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SUSTAINABLE MANAGEMENT AND OPTIMIZATION OF WATER-RESOURCE USE IN THE KARST AREAS OF HERZEGOVINA

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ABSTRACT

The problem of water resource scarcity and water supply in karst areas is significant and still insufficiently researched. Management of water resources is particularly demanding due to the high spatial and temporal variability of available water. The area of Herzegovina belongs to the Dinaric karst, one of the most developed karst regions in Europe. This paper analyzes the problem of sustainable water resource management in karst areas under climate change conditions, with particular reference to the Herzegovina region, for example the Municipality of Posušje and the Tribistovo Reservoir. The specific hydrogeological characteristics of karst, the pronounced seasonal variability of recharge, and the occurrence of longer dry periods can cause a reduction in available water quantities precisely during periods of increased demand. A conceptual dynamic model has been developed based on object-oriented modeling (OOM) and the application of the software system STELLA. The model links climatic and hydrological factors, available water resources, storage conditions, user demands, losses in the water supply system, and indicators of deficit and water supply security. Scenario analysis considers the reference state, the impact of climate change without optimization, and the state with the application of management and optimization

measures. The proposed approach enables the assessment of critical periods, the analysis of the relationship between availability and demand, and the evaluation of measures such as loss reduction, consumption management, and optimized use of the Tribistovo Reservoir. The model represents a basis for the development of decision support systems and adaptive management of water resources in karst areas.

Keywords: karst, water resources, climate change, water management, optimization, object-oriented modeling, STELLA, Tribistovo Reservoir, Posušje

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1. INTRODUCTION

In karst areas, water resource management is particularly challenging due to the large spatial and temporal variability of available water. The area of Herzegovina belongs to the Dinaric karst, one of the most developed karst regions in Europe. The hydrogeological characteristics of the area are primarily conditioned by the widespread occurrence of carbonate rocks, especially limestone and dolomite, in which complex systems of fractures, caverns, and underground channels have developed through karstification processes. Due to the high permeability of carbonate rocks, the surface hydrographic network is locally poorly developed, while underground flow is the dominant component of the hydrological cycle. [1,2]

The recharge of karst aquifers occurs through the infiltration of precipitation and the concentrated sinking of surface waters. Groundwater can move at high speeds through developed karst channels and reappear at powerful karst springs. The directions of underground flow do not have to coincide with the boundaries of surface catchments, which is why determining the actual hydrogeological divides represents one of the key problems in water resources management. [1,2] Herzegovina is characterized by a pronounced seasonal variability of water resources. In the wet part of the year, heavy rainfall causes intensive recharge of aquifers, an increase in spring yields, and the occurrence of occasional surface flows, while during the dry summer periods, there is a decrease in groundwater levels and spring yields. At the same time, water needs are increasing, which can lead to an unfavorable ratio between available quantities and water demand. [2–4]

Due to rapid water infiltration and relatively weak natural filtration, the karst aquifers of Herzegovina are also very sensitive to pollution. Therefore, sustainable management of these water resources requires joint consideration of the quantity and quality of groundwater and surface water, the protection of recharge zones, and continuous monitoring of precipitation, groundwater levels, spring flows, and water abstraction quantities. [1,5]

1.1. Specific characteristics of water resources in karst

Karst aquifers are characterized by well-developed fracture–conduit systems, high permeability, and a relatively limited capacity for natural flow regulation. This results in a very rapid response of springs to precipitation, but also in a rapid decline in discharge during prolonged dry periods. [1,2]

For the area of the Dinaric karst, including Herzegovina, the following are particularly important:

- pronounced seasonal unevenness of rainfall and flow;
- high dependence of water supply on karst springs;
- rapid transfer of water and potential pollutants through the subsurface;
- complex and often difficult-to-define watershed boundaries;
- increased summer consumption due to temperature and tourism;
- reduced source yield during dry periods;
- expected additional pressure from climate change.

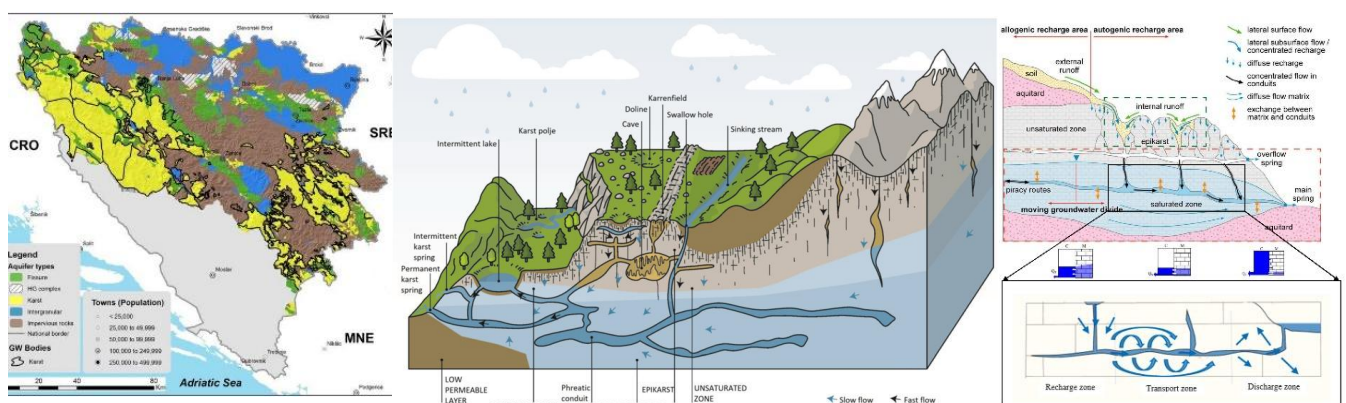


Figure 1. Conceptual model of water resource dynamics in a karst aquifer

Water resources represent one of the fundamental natural resources and a key prerequisite for sustainable social and economic development of a given area. Their availability is determined by natural hydrological and hydrogeological conditions, but also by the intensity of use, spatial management, population and economic development, and the increasingly

pronounced impact of climate change. The problem of ensuring sufficient quantities of water becomes particularly evident in areas where there is a significant temporal mismatch between the availability of water resources and the demand for water.

Karst areas, in this regard, represent particularly complex hydrological systems. The Dinaric karst, which includes large parts of Herzegovina and Dalmatia, is characterized by highly developed surface and underground karst forms, high permeability of carbonate rocks, and complex circulation of groundwater. The infiltration of rainwater through cracks, sinkholes, and karst channels enables the formation of significant underground water resources, but at the same time causes their high spatial and temporal variability. Surface and groundwater under such conditions form a strongly interconnected system, which is why the boundaries of hydrogeological catchments often do not correspond to surface topographic watersheds. [1,2]

The specific structure of the karst aquifer allows relatively rapid movement of water underground and a quick response of springs to precipitation events. However, during longer periods without rainfall, there can be a significant decrease in the recharge of the aquifers, the yield of the springs, and the available water quantities. For this reason, a large total amount of water passing through the karst system over the year does not necessarily simultaneously mean a sufficient amount of water available during periods of greatest need.

This problem is particularly pronounced in areas influenced by the Mediterranean climate. The greatest water needs generally occur during the summer months, when air temperatures are highest, evapotranspiration is increased, and the amount and frequency of precipitation are reduced. At the same time, the recharge of karst aquifers and the availability of surface waters decrease. A characteristic mismatch between water supply and demand arises: [3,4]

2. WATER RESOURCES IN KARST

2.1. Groundwater in karst

Groundwater represents a fundamental part of the water cycle in karst areas. Rainwater infiltrates through cracks and sinkholes, and then moves through a complex system of fractures, caverns, and karst channels.

Simplified:

PRECIPITATION → INFILTRATION → KARST AQUIFER → GROUNDWATER FLOW → SPRINGS → SURFACE FLOWS / SEA

Unlike a more homogeneous porous aquifer, the speed of underground flow in karst can be very uneven. Part of the water moves through smaller cracks and the rock matrix, while a significant portion can be transported very quickly through developed karst channels. [1,2]

For this reason, a karst aquifer can simultaneously have two seemingly opposite characteristics: very large amounts of groundwater, but also high vulnerability of the water supply during dry periods. Ensuring an adequate supply of groundwater during dry periods is precisely one of the main goals of the current UNESCO management program for the Dinaric karst. [1,2,6]

2.2. Surface waters

Surface waters in karst should not be considered separately from groundwater. A river can receive groundwater in one part of its course, then lose water by infiltration in another part, and afterwards partially or completely sink. The same water can reappear at a distant karst spring after flowing underground. In the Dinaric karst, we find numerous examples of such interaction. In the literature, among characteristic phenomena are mentioned, for example, the rivers Cetina, Krka, Zrmanja, Lika, and Gacka, as well as karst springs such as Jadro and Omble. [1,2]

For Herzegovina, particularly significant are the catchment areas of the Neretva, Trebišnjica, and Cetina rivers, as well as numerous karst fields and springs. Hydrogeological research in western Herzegovina shows very complex relationships between permeable carbonate rocks, hydrogeological barriers, springs, and deep underground flow. [5,7]

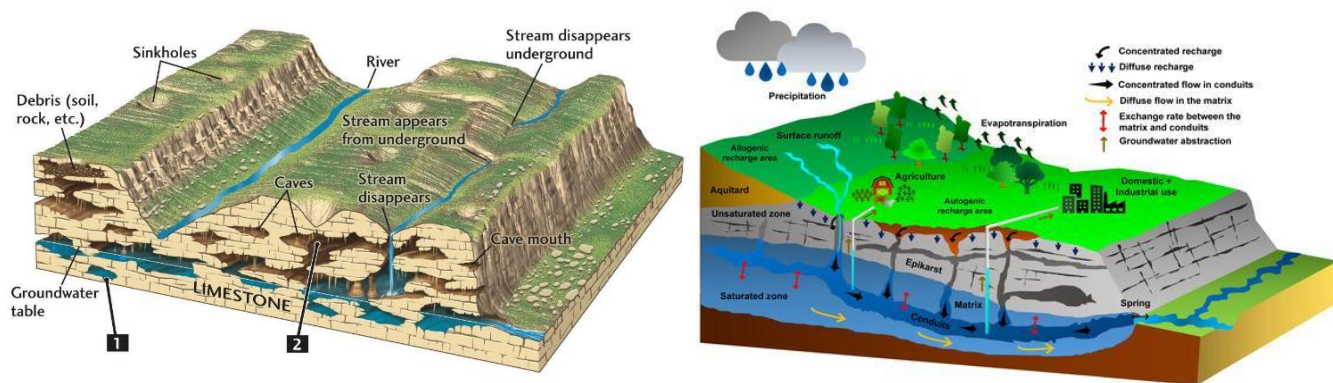


Figure 2. Structure of the connection between underground and surface waters in karst

2.3. Connection between underground and surface waters

One of the probably most important characteristics of karst: the connectivity and hydrohydraulic movement of water in karst. We can conceptually represent it:

$$P \rightarrow I \rightarrow V_{GW} \rightarrow Q_{GW} \rightarrow Q_{SP} \rightarrow Q_{SW}$$

where:

P – precipitation,

I – infiltration,

V_{GW} – groundwater storage,
 Q_{GW} – groundwater flow,
 Q_{SP} – karst – spring discharge
 Q_{SW} – surface – water flow.

But there is also feedback: $Q_{SW} \rightarrow Q_{GW}$

because surface water can, through sinkholes, cracks, and permeable channels, become groundwater again. Therefore, it is more appropriate to speak of a unified system of surface and groundwater in karst, rather than of two completely separate resources.

Typical behavior of water resources in karst areas during the year for rainy periods:

$$P \uparrow \Rightarrow I \uparrow \Rightarrow V_{GW} \uparrow \Rightarrow Q_{izvora} \uparrow \Rightarrow Q_{površinski} \uparrow$$

During a prolonged dry period:

$$P \downarrow \Rightarrow I \downarrow \Rightarrow V_{GW} \downarrow \Rightarrow Q_{izvora} \downarrow$$

At the same time, precisely during the summer, the following correlation can occur between increasing temperature and increasing water consumption:

$$T \uparrow \Rightarrow Q_{potrošnja} \uparrow$$

Thus, in general, the problem can be represented by the following relationship:

$$\boxed{\text{MANJA RASPOLOŽIVOST VODE} + \text{VEĆA POTROŠNJA} = \text{POVEĆANI RIZIK NESTAŠICE}}$$

This is especially important for the Mediterranean part of Dalmatia and Herzegovina.

2.4. Karst water quality

The high permeability of karst is an advantage from the point of view of the amount of water, but at the same time it increases the vulnerability of aquifers to pollution. A pollutant that gets into an abyss or an extremely permeable zone can be transported relatively quickly through karst channels to the source. At the same time, the natural filtration capacity is often lower than that of aquifers with thick layers of fine-grained material.

This is very important for:

- urban wastewater,
- septic tanks,
- landfills,
- Agriculture and nitrates.
- industrial pollution,
- roads and accidental pollution.

A recently published hydrogeochemical dataset specifically for southern Dalmatia and western Herzegovina encompasses groundwater from springs and surface waters and emphasizes the need to protect this complex transboundary karst catchment and to manage the quantity and quality of its waters [8]

2.5. Climate change and karst water resources

First of all, it is worth distinguishing the annual amount of precipitation from its temporal distribution. Even when the change in total annual precipitation is not markedly large, changes can occur due to:

longer dry periods + higher temperatures + more intense individual precipitation events.

In a highly permeable karst system, intense rainfall does not automatically mean that all that water will be available for long-term water supply. Some of the water can quickly pass through the system and appear at springs, watercourses, or coastal/submarine springs. [1,4]

Therefore, for management it would be useful to define:

$$V_{\text{rasp}} = V_{\text{groundwater}} + V_{\text{surface water}} + V_{\text{reservoirs}} - V_{\text{environmental flow requirements}}$$

and then compare:

$$K_S = \frac{V_{\text{rasp}}}{V_{\text{potrebe}}}$$

A value greater than 1 would indicate satisfactory availability, whereas approaching 1 and falling below it would indicate an increasing risk to water-supply security. K_S

2.6. Geological structure of the karst

The geological structure of karst areas consists mainly of carbonate rocks, primarily limestones and dolomites, which are susceptible to chemical dissolution by water enriched with carbon dioxide. Through a prolonged process of cracking (karstification) the primary fractures, faults, and bedding planes gradually expand, leading to the formation of a complex system of underground cavities, caverns, and channels. [1]

In hydrogeological terms, a karst system can be divided into a surface zone, epikarst, an unsaturated (vadose) zone, and a saturated (phreatic) zone. Epikarst represents an intensely fractured and cracked surface zone of a carbonate massif where precipitation water is temporarily retained and directed towards the deeper parts of the aquifer. In the unsaturated zone, water moves gravitationally through fractures and vertical channels, while in the saturated zone, underground flow occurs towards karst springs. A special feature of a karst aquifer is the simultaneous existence of diffuse and concentrated flow. Slower flow occurs through the rock

matrix and smaller fractures, while much faster flow occurs through developed karst channels. Because of this, a karst aquifer responds very quickly to intense rainfall, but it can also show a sudden decrease in yield during prolonged dry periods. [1]

The geological structure of karst is further determined by tectonic structures, especially faults, fracture systems, and folds. Impermeable or poorly permeable rocks, such as marl and flysch, can represent hydrogeological barriers that direct underground flow and condition the occurrence of springs. Therefore, in order to understand water resources in karst, it is necessary to jointly analyze the lithological composition, tectonic structure, degree of karstification, and spatial distribution of permeable and impermeable rocks. For the area of Herzegovina, which belongs to the Dinaric karst, such a complex geological structure determines the strong connection between surface and groundwater, the occurrence of sinkholes and strong karst springs, and the underground overflow of water between hydrologically neighboring areas. For this reason, the hydrogeological divide in karst often does not coincide with the topographical divide. [1,7]

2.7. Water balance of the system

Climate change represents an additional factor that can increase the existing imbalance. An increase in air temperature, changes in the amount and seasonal distribution of precipitation, longer and more frequent drought periods, as well as an increase in the frequency of extreme hydrological events, can affect the recharge of karst aquifers, the regime of surface flows, the state of reservoirs, and the overall availability of water. At the same time, increasing temperatures may affect the rise in specific water consumption, especially during the summer months. [3,4]

Therefore, managing water resources under such conditions can no longer be based solely on historical hydrological indicators and average annual values. An integrated approach is needed that simultaneously analyzes the availability of surface and groundwater, the state of reservoirs, climatic indicators, the needs of the population and the economy, the condition of water supply infrastructure, water losses, and the possibilities of applying various measures for rationalization and optimization of consumption.

The basic relationship between availability and needs can be expressed by the water balance:

$$B_W(t) = Q_{\text{rasp}}(t) - Q_{\text{pot}}(t) \quad (1)$$

where:

$B_W(t)$ – water balance of the system, L/s;

$Q_{rasp}(t)$ – available water quantity, L/s;

$Q_{pot}(t)$ – total water demand, L/s.

Note: It holds: $BW(t) > 0$ indicates a surplus, $BW(t) = 0$ a borderline state, and $BW(t) < 0$ a water deficit.

Thus, the availability of water decreases while the demand for water increases, which leads to an increased risk of water deficit.

To assess the security of the system, an index can also be defined:

$$K_S(t) = \frac{Q_{rasp}(t)}{Q_{pot}(t)} \quad (2)$$

where:

$KS(t)$ – water resource security index,

$Q_{rasp}(t)$ – available water quantity, L/s;

$Q_{pot}(t)$ – total water demand, L/s.

Note: A value greater than 1 means that availability exceeds demand; a value of 1 indicates equilibrium; and a value below 1 indicates insufficient availability. $K_S(t)K_S(t)K_S(t)$

Water resource management in the areas of the Herzegovinian karst, for example, the Municipality of Posušje as a case study, should be viewed through the interconnected processes of recharge, accumulation, abstraction, distribution, and water consumption. Special attention should be given to reducing losses in the water supply system, rationalizing consumption, managing peak summer demands, continuously monitoring the state of accumulation and hydrological indicators, and timely responding to the occurrence of drought periods.

A dynamic modeling approach is suitable for the analysis of such a complex system. By applying the STELLA model, it is possible to connect natural, infrastructural, and management components into a single structure and simulate changes in water availability and consumption over time. By modeling different scenarios, it is possible to estimate the occurrence and magnitude of seasonal deficits and analyze the effectiveness of individual optimization measures. [9–12]

The aim of this work is therefore to analyze the possibilities of sustainable management and optimization of water resource use in a karst area using the example of the Municipality of Posušje, considering the seasonal availability of water resources, climate impacts, the function of the Tribistovo Reservoir, user needs, and losses in the water supply system. By developing a dynamic model, it seeks to determine the relationship between water availability and needs,

identify critical periods, and assess measures that can increase the long-term security and resilience of the water supply system.

3. METHODOLOGY FOR DEVELOPING A WATER RESOURCE MANAGEMENT MODEL IN KARST

3.1. Research area

The Municipality of Posušje, located in the western part of Herzegovina, in an area of highly developed Dinaric karst, was chosen as the model application area. The hydrogeological characteristics of the area are conditioned by the dominant presence of carbonate rocks, developed fracture-channel porosity, and complex relationships between precipitation, infiltration, groundwater, and surface water phenomena. [7,13]

For water resources management purposes, seasonal unevenness is particularly significant. Periods of increased precipitation and water resource replenishment alternate with summer periods of reduced inflow, increased evapotranspiration, and increased water demand. Because of this, the assessment of water supply security is not based solely on the total annual water availability, but primarily on the relationship between availability and needs during critical months.

In the Posušje water supply system, the Tribistovo Reservoir plays an important role. In the model, the reservoir is considered as a component that allows temporal redistribution of water, that is, the accumulation of water during periods of greater availability and its use during periods of increased consumption.

3.2. Conceptual approach to modeling

For the analysis of the system, a system dynamics modeling approach was applied, with the possibility of implementing the model in the STELLA software environment. [9–12]

The basic assumption of the model is that the state of water resources at a given moment represents the result of the interaction of natural processes, user needs, infrastructure limitations, and management decisions. The conceptual structure and water management schemes can be illustrated as in Figures 3.4.5.6..

SCHEME 1 Climatic-hydrological sequence



Figure 3. Conceptual sequence of the impact of climate on the availability of water resources.

SCHEME 2 Water flow through the water supply system



Figure 4. Conceptual flow of water from the resource through storage to consumption.

SCHEME 3 Factors of water demand

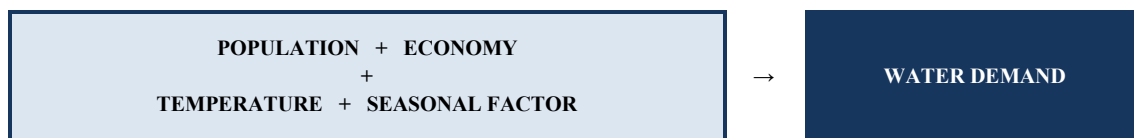


Figure 5. Set of input factors that determine water demand.

SCHEME 4 Water balance and system status

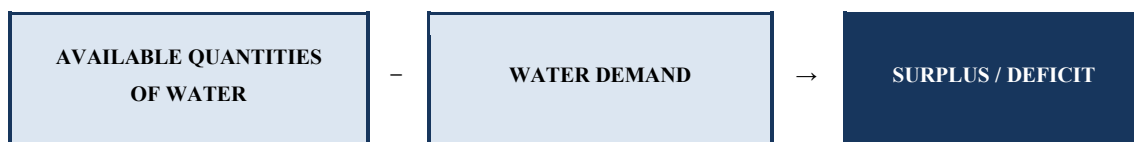


Figure 6. The difference between available water quantities and user needs determines the state of the system.

3.3. Conceptual STELLA/OOM model

The model represents the monthly dynamics of a karst aquifer and links precipitation, recharge, spring inflows, pumping, consumption, and management measures. [10–12]

The model can be organized into four reusable objects: [10,11]

- Catchment: precipitation, catchment area, and recharge coefficient.
- KarstAquifer: storage, spring outflow, pumping, and overflow.
- WaterSupplySystem: intake, external supply, treatment capacity and network losses.
- DemandAndManagement: sectoral demand, reductions, security index and deficit.

The conceptual STELLA/OOM water resources management model in the karst areas of Herzegovina and Dalmatia, including stock-flow structure, variables, equations and a monthly graph of summer water deficits can be illustratively presented as follows:

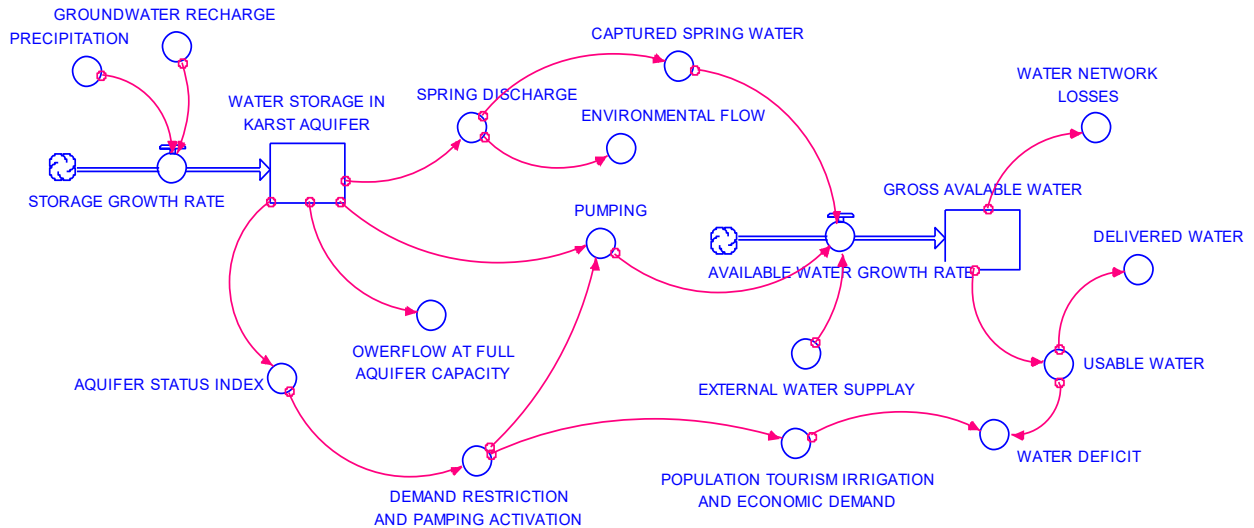


Figure 7. Graphical representation of the conceptual STELLA/OOM model for optimal water resources management in karst

3.4. Mathematical formulation of the model

In the following functional description of the model, we will present the mathematical formulation of the model and all essential parameters and structural elements in the model.

Basic water resources balance:

$$\frac{dV_R}{dt} = Q_{pr} - Q_{zah} - Q_{prirodni} - Q_{gub} \quad (3)$$

where:

V_R – total stock of available water resources, m^3 ;

t – time, month;

Q_{pr} – water resources replenishment, $m^3/month$;

Q_{zah} – water abstraction from the water system, $m^3/month$;

$Q_{prirodni}$ – natural outflow from the observed system, $m^3/month$;

Q_{gub} – other water losses from the system, $m^3/month$.

Replenishment of karst aquifer:

$$R(t) = \max[0, P(t) - ET(t)] A C_i(t) 10^{-3} \quad (4)$$

where:

$R(t)$ – effective replenishment of the karst aquifer, $m^3/month$;

$P(t)$ – amount of precipitation, $mm/month$;

$ET(t)$ – evapotranspiration, $mm/month$;

A – area of the observed watershed, m^2 ;

$C_i(t)$ – effective infiltration coefficient;

10^{-3} – conversion factor from millimeters to meters.

Tribistovo Reservoir balance:

$$\frac{dV_A}{dt} = Q_{\text{dot}} - Q_{\text{zah,A}} - Q_{\text{prel}} - Q_{\text{evap}} - Q_{\text{ost}} \quad (5)$$

where:*V_A – volume of water in the Tribistovo Reservoir, m³;**Q_{dot} – total inflow to the reservoir, m³/month;**Q_{zah,A} – water withdrawal from the reservoir for water supply, m³/month;**Q_{prel} – overflow from the reservoir, m³/month;**Q_{evap} – water loss due to evaporation, m³/month;**Q_{ost} – other water losses from the reservoir, m³/month.***Total demands**

$$Q_{\text{pot}} = Q_{\text{stan}} + Q_{\text{gosp}} + Q_{\text{jav}} + Q_{\text{ost}} \quad (6)$$

where:*Q_{pot} – total water demand, L/s;**Q_{stan} – population water demand, L/s;**Q_{gosp} – economic sector water demand, L/s;**Q_{jav} – public and institutional consumption, L/s;**Q_{ost} – other water needs, L/s.***Climatic consumption increase factor**

$$F_{\text{CC}}(t) = 1 + \alpha \Delta T(t) + \beta I_D(t) \quad (7)$$

where:*F_{CC}(t) – climatic factor of water consumption change;**ΔT(t) – temperature increase relative to the reference period, °C;**I_D(t) – normalized drought index;**α – coefficient of consumption sensitivity to temperature increase, °C⁻¹;**β – coefficient of consumption sensitivity to drought.***Needs with climatic impact**

$$Q_{\text{pot,CC}}(t) = Q_{\text{pot,0}}(t) \cdot F_{\text{CC}}(t) \quad (8)$$

where:*Q_{pot,CC}(t) – water needs with climatic impact, L/s;**Q_{pot,0}(t) – reference needs without additional climatic impact, L/s;**F_{CC}(t) – climatic consumption increase factor, –.***Abstraction with losses**

$$Q_{\text{zah}} = \frac{Q_{\text{kor}}}{1-L} \quad (9)$$

where:

Q_{zah} – required water quantity, L/s;

Q_{kor} – usefully delivered water quantity to consumers, L/s;

L – share of water losses in the distribution network.

Note: If L is given in percentages, it should be converted to decimal form before use.

Water deficit

$$D_W(t) = \max[0, Q_{pot}(t) - Q_{rasp}(t)] \quad (10)$$

where:

$DW(t)$ – water deficit, L/s;

$Q_{pot}(t)$ – total water demand, L/s;

$Q_{rasp}(t)$ – available water quantity, L/s.

Water resources safety index

$$K_S(t) = \frac{Q_{rasp}(t)}{Q_{pot}(t)} \quad (11)$$

where:

$K_S(t)$ – water-resource security index;

$Q_{rasp}(t)$ – available water quantity, L/s;

$Q_{pot}(t)$ – total water demand, L/s.

Note: It holds: $K_S > 1$ means availability is greater than demand; $K_S = 1$ denotes balance;

$K_S < 1$ denotes insufficient availability.

Objective function

$$\min Z = w_1 D_W + w_2 Q_{gub} + w_3 C_{upr} + w_4 R_E \quad (12)$$

where:

Z – value of the total optimization objective function;

DW – water deficit, according to normalization;

Q_{gub} – water losses, according to normalization;

C_{upr} – management and implementation costs of measures, according to normalization;

RE – environmental risk, according to normalization;

w_1 – weighting coefficient of water deficit;

w_2 – weighting coefficient of water losses;

w_3 – weighting coefficient of management costs;

w_4 – weighting coefficient of environmental risk.

Note: Before summing, criteria should be normalized or the weighting coefficients should ensure dimensional consistency.

4. OUTPUT RESULTS OF THE MODEL AND MANAGEMENT OPTIMIZATION

The modeling scenarios are presented as follows:

- **S0 – reference scenario: development of the system without additional climate change impacts.**
- **S1 – climate scenario without optimization: changes in resource availability and water demand due to climate change, without additional management measures.**
- **S2 – climate scenario with optimization: climate impacts with reduced losses, consumption rationalization, peak demand management, and optimized use of the Tribistovo Reservoir.**

For continuing the work, it is now most logical to produce output results, with four main charts: (1) Available water resources 2025–2050, (2) consumption S0–S2, (3) monthly deficit I–XII, and (4) security index (KS).

Table 1. Assumptions and local input parameters for the Municipality of Posušje (illustrative data) [13,14]

Parameter	Value	Unit
Initial KS index	1.150	–
Annual drop S0	0.005	KS/year
Annual drop S1	0.020	KS/year
Annual drop S2	0.010	KS/year
Safe state limit	1.100	KS
Warning limit	1,000	KS
Deficit threshold	0,900	KS
Tribistovo – active storage volume	4,50	million m ³
Tribistovo – water-surface area	0.70	km ²
Historical treatment capacity	100,00	l/s
Monthly capacity over 30 days	0,26	million m ³ /month
Network losses S1	35,0%	%
Network losses S2	20,0%	%
Maximum summer saving S2	15,0%	%
Area of the Municipality of Posušje	461	km ²

The planned analysis period is 25 years, i.e., the period 2025–2050.

The objective of optimization is not to maximize use of the available resource, but to minimize the deficit while preserving water-system security. The management problem therefore extends beyond merely meeting demand and involves identifying a long-term sustainable balance among resource availability, water-supply security, economic costs, and

environmental protection. A particularly important outcome is the identification of the critical month, or the period in which the relationship between availability and demand is least favorable. In this way, the dynamic model can serve as a decision-support tool for planning the use of the Tribistovo Reservoir, reducing losses, managing demand, and adapting the water-supply system of the Municipality of Posušje to expected climatic and hydrological changes.

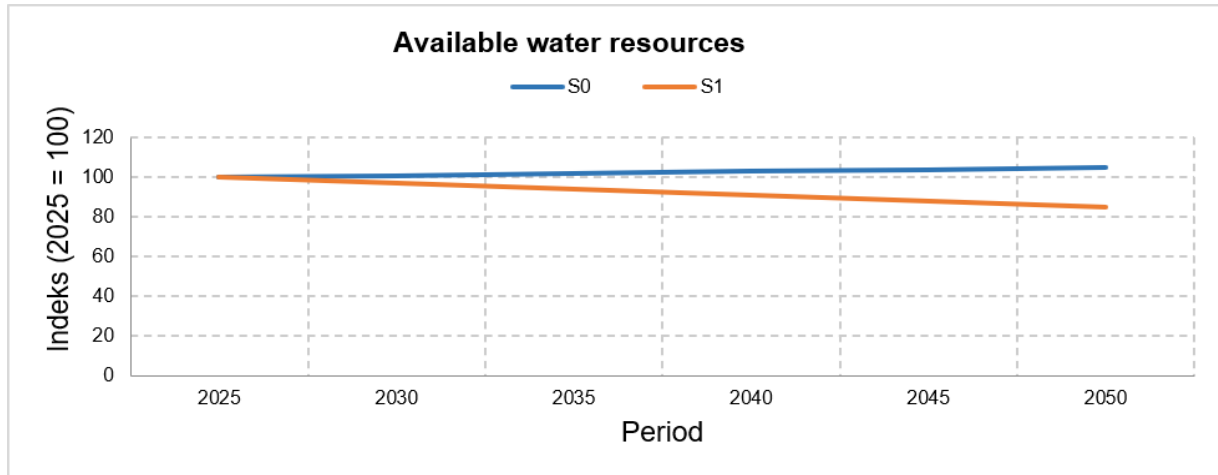


Figure 8. Change in available water resources, 2025–2050. Source: authors' own work; illustrative results of the authors' scenario-based STELLA model, requiring calibration against measured data from the Posušje–Tribistovo system; these are not official projections.

In the climate-change scenario, availability decreases from an index value of 100 to 85. This graph represents long-term climatic and hydrological pressure on the resource, rather than a projection of the reservoir's actual volume. $\Delta V_{\text{rasp}} = -15\%$

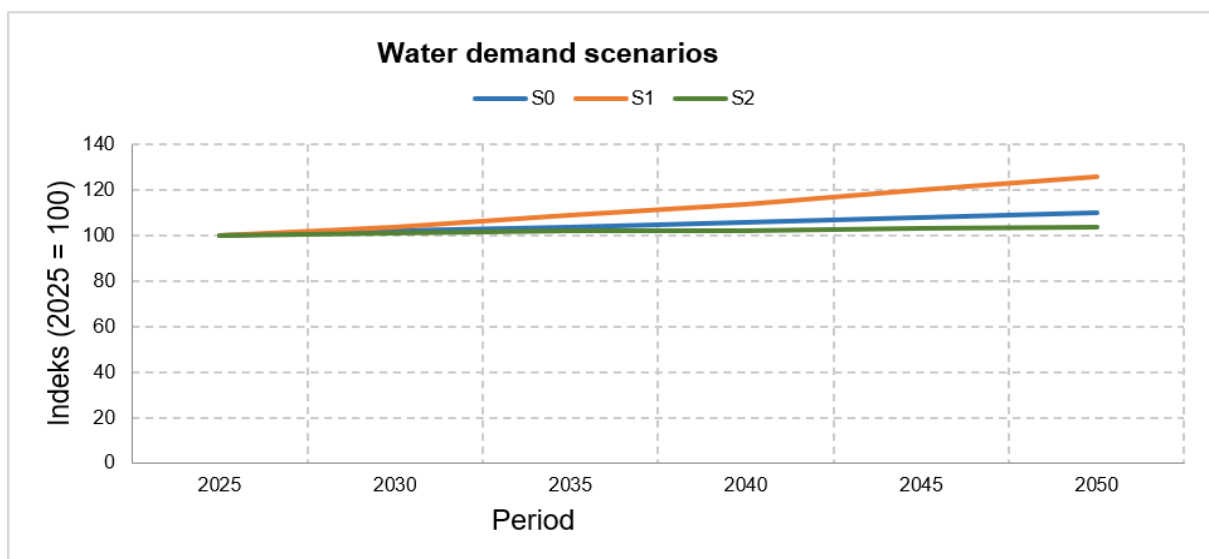


Figure 9. Water-demand scenarios for the Municipality of Posušje, 2025–2050. Source: authors'

S0 – reference development; S1 – climate impact without optimization; S2 – climate impact with optimization measures.

By 2050, the model yields: $S0 = 110$, $S1 = 126$, $S2 = 104$

so the effect of optimization compared to S1 amounts to:

$$\frac{126 - 104}{126} \times 100 \approx \boxed{17,5\%}$$

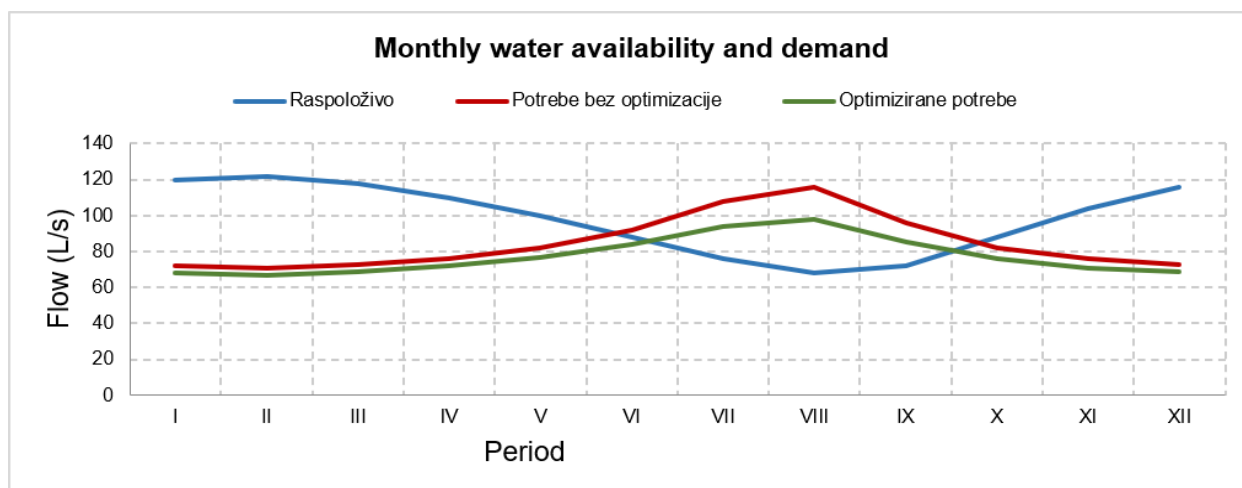


Figure 10. Monthly water availability and needs Source: author's own work;

The most critical month is August:

$$Q_{\text{rasp}} = 68 \text{ L/s} \quad Q_{\text{pot}} = 116 \text{ L/s}$$

so the deficit without optimization amounts to:

$$D_{VIII} = 116 - 68 = \boxed{48 \text{ L/s}}$$

With optimization:

$$D_{VIII, \text{opt}} = 98 - 68 = \boxed{30 \text{ L/s}}$$

Thus, the model shows a key characteristic of the karst area: the lowest water availability coincides in time with the highest consumption.

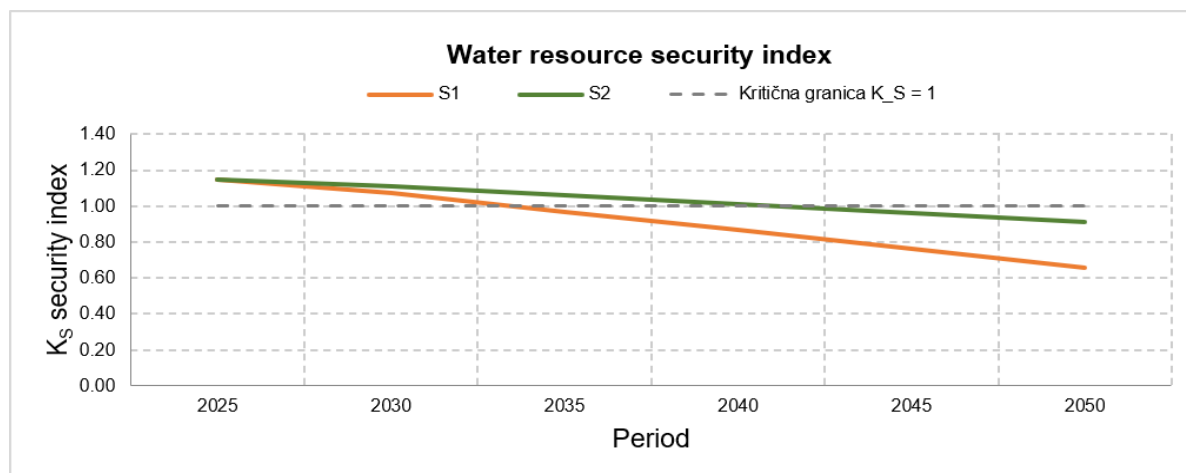


Figure 11. Water resources security index, 2025–2050. Source: author's own work;

The fourth graph combines previous results into a single indicator:

$$K_S(t) = \frac{Q_{\text{rasp}}(t)}{Q_{\text{pot}}(t)}$$

This graph is particularly important for the conclusion of the work. Without additional management measures:

$$K_S: 1,15 \rightarrow 0,66$$

while optimization gives:

$$K_{S,opt}: 1,15 \rightarrow 0,91$$

Management effect in 2050. can be expressed as:

$$\Delta K_S = K_{S,opt} - K_{S,bez} = 0,91 - 0,66 = \boxed{0,25}$$

Thus, optimization significantly increases water supply security, but according to this scenario alone, it is not sufficient to completely eliminate the long-term risk of deficit.

Note: Figures 8–11 show illustrative results of the author's STELLA scenario model. Values require calibration according to measured data from the Posušje–Tribistovo system and do not represent official projections.

5. SHORT DISCUSSION

In the discussion of this issue and the analysis of optimization results, all output results should be included on the basis of which a significant conclusion can be drawn, as well as a proposal for further research.

The next step is the presentation of performance indicators. We selected three main indicators that would be sufficient to depict the state of water resources in karst:

- water balance: $B_W = Q_{\text{rasp}} - Q_{\text{pot}}$
- water deficit: $D_W = \max(0, Q_{\text{pot}} - Q_{\text{rasp}})$
- security index: Particular attention should be given to: $K_S = \frac{Q_{\text{rasp}}}{Q_{\text{pot}}}$

$$K_{S,min} = \min(K_S)$$

because for the karst area the critical summer month is more important than the annual average value.

The effect of optimization can be represented with two important parameters:

a.) Reduction of deficit through optimization:

$$\Delta D_W = D_{W,S1} - D_{W,S2} \quad (19)$$

where:

ΔDW – water deficit reduction achieved through optimization, L/s;

$DW, S1$ – water deficit in scenario S1 without optimization, L/s;

$DW, S2$ – water deficit in scenario S2 with optimization, L/s

b.) Relative efficiency of optimization:

$$\eta_D = \frac{D_{W,S1} - D_{W,S2}}{D_{W,S1}} \cdot 100\% \quad (20)$$

where:

η_D – relative efficiency of deficit reduction, %;

$DW, S1$ – water deficit in scenario S1 without optimization, L/s;

$DW, S2$ – water deficit in scenario S2 with optimization, L/s.

This provides you with a very clear numerical indicator of how the proposed measures improve the system's condition.

Direct the summary of the discussion towards the following key issues, which may also be the subject of further research:

- Climate change and the availability of karst water resources – results presented in graphs,
- the role of the Tribistovo Reservoir as a regulator of the temporal mismatch between natural water availability and user demand.

In other words:

VIŠAK VODE U VLAŽNOM RAZDOBLJU → AKUMULACIJA → KORIŠTENJE U SUŠNOM RAZDOBLJU.

- Seasonal vulnerability of water supply, presented in the following correlations and question: Why, for example, during the season (dry period) do precipitation, aquifer recharge, and available water quantities decrease,

$$P \downarrow \Rightarrow R \downarrow \Rightarrow Q_{rasp} \downarrow$$

while temperature and water consumption increase simultaneously: $T \uparrow \Rightarrow Q_{pot} \uparrow$.

The effect of reducing water losses in the water supply system – this is important because reducing losses can increase the effective safety of the system without developing a new source.

Based on the previous questions and observations, a model of sustainable management can also be made and proposed. The proposed model can have five main components:

water resources monitoring → forecasting → reservoir management → loss reduction and consumption management → feedback control of system status.

Basic management criterion: $Q_{rasp}(t) \geq Q_{pot}(t)$

subject to: $D_W \rightarrow \min$

and $K_S \rightarrow \max$.

This shifts from the classical approach of "ensuring sufficient water quantity" towards adaptive water resources management based on the system status.

6. CONCLUSION

Water-resources management in karst areas is a complex process because of the specific hydrogeological characteristics of karst, the marked spatial and temporal variability of available water quantities, and the strong connection between surface water and groundwater. The high infiltration capacity of carbonate rocks, well-developed fracture–conduit systems, and rapid groundwater flow enable the formation of substantial groundwater reserves, while at the same time causing large fluctuations in spring discharge and increasing the system's sensitivity to prolonged droughts and pollution. Climate change further intensifies the management challenge. Rising air temperatures, changes in the seasonal distribution of precipitation, longer droughts, and more frequent hydrological extremes can cause a temporal mismatch between water availability and user demand. In Mediterranean karst areas, the critical period is usually summer, when reduced aquifer recharge and water availability may coincide with increased consumption. Sustainable management therefore cannot be based solely on total annual water quantities, but must include monthly and seasonal water balances, monitoring of aquifers and reservoirs, demand forecasting, and the timely activation of management measures.

This issue is particularly important for the Municipality of Posušje. The area has limited local sources, while the Tribistovo Reservoir is a key resource for the water-supply system. According to official municipal data, the reservoir has a total volume of approximately 5.0 million m³, of which about 4.5 million m³ is active storage, and a water-surface area of approximately 700,000 m². Water-supply security in Posušje therefore depends not only on the reservoir's total capacity, but also on its replenishment, seasonal water-level dynamics, the condition of its structures, losses in the distribution network, and changes in consumption. Continuous monitoring of water quantity and quality is particularly important. At Tribistovo, the water level, seepage, and groundwater levels are already monitored, while air temperature and precipitation are recorded at the meteorological station in Posušje. In 2025, a preliminary baseline study of biological and ichthyological parameters was also prepared, including data on water quantity and quality. [13–15]

Reducing losses in the water-supply network is an important element of future management. Older official data show that losses in 2015 were very high, at approximately

76%, indicating considerable potential to manage demand and improve system efficiency without having to provide an equivalent amount of additional water through increased abstraction. Because this is a historical figure, a contemporary model should use the current level of non-revenue water and actual network losses. [16]

Therefore, a basic criterion for sustainable management can be defined for Posušje

$$Q_{\text{rasp}}(t) \geq Q_{\text{pot}}(t)$$

that is, the security index: $K_S(t) = \frac{Q_{\text{rasp}}(t)}{Q_{\text{pot}}(t)}$

where values of $K_S < 1$ indicate a potential water deficit. The management objective should be to maintain the index above the critical value not only annually, but particularly during July, August, and September. Accordingly, optimization of the Posušje system should be based on integrated management linking the Tribistovo Reservoir, climatic and hydrological indicators, household and economic-sector consumption, network losses, available storage, and infrastructural and operational measures. Current investments in rehabilitation of the reservoir embankment, construction of a water-treatment plant, a new service reservoir, and associated infrastructure confirm that the security of this water resource is already treated as a strategic issue for the local water supply. In July 2026, a contract was also signed for grouting works on the Tribistovo dam embankment. [17]

Conceptually, the future management system can be represented as follows:

CLIMATE → PRECIPITATION → RECHARGE → TRIBISTOVO → AVAILABLE WATER

POPULATION + ECONOMY + CLIMATE → CONSUMPTION → DEFICIT/SURPLUS → MANAGEMENT MEASURES

Applying the dynamic STELLA model would make it possible to link these components into an integrated system and simulate different scenarios of climate change, consumption, and management measures. Such a model could serve as a tool for identifying critical summer periods, estimating future deficits, analyzing the effects of loss reduction, and determining the optimal operating regime of the reservoir.

In conclusion, sustainable management of water resources in the Municipality of Posušje, and for karst areas in general, should be oriented from the traditional approach of "ensuring a sufficient amount of water" toward integrated and adaptive management of the entire system. The Tribistovo Reservoir represents the central strategic water resource, while reducing losses, protecting water quality, continuous monitoring, managing peak summer demands, and

applying models to predict future conditions represent key measures to increase the system's resilience to climate change and to ensure long-term reliable water supply for the population and economy of Posušje.

Accordingly:

- karst water resources show pronounced seasonal variability;
- climate change may further increase the mismatch between availability and demand;
- the most critical period is the summer season;
- reducing losses and optimizing reservoir management can significantly increase system security;
- this dynamic OOM/STELLA model allows scenario assessment and can serve as a decision support tool.

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