} groups for 1947–2015 are presented in Table 3.

The k^x regression model for the Krka River located at "Skradinski buk gornji" was obtained as $Y = 0.0807X^2 - 0.4024X + 1.5217$. It is a polynomial order-two function with $k^x > 1$, where the upper extreme is at k^{max} and the minimal extreme is between $k^{average}$ and k^{max}. The indicator used for the determination was $R^2 = 1$.

Table 3. Characteristic discharges and range of fluctuations in the discharge measured at the "Skradinski Buk gornji" station, 1947–2015 [29].

Characteristic Values	Discharge Group		
	$Q^{average}$ (m³/s)	Q^{max} (m³/s)	Q^{min} (m³/s)
Average	51.3	258	10.9
Max	84.2	481	20.7
Min	22.5	83.5	4.99
D(max − min)	61.7	397.5	15.71
Indicator k^x	1.20	1.54	1.44

k^x is a positive real number $R_{>0} = \{x \in R | x > 0\}$ with values of $1 < k^x < 2$. The discharge in the hydrological system was characterized by $Q^x{}_{average} < D(Q^x)$. It is a hydrological system that is sensitive to climatic variations. This applies to all the Q^x ($1 < k^x < 1.5$). The highest sensitivity was for annual Q^{max}, followed by a slightly lower Q^{min} and the lowest $Q^{average}$, and k^x had a hierarchical trend *average* < *min* < *max*.

From this, it follows that the relative magnitude of the oscillations and the sensitivity of the characteristic values of annual streamflow increased in the annual maximum and minimum values. This implies that the average annual streamflow has a relatively smaller uncertainty related to input changes than the annual maximum or minimum streamflow. The area of operation of the water intake is very wide, and the forecasted variations in precipitation will be greater. This considerably affects the natural capacity of the system and increases the flooding and drought hazards.

The deviation from the average in the case of annual minimum streamflow is 144%, annual average streamflow 120%, and for annual maximum streamflow, it is 154%, whereas the absolute range of operation of the system is 476.0 m³/s, and in the case of annual Q_{min}, it is 15.71 m³/s, $Q_{average}$ is 61.7 m³/s , and Q_{max} is 397.5 m³/s.

As in the case of the Jadro Spring, the future variables were calculated (Table 4), and the necessary analyses were conducted to determine a comprehensive solution. The area of operation increased the least for annual flows, which were slightly higher than the average flow, and the most for annual maximum flows. Therefore, the required safety factors and design parameters must be selected accordingly.

Table 4. Krka River at the "Skradinski Buk gornji" including estimated variables for the year 2100, first iteration.

$Q_{historic}$ (m³/s)	Precipitation Change (%)	$Q^x{}_{average,future}$ (m³/s)	$k^x{}_{future}$	$D^x{}_{future}$ (m³/s)	FOS	$D^x{}_{design}$ (m³/s)	$Q^x{}_{average,design}$ (m³/s)
		Maximal change scenario for 2100 year					
$Q^{average}_{average}$ (51.3)	Annual (−7)	47.71	1.20	57.25	0.8	45.80	38.27
$Q^{max}_{average}$ (258)	Wet period (+7)	276.06	1.90	523.20	1.2	627.84	331.27
$Q^{min}_{average}$ (10.9)	Dry period (−25)	8.18	1.46	11.90	0.8	9.52	6.54
		Minimal change scenario for 2100 year					
$Q^{average}_{average}$ (51.3)	Annual (−2)	50.27	1.20	60.33	0.8	48.26	40.22
$Q^{max}_{average}$ (258)	Wet period (+2)	263.16	1.63	428.04	1.2	513.64	315.79
$Q^{min}_{average}$ (10.9)	Dry period (−5)	10.35	1.44	14.93	0.8	11.94	8.28

The maximal streamflow and variability (range) in streamflow (Q_{flood}) exhibit a major increase, whereas, in the case of minimal streamflow (Q_{supply}), the reaction is lower with different ranges depending on the forecast precipitation change. Krka River is very sensitive to climate change, and its risk is high; therefore, higher FOS^X values need to be applied.

The drinking water abstraction facility is located in Krka National Park, which makes it impossible to solve problems related to the water supply. The environmental constraints related to streamflow changes ($E_{nvironmental}$) are rigid and obstruct the increase in $Q_{abstraction}$. Therefore, a solution should be sought, mostly with the application of a water demand management approach. However, because annual $Q_{supply} > Q_{demand}$, the usual measures of redistribution of water in time can provide the necessary capacity for water abstraction, $Q_{abstraction}$, provided that seasonal water storage can be developed or exists in hydroelectric power plants. Otherwise, the problem can be solved using a suitable combination of supply and demand management measures [30]. An acceptable solution should be defined by a comprehensive analysis that considers a wider set of local technical and nontechnical factors and impacts, that is, sustainability indicators.

Therefore, there is a need to upgrade traditional engineering design strategies to improve infrastructure reliability under socioeconomic and environmental changes. A safety factor approach is necessary to design water infrastructure in a changing climate. It is necessary to quantify the intense uncertainty surrounding extreme rainfall and streamflow projections, watershed surface imperviousness, and infrastructure lifetime to inform water intake system design. The lifespan of a design is the period over which its designers expect the intake to work within its specified parameters; that is, the life expectancy of the intake. Climate has a major influence on the location of the water structure, type, position, orientation of the structure, and type of materials used. Therefore, implementing an adequate durability of the design process is necessary [31].

4. Discussion

The proposed approach is characterized by interconnected water resource system processes, input–output relationships, sensitivity, autonomous capacity and vulnerability, overlapping climate change, water supply, and infrastructure. The obtained results comprehensively show the essential difference in extreme flow reactions in the two karst hydrological systems related to the potential energy arising from rainfall in the watershed system in dry and wet periods and streamflow (water abstraction) vulnerability. The estimated vulnerability is the cumulative response of the entire river system network to the input (precipitation–evapotranspiration) variability during the considered period at the reference point for water abstraction. The coefficient k^x is presented as a function of the ratio of $\frac{Q^x_{average}}{Q_{average}}$. It is a relevant predictor variable (assumed non-random) for k^x as a response variable (assumed random) because natural river system variations follow typical average behavior in response to climate (rainfall) fluctuations and susceptibility to change. Such a predictor is the foundation for assessing vulnerability to climate streamflow hazard Q^x expressed by the k^x value, where k^x is an incommensurable quantity for cumulative vulnerability. Therefore, R^2 is the coefficient of the multiple determinations (sensitivity and adaptive capacity).

The coefficient of determination, R^2, has a value of 1, indicating that the regression line perfectly fits the data. Thus, the fitted model explains all the variability in k^x in accordance with the features of the available streamflow time series. However, a high correlation does not provide adequate evidence that changing one variable has resulted in or may have resulted from changing other variables. Thus, the regression equation depicts the type of hydrological system, structure, and magnitude of streamflow (i.e., cumulative vulnerability) in a simplified presentation.

Generally, the fitted model presents a rate function and formulates a large deviation principle for future climate periods using a continuous streamflow parameter. River systems will retain the same internal characteristics and thus present a model of the large deviation principle in the future uncertain climate period, with the variability proportional to the current ones, allowing engineers to apply appropriate FOS in relation to the (hazard) design parameters Q^x. The final decision regarding the design parameters was made by considering the forecasted values of precipitation and temperature variability during the life of the project/planning period and/or the trends in the changes. The final decision is generally based on the application of an evaluation method using expert judgment estimation.

The results show that the most important factor influencing the vulnerability of the water resource system is the flexibility between the output and input variation, as defined by the system characteristics related to the dynamic capture and storage of water and energy under water/energy flow. This issue can be effectively solved by installing manmade surfaces and underground structures required for dynamic flow capture and regulations. The appropriate dimensions and positions of such water structures were determined using the usual methods of leveling the flow in accordance with the inflow nature and water demand.

The Jadro Spring, with its dominant flow patterns, is optimal in terms of minimizing the total energy dissipation at a given recharge under the constraint of a given total porosity, whereas the Krka River has the lowest energy expenditure in the river network. In these hypotheses, the network systems are viewed as a completely integrated unit. The sensitivity and autonomous adaptive capacity of the system, consequences of the energy minimization principle at the reference point, and impacts on streamflow characteristics and water structures (for example, water abstraction facilities) cannot be realistically modeled by a single or several representative system elements. Therefore, it is important to consider the relationships between the inputs and outputs from the system during dry and rainy periods, as well as the transformation processes that occur in the system.

For the Jadro Spring, the concept of processes in karst aquifers is frequently discussed using three types of porosity: micropores, small cracks and fractures, and large fractures or conduits [26]. In this system, the surface channel network and storage are not developed, and the infiltration of water into the ground occurs rapidly [32]. During the wet period, the energy system had greater potential energy and lower resistance to flow, whereas the situation was reversed during the dry period. Therefore, the reactions to rainfall input energy are majorly different, which affects the sustainability of the abstraction facility. These results comprehensively illustrate this phenomenon.

The Krka River presents a different situation because the topological structure of the river network controls discharge and drains through different links. Hillslopes are runoff-producing elements that are connected by networks. The spatially distributed potential energy generated by rainfall and snow in the watershed was converted into kinetic energy in the flow through the channel reaches. This occurs in the dry and wet seasons so that the river flow reacts/oscillates similarly to the rainfall input in the dry and rainy periods but with varied capacity/flow.

The water resource system differences are simplified by comparing $Q^x{}_{average}$ <=> $D(Q^x)$, which confirms that the proposed indicator k^x is an excellent indicator of climate hazard-related sensitivity and adaptive capacity, that is, the vulnerability of the water resource system and associated water structures at a particular location. This relationship qualitatively indicates the system's residence time, and thus provides information about the storage and flow processes in the system in the current climate. Together with the value of k^x, this directly indicates the need to strengthen resilience and adapt the water abstraction facility in relation to specific climate hazards (floods and droughts) and their priorities. The presented information should be used to supplement other standard project evaluation criteria, including the distribution of project benefits and costs as well as various social and environmental impacts (sustainability).

This method can be applied to other locations where data on the time series of daily flows are available, either as a result of measurements at the gauging station or generated using appropriate methods from locations where measurements are conducted in the river system. This application is universal because it considers the processes of energy/water flow and energy/water capture and storage under energy/water flow in the water resource system, that is, thermodynamic aspects or streamflow sensitivity and vulnerability as the internal properties of the system.

5. Conclusions

Uncertainty is a fundamental characteristic of water abstraction because the future is unpredictable. This raises the question of whether regional-to-global hydrological model calculations are locally relevant and reliable, considering the uncertainty in hydrological inputs. A safety factor design approach for water supply decision problems referred to as the choice of intake size in the face of extremely uncertain projections of extreme rainfall, river streamflow characteristics, and infrastructure lifetime, is proposed. In this approach, the design analysis of the water intake infrastructure generally considers climate (effective rainfall), streamflow statistics (extreme values and average distribution), vulnerability and risk projections, hydraulic analysis, and infrastructure design. The key driver of the uncertainty surrounding hydraulic reliability, that is, risk, is the intense uncertainty surrounding extreme rainfall and streamflow projections. The proposed method, based on a simplified and scientific approach, can be used to design safety factors in the case of intense uncertain projections of extreme streamflow to produce a robust performance of water intake.

The proposed method assesses future vulnerability without forecasting the future sequences of flow encountered during the design life of a water structure. This method is locally relevant because it is based on historical streamflow data, internal properties of the water resource system, water utilities, and knowledge. It appropriately considers the uncertainty arising from the insufficiently understood impact of climate on hydrological processes and water abstraction. Thus, the biggest limitation in the application of the proposed method is related to historical streamflow data availability, because the method is based on sequences of streamflow in the past period. If flow data are not available at the water abstraction location, they can be generated using the data from the measuring points.

The proposed approach is practical because it independently assesses the vulnerability of the water resource system at the location of water abstraction, that is, natural vulnerability, and the vulnerability of water abstraction facilities, that is, technical vulnerability, because they are generated and marked by different causes and indicators. This enables the adequate treatment of natural processes, causes, and indicators of vulnerability by applying an appropriate methodology and technical vulnerability generated by socioeconomic, technical, and other causes and indicators. This is a positive characteristic of the proposed approach, which makes it easier to assess the optimal decisions related to the adaptation and strengthening of the resilience of existing and planned water intake and associated water resource systems.

An important feature of the proposed procedure is the simplicity of the vulnerability analysis resulting from the development of the vulnerability index k^x. This index depicts the thermodynamic features of the system related to water and energy flows and the transformation from the input to the output of the system, which includes the components of water/energy flow, water/energy dynamic capture and storage, and entropy generation. The index can track changes and benchmark the current stress of the system, thus enabling stakeholders to take timely measures to strengthen resilience and increase FOS in terms of capabilities, persistence, adaptability, and transformability. This is a reasonable approach and design for an effective risk-reduction strategy because the future is unpredictable. The proposed method is practical because it can easily be adapted to different natural and artificial water systems.

The validation presented with illustrative examples is promising; however, further studies are required to investigate the universal applicability of this hypothesis.

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