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Research Article

Sustainable Water Resource Management in the Dinaric Karst Under Climate Change: A System Dynamics Approach for the Posušje Municipality, Bosnia and Herzegovina

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Abstract: Water resource management in karst regions presents a distinctive set of challenges that conventional hydrological approaches often fail to address adequately. The Dinaric karst of Herzegovina, characterised by highly permeable carbonate formations, complex underground conduit networks, and pronounced seasonal variability in recharge, exemplifies these difficulties. This paper develops a system dynamics model using object-oriented modelling principles in the STELLA environment to analyse the sustainability of water supply in the Municipality of Posušje, with particular attention to the role of the Tribistovo Reservoir. The model integrates climatic inputs, aquifer recharge dynamics, reservoir storage, distribution losses, and sectoral demand to simulate three scenarios between 2025 and 2050: a reference scenario, a climate change scenario without management intervention, and a climate change scenario incorporating optimisation measures. Results indicate that without intervention, the water security index for the system declines from 1.15 to 0.66 by 2050, with the most critical deficit occurring in August when availability drops to 68 L/s against a demand of 116 L/s. Optimisation measures—including network loss reduction from 35% to 20%, summer demand management, and improved reservoir operation—raise the terminal security index to 0.91 and reduce the August deficit by approximately 17.5%. The analysis underscores the importance of adaptive management strategies that address both supply-side and demand-side factors in karst systems, where the temporal mismatch between water availability and consumption is more consequential than annual water balance totals.

Keywords: *karst hydrology, water resource management, Dinaric karst, climate change adaptation, system dynamics, Tribistovo Reservoir, STELLA modelling*

1. Introduction

Water resources in karst regions occupy a paradoxical position in hydrological science and water management practice. On one hand, karst aquifers represent some of the most productive groundwater reservoirs in the world, capable of yielding substantial quantities of high-quality water through large karst springs. On the other hand, the same geological characteristics that make these aquifers productive—high permeability, well-developed conduit networks, and rapid groundwater flow—also render them exceptionally vulnerable to contamination and highly variable in their seasonal yield. More than a quarter of the global population depends on water derived from karst aquifers, yet the management of these resources remains insufficiently understood and inadequately integrated into water policy frameworks.

The Dinaric karst, which extends along the eastern Adriatic coast through Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, and Albania, constitutes one of the most extensively karstified regions in Europe. The carbonate rock formations of this region, primarily limestone and dolomite, have undergone millions of years of chemical dissolution, creating complex systems of fractures, caverns, and underground channels through which water moves with remarkable speed. The practical consequence of this geological heritage is that surface water is scarce while groundwater is abundant but unevenly distributed in time and space. Rivers may disappear into sinkholes only to reappear kilometres away as powerful springs; catchment boundaries at the surface rarely coincide with actual hydrogeological divides; and the response of springs to precipitation events can be measured in hours rather than days or weeks.

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These characteristics create a fundamental management problem that conventional water resource planning tools struggle to address. The total annual precipitation in the Dinaric karst is substantial, often exceeding 1,500 mm in the higher elevations. However, this precipitation is concentrated in the cooler months, while water demand peaks during the hot, dry summers when tourism and agricultural irrigation add pressure to already-reduced supplies. The karst aquifer, despite its enormous storage capacity, cannot retain water effectively during extended dry periods because the conduit systems drain rapidly. A reservoir such as Tribistovo, which serves the Municipality of Posušje in western Herzegovina, becomes the critical infrastructure that bridges this temporal gap by storing winter and spring runoff for summer distribution.

This paper examines the sustainability of water resource management in the Posušje municipality, a representative case study within the Dinaric karst region. The specific objectives are threefold: first, to develop a system dynamics model that captures the essential interactions between climate, hydrology, infrastructure, and demand in a karst water supply system; second, to simulate future scenarios that account for the anticipated impacts of climate change on both water availability and consumption patterns; and third, to evaluate the effectiveness of management interventions designed to improve system resilience. The analysis is positioned within the broader context of transboundary water governance in the Dinaric region, which has received increasing attention through international initiatives such as the DIKTAS project implemented by UNDP and UNESCO.

2. The Hydrogeological Context

2.1 Geological Structure and Karstification

The geological foundation of the Dinaric karst consists predominantly of Mesozoic carbonate rocks, particularly thick-bedded limestones and dolomites that were deposited on shallow marine platforms during the Triassic, Jurassic, and Cretaceous periods. Subsequent tectonic activity associated with the Alpine orogeny fractured these formations extensively, creating networks of faults, joints, and bedding planes that provided initial pathways for water infiltration. Over geological time, the chemical dissolution of carbonate minerals by water enriched with carbon dioxide widened these pathways into the complex conduit systems that characterise karst aquifers today.

The karstification process has produced a distinctive vertical zonation within the carbonate massif. At the surface, the epikarst represents an intensely weathered and fractured zone where precipitation water is temporarily retained before percolating downward. Below this, the unsaturated or vadose zone contains mostly vertical channels and fissures through which water descends under gravity. The saturated or phreatic zone at the base of the system contains the main groundwater body, which discharges through springs and seepage faces where the water table intersects the land surface or the base level of erosion.

A critical feature of karst aquifers is the simultaneous existence of two distinct flow regimes. Diffuse flow occurs through the rock matrix and smaller fractures, characterised by relatively slow velocities and long residence times. Concentrated flow, by contrast, occurs through well-developed conduits and channels, where water can travel at velocities of hundreds of metres per day or even faster during flood events. The proportion of flow carried by each pathway varies seasonally and depends on the degree of karst development in the specific aquifer. In the Dinaric karst, conduit flow often dominates, which explains the rapid response of springs to precipitation and the equally rapid decline in discharge during dry periods.

2.2 The Tribistovo System

The Municipality of Posušje, located in the western Herzegovina region of Bosnia and Herzegovina, occupies an area of approximately 461 km² within the high karst zone of the Dinarides. The municipality experiences a modified Mediterranean climate, with hot, dry summers and relatively mild, wet winters. Mean annual precipitation ranges between 1,200 and 1,800 mm depending on elevation, but the seasonal distribution is highly uneven, with the majority falling between October and March.

The Tribistovo Reservoir, constructed in the 1970s, serves as the principal water source for the Posušje water supply system. The reservoir has a total volume of approximately 5.0 million cubic metres, of which approximately 4.5 million cubic metres constitutes active storage available for water supply operations. The water surface area extends over approximately 0.70 km² at full supply level. The reservoir receives inflows from a catchment dominated by karst terrain, including several spring sources that contribute both diffuse and concentrated recharge depending on hydrological conditions.

The water supply system of Posušje has historically experienced significant operational challenges. Network losses have been documented at high levels, with a 2015 assessment reporting losses of approximately 76% of treated water entering the distribution system. This extraordinarily high loss rate, while reflecting the deteriorated condition of the distribution infrastructure, also indicates substantial potential for demand-side management. A more recent estimate places network losses at approximately 35% under improved operating conditions, suggesting that rehabilitation efforts have produced measurable but incomplete progress.

3. Climate Change Impacts on Karst Water Resources

3.1 Observed and Projected Changes

The Mediterranean region, including the Dinaric karst, is widely recognised as a climate change hotspot where warming trends and precipitation changes are occurring more rapidly than the global average. A recent analysis of meteorological records from Slovenia‘s Dinaric karst region documents that between 1961 and 2020, mean temperatures increased by approximately 2.5°C, precipitation totals declined by 50 to 400 mm depending on location, and the number of days with snow cover decreased by 30 to 60%. These trends have direct implications for karst hydrology because snowmelt contributes to spring recharge in many Dinaric catchments, and earlier snowmelt shifts the timing of recharge away from the spring and summer months when water is most needed.

Projections for the Mediterranean region consistently indicate further warming and drying through the twenty-first century. Under the most severe emission scenarios, mountain karst aquifers in the Mediterranean could experience reductions in recharge exceeding 75% by the end of the century. Even under more moderate scenarios, significant reductions in summer and autumn recharge are anticipated. In karst systems, the hydrological consequences of climate change extend beyond simple changes in annual water balance because the highly nonlinear relationship between precipitation, infiltration, and spring discharge means that modest reductions in rainfall can produce disproportionately large reductions in dry-season availability.

3.2 The Seasonality Problem

Perhaps the most important climate-related challenge for karst water management is the intensification of seasonal contrasts. Available evidence suggests that while total annual precipitation may decline moderately, the distribution of that precipitation is becoming increasingly concentrated into shorter, more intense events separated by longer dry periods. For karst aquifers, intense rainfall events are not necessarily beneficial because a substantial proportion of the water from such events may pass rapidly through the conduit system and discharge at springs before it can be stored in the aquifer matrix. The effective recharge, which is the portion of precipitation that actually replenishes the groundwater system, may decline even if total precipitation remains relatively constant.

At the same time, rising temperatures increase water demand for domestic use, irrigation, and tourism-related activities. In the Posušje area, summer water consumption increases substantially due to garden irrigation, swimming pool filling, and the general increase in outdoor water use that accompanies hot weather. The coincidence of reduced availability and increased demand during the summer months creates the critical period for water supply security in karst regions. This temporal mismatch—rather than absolute water scarcity—is the defining management challenge.

4. Methodology

4.1 System Dynamics Modelling Approach

The complexity of karst water resource systems, characterised by nonlinear feedback loops, multiple interacting components, and significant time delays, makes them well suited to system dynamics modelling. This approach, developed initially by Forrester and subsequently refined by Sterman and others, represents systems as networks of stocks (state variables that accumulate over time), flows (rates of change that affect stocks), and auxiliary variables that define the relationships between system components.

The STELLA software environment, developed by isee systems, provides a graphical interface for constructing system dynamics models using object-oriented principles. The modelling process in STELLA involves defining a conceptual model that captures the essential structure of the system, quantifying the relationships between variables through mathematical equations, and then simulating the behaviour of the system over time under alternative assumptions about external drivers and internal parameters. The software also includes optimisation capabilities that can be used to identify parameter values or management strategies that best achieve specified objectives.

For this application, the model was constructed with four interconnected modules representing the principal subsystems of the karst water supply system: the catchment module, the aquifer module, the reservoir and distribution module, and the demand module. These modules are linked through water fluxes that represent recharge, abstraction, storage changes, losses, and consumption.

4.2 Model Structure and Equations

Catchment and Recharge Module

The catchment module computes effective recharge to the karst aquifer based on precipitation, evapotranspiration, and an infiltration coefficient that reflects the proportion of effective precipitation that enters the groundwater system. The recharge equation is expressed as:

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

where R(t) is the effective recharge in cubic metres per month, P(t) is precipitation in millimetres per month, ET(t) is actual evapotranspiration in millimetres per month, A is the catchment area in square metres, and C_i(t) is the effective infiltration coefficient (dimensionless). The factor 10^{-3} converts millimetres to metres. The max function ensures that recharge cannot be negative when evapotranspiration exceeds precipitation, a situation that can occur during extended dry periods.

The infiltration coefficient C_i varies seasonally and depends on antecedent moisture conditions, soil

development in the epikarst, and the intensity of precipitation events. For the Posušje catchment, values of C_i typically range from 0.25 during dry summer conditions to 0.70 during wet winter periods when the epikarst is saturated and infiltration capacity is high.

Aquifer Storage Module

The karst aquifer is represented as a single storage reservoir with a dynamic water balance:

$$dV_A/dt = R(t) - Q_{spring}(t) - Q_{pump}(t) - Q_{overflow}(t)$$

where V_A is the volume of water stored in the aquifer (m³), R(t) is recharge (m³/month), Q_spring(t) is natural spring discharge (m³/month), Q_pump(t) is groundwater abstraction for water supply (m³/month), and Q_overflow(t) is overflow from the aquifer when storage exceeds the maximum capacity (m³/month).

Spring discharge is modelled as a nonlinear function of aquifer storage, reflecting the dual-porosity behaviour of karst aquifers. The relationship takes the form:

$$Q_{spring}(t) = k_1 \times V_A(t)^{b_1} + k_2 \times V_A(t)^{b_2}$$

where k_1 and b_1 describe the slow, diffuse flow component and k_2 and b_2 describe the fast, conduit flow component. The exponents are typically greater than one for the conduit component, reflecting the threshold behaviour of conduit activation, while the diffuse component may exhibit a more nearly linear response.

Reservoir Module

The Tribistovo Reservoir is modelled with a monthly water balance:

$$dV_R/dt = Q_{inflow}(t) - Q_{withdrawal}(t) - Q_{spill}(t) - Q_{evap}(t)$$

where V_R is the reservoir volume (m³), Q_inflow(t) is the total inflow from springs and captured surface water (m³/month), Q_withdrawal(t) is the withdrawal for water supply (m³/month), Q_spill(t) is spillage when the reservoir is full (m³/month), and Q_evap(t) is evaporation loss (m³/month). The reservoir has a maximum active storage capacity of 4.5 million m³, below which no spillage occurs, and a minimum operating volume that must be maintained to protect water quality and aquatic habitat.

Demand Module

Total water demand is computed as the sum of domestic, commercial, institutional, and other uses:

$$Q_{demand}(t) = Q_{domestic}(t) + Q_{commercial}(t) + Q_{institutional}(t) + Q_{other}(t)$$

Each demand component is estimated from population and economic activity projections and modified by a seasonal factor that reflects increased consumption during summer months. The seasonal factor is derived from the ratio of observed monthly consumption to average annual consumption, which in the Posušje system exhibits a pronounced peak in July and August when temperatures are highest.

A climate adjustment factor is applied to account for the effect of temperature increases on water consumption:

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

where $\Delta T(t)$ is the temperature increase relative to the reference period (°C), $I_D(t)$ is a normalised drought index, and α and β are sensitivity coefficients. Based on literature values for Mediterranean regions, α is set at 0.05 per °C and β at 0.10 per unit of drought index.

Loss and Efficiency Module

Water losses in the distribution network are modelled as a percentage of the water entering the system:

$$Q_{loss}(t) = L(t) \times Q_{input}(t)$$

where L(t) is the loss rate (dimensionless) and Q_input(t) is the total water input to the distribution system. The loss rate is treated as a management variable that can be reduced through rehabilitation and active leakage control. For the Posušje system, the baseline loss rate is assumed to decline from 35% in 2025 to 20% by 2050 under the optimisation scenario, reflecting a phased programme of infrastructure renewal.

4.3 Scenario Definitions

Three scenarios were developed to explore the range of possible futures for the Posušje water supply system:

Scenario S0 (Reference): This scenario assumes no additional climate change impacts beyond those already observed and no new management interventions. Precipitation and temperature follow historical patterns, demand grows modestly with population and economic development, and network losses remain at their current level.

Scenario S1 (Climate Change without Optimisation): This scenario incorporates projected climate change impacts, including a gradual decline in precipitation of 15% by 2050, temperature increases averaging 0.04°C per year, and an increased frequency of drought years. Demand is elevated by the climate adjustment factor. Network losses remain at 35%, and no additional demand management measures are implemented.

Scenario S2 (Climate Change with Optimisation): This scenario includes the same climate change impacts as S1 but adds a package of management interventions. Network losses are reduced from 35% to 20% through infrastructure rehabilitation and active leakage control. A summer demand management programme, including public education, tariff restructuring, and restrictions on non-essential outdoor use, achieves a 15% reduction in peak summer consumption. Reservoir operation is optimised to maintain higher storage levels entering the summer season and to reduce spillage during wet periods.

4.4 Model Calibration and Validation

The model was calibrated using available hydrological and operational data from the Posušje water supply system. Historical precipitation and temperature records were obtained from the meteorological station at Posušje. Spring discharge measurements and reservoir level records provided the basis for estimating aquifer parameters and reservoir operating characteristics. Water consumption data were derived from billing records of the municipal water utility.

The calibration process involved adjusting the infiltration coefficient, aquifer discharge parameters, and demand coefficients to achieve the best fit between simulated and observed spring discharge, reservoir levels, and consumption patterns. The STELLA optimisation function was used for this purpose, minimising the sum of squared errors between simulated and observed values. Given the illustrative nature of the data and the simplifications inherent in any model of a complex karst system, the model should be regarded as a tool for exploring relative differences between scenarios rather than as a precise predictor of future conditions.

5. Results

5.1 Available Water Resources

Under the reference scenario S0, the available water resource index, normalised to 100 in 2025, declines only slightly over the simulation period, reaching approximately 107 by 2050. This slight increase reflects the assumption of stable climatic conditions and gradual improvements in system efficiency that are implicit in the reference case.

Under the climate change scenario S1, the available water resource index declines from 100 in 2025 to approximately 85 by 2050, a reduction of 15% (Figure 8). This decline is driven primarily by reduced precipitation and increased evapotranspiration, with the latter effect intensifying as temperatures rise. The decline is not uniform across years; drought years produce sharper reductions that are only partially offset by wetter years.

The optimisation scenario S2 does not directly affect the available water resource, which is determined by climatic and hydrogeological factors beyond management control. However, by reducing losses and managing demand, the optimisation measures effectively increase the proportion of available water that reaches consumers, thereby improving the relationship between availability and effective supply.

5.2 Water Demand

Total water demand under scenario S0 remains relatively stable, increasing modestly from an index value of 100 in 2025 to 110 by 2050. This increase reflects population growth and economic development in the Posušje area, partially offset by improvements in water use efficiency.

Under scenario S1, demand rises more steeply, reaching an index value of 126 by 2050. The additional increase compared to S0 is attributable to the climate adjustment factor, which captures the effect of higher temperatures and more frequent drought conditions on water consumption. The demand increase is particularly pronounced during summer months, when the climate effect is most intense.

Under scenario S2, demand reaches an index value of 104 by 2050, substantially lower than in S1. The difference between S1 and S2 demand reflects the effect of demand management measures, which reduce consumption by approximately 17.5% relative to the unmanaged climate change scenario. The management measures are most effective during peak summer periods when the potential for conservation is greatest.

5.3 Monthly Deficit Analysis

The monthly water balance reveals the critical nature of seasonal water availability in the karst system. During winter and spring months, available water exceeds demand under all scenarios, and surplus water is stored in the Tribistovo Reservoir or discharged through spillways. However, as summer progresses, the situation reverses dramatically.

August emerges as the most critical month in all scenarios. Under the climate change scenario S1, available water in August declines to 68 L/s while demand rises to 116 L/s, producing a deficit of 48 L/s. This represents a substantial shortfall that cannot be met from existing sources without severe restrictions on consumption.

Under scenario S2, the optimisation measures reduce the August deficit to 30 L/s. The reduction is achieved through two mechanisms: demand management lowers the August demand from 116 L/s to 98 L/s, and loss reduction increases the effective supply from the available resource. While the deficit is not eliminated, it is reduced by approximately 37.5%, which would substantially reduce the severity of restrictions that might be required during critical periods.

5.4 Water Security Index

The water security index K_S, defined as the ratio of available water to demand, provides an integrated measure of system performance. Under the reference scenario S0, K_S remains above 1.0 throughout the simulation period, indicating that water availability exceeds demand on an annual average basis.

Under scenario S1, K_S declines from an initial value of 1.15 in 2025 to 0.66 by 2050. Values below 1.0 indicate that demand exceeds availability, meaning that the system cannot meet all demands from available sources without drawing down storage below sustainable levels. The decline is most rapid during the 2035–2050 period, when the cumulative effects of climate change become increasingly pronounced.

Under scenario S2, the optimisation measures slow the decline in K_S. The index reaches 0.91 by 2050, which, while still below 1.0, represents a much more manageable situation than the 0.66 value under S1. The difference in K_S between scenarios, 0.25, represents the management effect and quantifies the improvement in water security that can be achieved through the optimisation package.

It is important to note that annual average K_S values conceal the more severe seasonal deficits that occur during summer months. Even when K_S exceeds 1.0 on an annual basis, monthly values may fall well below this threshold during July, August, and September. For the karst system, the critical metric is the minimum monthly K_S value, which determines the severity of restrictions that must be imposed during dry periods.

5.5 Sensitivity Analysis

Sensitivity analysis was conducted to assess how the model results respond to changes in key parameters and assumptions. The parameters tested included the climate change precipitation reduction factor, the temperature sensitivity of demand, the infiltration coefficient, and the assumed loss reduction rate.

The results are most sensitive to the precipitation reduction factor. A 10% reduction in precipitation produces a disproportionately larger reduction in dry-season spring discharge, reflecting the nonlinear relationship between recharge and discharge in karst aquifers. This sensitivity underscores the importance of accurately characterising future precipitation changes and of implementing management measures that can buffer the system against reductions in natural recharge.

The temperature sensitivity of demand also has a significant effect on water security. If the temperature sensitivity coefficient is doubled from 0.05 to 0.10 per °C, the August deficit under S1 increases from 48 L/s to approximately 58 L/s. This finding highlights the importance of demand management strategies that specifically target temperature-sensitive uses such as outdoor irrigation and pool filling.

The model is less sensitive to the assumed loss reduction rate, primarily because loss reduction affects the entire distribution system and therefore produces broad but relatively modest improvements in delivered water. Nevertheless, loss reduction remains an important component of the optimisation package because it reduces the total abstraction required from the reservoir and thereby preserves storage for critical periods.

6. Discussion

6.1 The Karst Water Management Challenge

The results of this modelling exercise confirm that the fundamental challenge of water resource management in the Dinaric karst is not absolute scarcity but temporal mismatch. Even under the most pessimistic climate change scenario, total annual precipitation in the Posušje area remains substantial, sufficient in principle to meet annual water demands. The problem is that this precipitation is not available when it is needed. The karst aquifer, despite its enormous storage potential, cannot effectively retain water from the wet season to the dry season because the conduit-dominated flow system drains rapidly. The Tribistovo Reservoir fills this gap, but its capacity is limited relative to the volume of water that passes through the system during the wet season.

This mismatch has profound implications for management strategy. Traditional water resource planning, focused on ensuring adequate annual supply through the development of new sources, is poorly suited to karst systems. What is required instead is a dual strategy that addresses both the supply side—through reservoir operation, loss reduction, and possibly artificial recharge—and the demand side through conservation, efficiency, and demand management. The optimisation scenario S2 demonstrates that such a dual strategy can substantially improve water security outcomes, but it also shows that even aggressive management cannot fully eliminate the risk of summer deficits under severe climate change.

6.2 The Role of Reservoirs in Karst Systems

The Tribistovo Reservoir plays a critical role in the Posušje water supply system, effectively creating a managed buffer between the natural variability of karst spring discharge and the relatively constant demand of consumers. The reservoir‘s value lies not in its total storage capacity—which is modest relative to the total annual yield of the catchment—but in its ability to shift water from periods of surplus to periods of deficit.

Reservoir operation in karst systems presents particular challenges that are not encountered in less variable hydrological environments. The highly nonlinear relationship between precipitation, recharge, and spring discharge means that inflow to the reservoir can vary by an order of magnitude between wet and dry periods, and can change rapidly in response to individual storm events. Reservoir managers must balance the need to maintain sufficient storage to meet summer demand against the risk of spillage during wet periods—water that is lost from the system and cannot be recovered.

Improved reservoir operation, as represented in scenario S2, involves several specific measures. These include: maintaining higher storage levels entering the summer season by reducing winter withdrawals when demand is low; using seasonal forecasts to inform decisions about when to begin accumulating storage; and implementing active spill management to capture early wet-season flows that might otherwise be lost. The effectiveness of these measures depends on the availability of reliable hydrological data and forecasts, which requires investment in monitoring infrastructure and analytical capacity.

6.3 Demand Management in Karst Water Systems

Demand management has traditionally received less attention than supply-side measures in karst water systems, partly because the apparent abundance of water in wet periods creates a false sense of security. However, the results of this study show that demand management can make a substantial contribution to water security, particularly during critical summer months.

The 15% summer saving assumed in scenario S2 is modest compared to what is technically achievable in many Mediterranean water systems. Studies have documented savings of 20% or more through a combination of tariff restructuring, public education, use restrictions, and technology adoption. The challenge in Posušje is that the water utility has historically faced financial and institutional constraints that limit its capacity to implement comprehensive demand management programmes.

Tariff design is a particularly powerful tool that has been underutilised. Seasonal tariffs that charge higher rates during summer months provide a direct economic incentive for conservation precisely when water is most scarce. Inclining block tariffs, where the marginal price increases with consumption, achieve a similar effect while also generating revenue that can be invested in system improvements. The design of such tariffs must take into account equity considerations, ensuring that essential water uses remain affordable for low-income households.

6.4 Loss Reduction and Infrastructure Renewal

The high level of water losses in the Posušje distribution network—historically documented at 76% and more recently estimated at 35%—represents both a challenge and an opportunity. From a system efficiency perspective, losses of this magnitude are unacceptable and indicate that a substantial proportion of the water abstracted from the Tribistovo Reservoir never reaches consumers. From a management perspective, however, the high loss rate means that relatively modest investments in infrastructure rehabilitation can produce significant improvements in delivered water supply without requiring additional abstraction from already-stressed sources.

Loss reduction programmes typically involve a combination of activities: systematic leakage detection and repair, replacement of deteriorated pipes, installation of pressure management systems, and improved metering and billing systems. In the Posušje context, the aging asbestos-cement pipes that constitute a significant portion of the network are particularly vulnerable to cracking and failure, and their replacement should be a priority for investment.

The economic analysis of loss reduction investments is generally favourable. The marginal cost of water saved through leakage control is often lower than the marginal cost of developing new water sources, particularly in karst regions where new source development is expensive and environmentally sensitive. However, the financing of such investments remains a challenge for municipal utilities that operate under tight budget constraints and face political pressure to keep tariffs low.

6.5 Climate Change Adaptation in Karst Systems

The analysis presented in this paper highlights the vulnerability of karst water systems to climate change and the importance of adaptation planning. The projected decline in the water security index from 1.15 to 0.66 under the climate change scenario without optimisation would have severe consequences for the Posušje area, including prolonged and severe water restrictions during summer months, potential economic losses in water-dependent sectors, and deterioration of ecosystem health in groundwater-dependent habitats.

Adaptation to climate change in karst water systems requires a portfolio approach that addresses both supply and demand and that combines infrastructure investments with institutional and behavioural changes. The optimisation scenario evaluated in this paper represents one such portfolio, but it is by no means exhaustive. Other adaptation measures that warrant consideration include: the development of alternative water sources such as desalination or water reuse; managed aquifer recharge to enhance storage of surplus wet-season water; inter-basin water transfers from less climate-sensitive catchments; and the establishment of water banks or other institutional mechanisms for allocating water during scarcity.

The transboundary dimension of karst water management adds another layer of complexity to adaptation planning. The Dinaric karst aquifer system extends across the borders of Bosnia and Herzegovina, Croatia, Montenegro, and Albania, and the management decisions taken in one country can affect water availability in neighbouring countries. International cooperation frameworks such as the DIKTAS project provide a platform for coordinated adaptation planning, but their effectiveness depends on the willingness of participating countries to share data, harmonise policies, and implement joint management measures.

7. Conclusion

This study has developed and applied a system dynamics model to analyse the sustainability of water resource management in the karst region of Herzegovina, using the Municipality of Posušje and the Tribistovo Reservoir as a case study. The model integrates climatic, hydrological, infrastructural, and demand components to simulate the behaviour of the water supply system under alternative scenarios for the period 2025–2050.

The principal findings are as follows. First, the Posušje water supply system is intrinsically vulnerable to seasonal water shortages, a vulnerability that arises from

the karst aquifer's limited capacity to retain water from wet periods to dry periods. The Tribistovo Reservoir provides a crucial buffering function but is insufficient on its own to guarantee water security under climate change. Second, climate change is projected to reduce available water resources while simultaneously increasing water demand, particularly during summer months, thereby intensifying the seasonal mismatch between availability and demand. Third, management interventions that combine demand management with loss reduction and improved reservoir operation can substantially improve water security outcomes, although they cannot fully eliminate the risk of deficit under severe climate change.

The most critical period for the Posušje system is August, when the combination of low water availability and high demand creates the greatest stress on the supply system. Under the climate change scenario without optimisation, the August deficit amounts to 48 L/s, which would require severe restrictions on consumption. Optimisation reduces this deficit to 30 L/s, a significant improvement but not a complete solution.

The practical implications of this analysis are clear. Water managers in the Posušje area should prioritise the implementation of demand management programmes, particularly those targeting summer consumption; accelerate the rehabilitation of the distribution network to reduce losses; and optimise the operation of the Tribistovo Reservoir to maximise the availability of stored water during critical periods. These measures should be implemented as part of a comprehensive adaptation strategy that anticipates the effects of climate change on both water resources and water demands.

Future research should focus on improving the characterisation of karst aquifer dynamics through more extensive hydrogeological investigations and monitoring; refining the model to include spatial variability in recharge, storage, and discharge; exploring the effectiveness of additional adaptation measures such as managed aquifer recharge and water reuse; and assessing the institutional and financial barriers to the implementation of sustainable water management in the Dinaric karst region.

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