

Original Research

**NATURE-BASED SOLUTIONS UNDER CLIMATE CHANGE: AN OVERVIEW OF
KEY FINDINGS FROM THE UNSFA PILOT SITE WITHIN THE DALIA AND
SWIM PROJECTS**

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Abstract

Constructed wetlands (CWs) are nature-based solutions increasingly applied for domestic wastewater treatment, yet their performance is sensitive to climatic conditions. This study presents an overview of key findings from the Gložan CW pilot site in Vojvodina, Serbia, assessed within the framework of the DALIA and SWIM Horizon Europe projects. Long-term treatment performance analysis demonstrated high and stable removal efficiency for organic matter, with average BOD₅ removal exceeding 90%, while phosphorus and suspended solids exhibited greater variability. Seasonal analysis indicated significantly lower BOD₅ removal during summer. Future climate projections were analysed using an ensemble of eight bias-corrected EURO-CORDEX regional climate models under the RCP8.5 scenario. Results indicate a progressive increase in thermal stress, with tropical days nearly doubling by 2071–2100, alongside a 49% reduction in frost days, a 21% increase in maximum one-day precipitation, and a modest decline in the Seljaninov Hydrothermal Coefficient. These changes present both opportunities — through extended frost-free operational seasons — and challenges, including increased hydraulic loading from extreme rainfall and moisture deficits during the growing season. Integrating climate adaptation into the long-term management of nature-based wastewater treatment systems is strongly recommended.

Keywords: constructed wetlands, nature-based solutions, wastewater treatment, climate change, treatment performance.

INTRODUCTION

Constructed wetlands are increasingly recognized as cost-effective nature-based solutions for the treatment of domestic wastewater, industrial effluents, and urban runoff [1]. These systems utilize natural biogeochemical and physical processes to remove organic matter and nutrients, while simultaneously providing additional environmental and social benefits [2]. As constructed wetlands represent nature-based solutions that utilize natural processes for pollutant removal, their performance may be influenced by changes in weather conditions caused by climate change. Numerous studies worldwide have investigated the impacts of climatic conditions, seasonal variability, and climate extremes on the pollutant removal efficiency of constructed wetlands [3–9].

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This study focused on a constructed wetland system that has been used for wastewater treatment in the settlement of Gložan, located in the Vojvodina region of Serbia, through previously published studies [6,8,9] and new analyses conducted within this paper. Research activities related to the Gložan constructed wetland system started within the Horizon Europe project DALIA as part of the demo site activities at “Begečka Jama”, whose activities were completed in 2025, and are continuing through newly initiated activities within the Horizon Europe project SWIM.

MATERIALS AND METHODS

Study Area

The study was conducted in relation to a constructed wetland (CW) system for wastewater treatment located in Gložan, a settlement in the Vojvodina region, northern Serbia (approximately 45.27°N, 19.57°E) (Figure 1). The region is characterised by a continental climate with warm summers and cold winters. Given that temperature and moisture conditions directly govern microbial community dynamics, plant productivity, and biogeochemical cycling within CW systems, detailed climate analysis is essential for contextualising both current treatment performance and long-term system sustainability.



Figure 1 Location of the constructed wetland in Gložan and an aerial view of the site

Treatment Performance of the Gložan Constructed Wetland

In addition to the climate change analysis, the long-term treatment performance of the Gložan constructed wetland (CW) was evaluated using previously published monitoring results [6]. The analysis included pollutant removal efficiency for biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), suspended solids (SS), ammonium nitrogen (NH₄-N), total nitrogen (TN), and total phosphorus (TP). Descriptive statistical analysis, seasonal comparison, and trend analysis were performed in order to assess treatment stability and long-term operational behaviour of the CW system. Seasonal differences were evaluated using analysis of variance (ANOVA), while temporal trends were analysed through regression analysis and significance testing.

Climate Data and Model Ensemble

Historical reference and projected future climate conditions were analysed using an ensemble of eight [10] bias-corrected Regional Climate Models (RCMs) from the EURO-CORDEX project database, at a spatial resolution of 0.1° (~11 km). The historical

period was used as a model-based reference baseline to ensure methodological consistency with future climate projections. The selection of this specific ensemble was based on the recommendations of the Digital Climate and Climate Change Atlas of the Republic of Serbia, developed within the framework of the project “Advancing Medium and Long-Term Adaptation Planning in the Republic of Serbia,” funded by the Green Climate Fund in collaboration with the Ministry of Agriculture, Forestry and Water Management and the Ministry of Environmental Protection of the Republic of Serbia [10]. This ensemble has undergone verification of climate simulations over the territory of Serbia and is considered an appropriate multi-model configuration for national and regional climate assessments [10].

The eight ensemble members comprised combinations of three Global Climate Models (GCMs) — ICHEC-EC-EARTH, MOHC-HadGEM2-ES, and MPI-M-MPI-ESM-LR — dynamically downscaled by four regional models: CLMcom-CCLM4-8-17, DMI-HIRHAM5, KNMI-RACMO22E, and MPI-CSC-REMO2009. The full list of ensemble members is provided in Table 1.

Table 1 EURO-CORDEX regional climate model ensemble used in this study [10]

Ensemble Member Acronym	Regional Model	Global Model
gcm-ICHEC-EC-EARTH-rcm-CLMcom-CCLM4-8-17	CLMcom-CCLM4-8-17	ICHEC-EC-EARTH
gcm-ICHEC-EC-EARTH-rcm-DMI-HIRHAM5	DMI-HIRHAM5	ICHEC-EC-EARTH
gcm-ICHEC-EC-EARTH-rcm-KNMI-RACMO22E	KNMI-RACMO22E	ICHEC-EC-EARTH
gcm-MOHC-HadGEM2-ES-rcm-CLMcom-CCLM4-8-17	CLMcom-CCLM4-8-17	MOHC-HadGEM2-ES
gcm-MOHC-HadGEM2-ES-rcm-KNMI-RACMO22E	KNMI-RACMO22E	MOHC-HadGEM2-ES
gcm-MPI-M-MPI-ESM-LR-rcm-CLMcom-CCLM4-8-17	CLMcom-CCLM4-8-17	MPI-M-MPI-ESM-LR
gcm-MPI-M-MPI-ESM-LR-rcm-MPI-CSC-REMO2009	MPI-CSC-REMO2009	MPI-M-MPI-ESM-LR (r1i1p1)
gcm-MPI-M-MPI-ESM-LR-rcm-MPI-CSC-REMO2009	MPI-CSC-REMO2009	MPI-M-MPI-ESM-LR (r2i1p1)

For each ensemble member, median values across the eight models were calculated for each climate index and time period, following standard practice for ensemble-based climate projections. The use of the ensemble median rather than the mean reduces sensitivity to outlier model realisations and provides a robust central estimate of projected change.

All future climate projections were conducted using the Representative Concentration Pathway 8.5 (RCP8.5) scenario, which describes a high greenhouse gas emission trajectory characterized by continuously increasing emissions throughout the 21st century. The RCP8.5 scenario from the IPCC Fifth Assessment Report (AR5) was selected because recent climate trends in Serbia already correspond to temperature changes projected under this scenario for the coming decades, making the application of lower-emission scenarios less representative for the study area [11,12].

Climate Indices

Five climate indices were selected to characterise conditions relevant to the hydrological and thermal functioning of the constructed wetland system. These indices were computed for three time periods: a historical/reference period (1996–2025), which covers the operational period of the constructed wetland since 2004, and two future periods (2041–2070 and 2071–2100). The indices are described below:

a) Seljaninov Hydrothermal Coefficient (SHC)

The Seljaninov Hydrothermal Coefficient (SHC) is a compound agro-climatic index defined as:

$$SHC = \frac{10 \cdot P_{sum}}{T_{sum}}, \quad (1)$$

where P_{sum} is the sum of daily precipitation (mm) and T_{sum} is the temperature sum (°C), both calculated over the period when monthly mean air temperature exceeds 10°C [13].

The SHC reflects the balance between moisture availability and thermal energy during the biologically active growing season, making it a useful proxy for wetland productivity and treatment efficiency.

b) Consecutive Dry Days Index (CDD)

The Consecutive Dry Days Index (CDD) represents the maximum number of consecutive days within a year with daily precipitation below 1 mm. This index characterises the severity and duration of dry spells, which may reduce water levels in the wetland, increase pollutant concentrations, and stress vegetation and microbial communities involved in wastewater treatment processes.

c) Highest One-Day Precipitation Amount (Rx1d)

The Highest One-Day Precipitation Amount (Rx1d) represents the annual maximum 24-hour precipitation amount (mm). This index captures extreme precipitation events that may cause hydraulic overloading of constructed wetland (CW) systems, mobilise accumulated sediments, and temporarily impair treatment performance through reduced hydraulic retention time, influent dilution, or bypass flows that result in incomplete treatment [14].

d) Frost Days Index (FD)

The Frost Days Index (FD) represents the annual number of days with minimum temperatures below 0°C. Frost conditions are critical for CW operation, as near-zero temperatures suppress microbial metabolic activity, reduce nitrification and denitrification rates, and may cause surface freezing that alters hydraulic pathways [15].

e) Tropical Days Index (TD)

The Tropical Days Index (TD) represents the annual number of days with maximum temperatures exceeding 30°C. Elevated temperatures accelerate evapotranspiration, reduce dissolved oxygen levels, and may favour specific microbial degradation pathways within the wetland [16,17].

RESULTS AND DISCUSSION

Treatment Performance and Operational Stability of the Gložan Constructed Wetland

The previously published assessment of treatment performance at the Gložan CW indicated generally high and stable pollutant removal efficiency, particularly for organic matter [6] (Table 2, Figure 2). Average BOD₅ removal efficiency exceeded 90%, with relatively low variability, suggesting stable biological treatment performance over the analysed period. COD and TN removal efficiencies were also comparatively high, averaging approximately 78% and 79%, respectively, while NH₄-N and suspended solids showed moderate variability. In contrast, TP removal exhibited the highest variability, indicating less stable phosphorus retention processes. Seasonal analysis showed significantly lower BOD₅ removal efficiency during summer periods, likely associated with elevated temperatures, altered oxygen dynamics, and hydrological variability. Trend analysis indicated statistically significant long-term increases in TP, NH₄-N, and TN removal efficiency, while suspended solids removal showed a slight decreasing trend. These findings provide important context for the climate change analysis, as future increases in thermal stress, drought occurrence, and precipitation extremes may further influence the biological and hydraulic functioning of the CW system.

Table 2 Long-term pollutant removal efficiency and variability of the Gložan constructed wetland

Parameter	Mean Removal Efficiency (%)	Standard Deviation	CV (%)
BOD ₅	90.6	7.6	8.3
COD	78.5	15.1	19.2
Suspended solids	69.6	31.5	45.2
NH ₄ -N	71.3	29.0	40.7
TN	79.1	18.4	23.2
TP	58.7	36.4	61.9

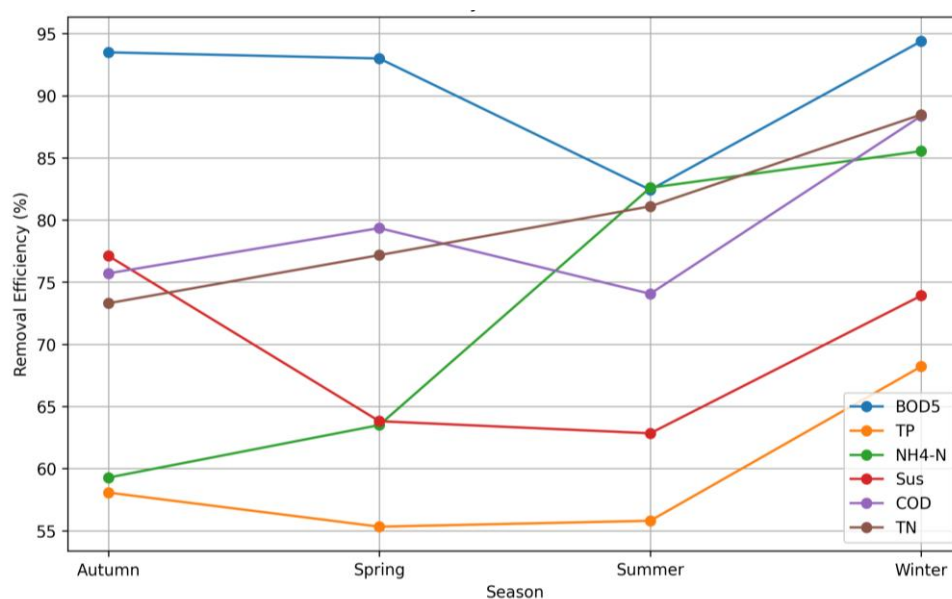


Figure 2 Seasonal removal efficiency of the Gložan constructed wetland

Overview of Projected Climate Change

The results of the multi-model ensemble analysis reveal a clear and consistent pattern of climate change at the Gložan site over the 21st century under the RCP8.5 scenario. The projected changes encompass warming-driven shifts in both temperature-related and precipitation-related indices, with implications for the seasonal functioning, treatment capacity, and ecological stability of the constructed wetland. Median values of all five climate indices across the three time periods are summarised in Table 3.

Table 3 Median values of selected climate indices for the baseline and future periods under RCP8.5

Climate Index	Unit	1996–2025	2041–2070	2071–2100	Trend
Seljaninov Hydrothermal Coefficient (SHC)	–	1.08	1.06	0.98	Decreasing
Consecutive Dry Days (CDD)	days	26	26	28	Slightly increasing
Max 1-day Precipitation (Rx1d)	mm	40.4	44.3	48.9	Increasing
Frost Days (FD)	days	79	62	40	Strongly decreasing
Tropical Days (TD)	days	36	51	79	Strongly increasing

Seljaninov Hydrothermal Coefficient (SHC)

The Seljaninov Hydrothermal Coefficient (SHC) showed a modest but progressive decline from 1.08 in the baseline period (1996–2025) to 1.06 in the mid-century period (2041–2070), and further to 0.98 by the end of the century (2071–2100). Although SHC values across all analysed periods generally correspond to humid growing-season conditions, the projected late-century value approaches the threshold of insufficient moisture supply relative to increasing thermal demand. According to commonly used classifications, SHC values between 1.0 and 1.4 indicate slightly to moderately humid conditions, while values between 0.8 and 1.0 are considered slightly dry [10].

In the context of constructed wetlands, the SHC reflects the balance between water availability and biological activity during the warm season. A declining SHC indicates that future growing seasons are likely to become warmer and/or drier, potentially reducing water availability in surface-flow or free-water systems and increasing evapotranspiration losses from vegetated beds. In subsurface-flow CW systems, reduced precipitation during active treatment periods may alter hydraulic retention times and affect pollutant removal processes. Although the absolute change is relatively modest, the observed trend towards reduced moisture availability should be taken into account in the long-term design and operational planning of the facility.

Consecutive Dry Days

The Consecutive Dry Days (CDD) index remained stable at 26 days in both the baseline and mid-century periods, with a moderate increase to 28 days projected by 2071–2100. Although this change is numerically small, the persistence and gradual extension of dry spells during the second half of the century is consistent with broader regional projections for the Western Balkans, which anticipate more pronounced summer dryness under high-emission scenarios [13].

For constructed wetland operation, extended dry periods without significant rainfall can reduce influent dilution, and increase the concentration of incoming wastewater loads [14]. The projected increase in maximum dry spell duration, while modest under the current ensemble, should be considered when planning for resilience against drought-induced hydraulic stress, particularly in combination with increasing temperatures and evapotranspiration demand.

Extreme Precipitation: Maximum One-Day Rainfall

In contrast to the general tendency toward drying, the maximum one-day precipitation (Rx1d) showed a clear increasing trend across all periods: from 40.4 mm in the baseline to 44.3 mm by mid-century (+9.7%) and 48.9 mm by end-of-century (+21.0%). This finding is consistent with the well-established thermodynamic relationship between atmospheric warming and the intensification of extreme precipitation events, whereby a warmer atmosphere can hold and subsequently release more moisture.

The intensification of extreme rainfall events presents a significant operational challenge for CW systems. Events exceeding the hydraulic design capacity of the wetland can cause surface overflow, bypass of the treatment zone, and the mobilisation of previously deposited organic matter and sediment-bound nutrients. A 21% increase in maximum single-day rainfall by the end of the century suggests the need to revise stormwater management infrastructure and inlet/outlet engineering at the Gložan facility. Buffer storage capacity and overflow contingency design may need to be upgraded to accommodate more intense peak inflows without compromising treatment quality. Additionally, frequent intense rainfall events may periodically accelerate water transfer through the system, shortening effective hydraulic retention times and transiently reducing pollutant removal efficiency [18].

Frost Days

One of the most striking projected changes is the substantial reduction in frost days (FD), declining from 79 days per year in the baseline period to 62 days by mid-century and just 40 days by 2071–2100. This represents a reduction of approximately 49% in annual frost days over the course of the century, reflecting the strong warming signal embedded in the RCP8.5 scenario.

Frost conditions represent one of the primary operational constraints for constructed wetlands in continental climates. At temperatures near or below 0°C, microbial metabolic rates — including those driving nitrification, denitrification, BOD removal, and phosphorus cycling — are markedly reduced. The projected reduction in frost days by nearly 40 days per year by the end of the century therefore represents a potentially significant improvement in year-round treatment performance. Longer frost-free operating periods would extend the season of optimal biological activity, and improve the reliability of treatment during the winter months [4]. This finding suggests that the long-term efficacy of CW-based wastewater treatment in the region is likely to improve in terms of cold-season constraints, even as warm-season challenges intensify.

Tropical Days

The tropical days (TD) index, representing days with maximum temperature exceeding 30°C, showed the most dramatic increase of all indices analysed: from 36 days in the baseline to 51 days by mid-century (+42%) and 79 days by the end of the century (+119%). This more

than doubling of tropical day frequency by 2071–2100 underscores the severity of the projected warming and its potential consequences for warm-season CW operation.

High temperatures have a complex and often opposing set of effects on constructed wetland treatment processes [19]. On one hand, elevated temperatures accelerate microbial metabolic rates, potentially enhancing organic matter degradation and nitrogen transformation during warm periods. On the other hand, increasing temperatures reduce oxygen solubility in water, which may compromise aerobic treatment processes and promote the development of anaerobic zones in saturated substrates. Increased evapotranspiration during tropical days can further reduce the system water balance, increase pollutant concentrations in the effluent, and stress macrophytes commonly used in CW systems. Furthermore, very high temperatures can shift microbial community composition towards thermophilic or heat-tolerant species, potentially altering biological treatment dynamics and affecting the efficiency and stability of pollutant removal processes [20]. The projected near-doubling of tropical day frequency over the century suggests that summer operational management of the Gložan CW will need to evolve substantially, potentially including water level adjustments and more frequent monitoring of dissolved oxygen and nutrient effluent concentrations.

CONCLUSION

Overall, the analysis of long-term treatment performance demonstrated that the Gložan CW currently provides relatively high and stable removal efficiency for several key wastewater quality parameters, particularly BOD₅, COD, and TN. Nevertheless, higher variability observed for phosphorus, suspended solids, and ammonium removal suggests that some treatment processes may be more sensitive to external environmental and hydrological fluctuations.

The projected climate changes further indicate increasing climatic variability and thermal stress for the Gložan constructed wetland over the 21st century. The emerging pattern under RCP8.5 is characterised by warmer, drier growing seasons (declining SHC), longer dry spells (increasing CDD), more intense individual precipitation events (increasing Rx1d), substantially shorter frost seasons (decreasing FD), and significantly more frequent extreme heat days (increasing TD).

These changes have varying implications for CW treatment performance. The reduction in frost days is likely to have a net positive effect on year-round treatment efficiency, reducing the duration of cold-season performance suppression. However, the increasing frequency of extreme heat events, intensified peak rainfall, and growing moisture deficit during the growing season collectively represent new operational challenges that could progressively offset these gains if not proactively managed.

The obtained findings indicate that climate adaptation strategies should become an integral part of the long-term management, monitoring, and operational planning of nature-based wastewater treatment systems.

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