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PREFACE

The responsibilities of water-oriented researchers are becoming increasingly demanding: climate change is altering hydrological regimes and intensifying water-related risks; urbanization and ageing infrastructure are placing additional pressure on water supply, sewerage and drainage systems; concerns over water quality and environmental degradation are becoming more complex; and engineering solutions are increasingly expected to combine technical efficiency with ecological sustainability and resilience. WMHE2026 takes place within this evolving scientific and professional landscape while continuing a tradition that extends over more than four decades. The Symposium series began in 1984 as a bilateral activity between the faculties of Gdańsk University of Technology and the University of Zagreb. Since the 1998 Symposium in Dubrovnik, the Slovak University of Technology, Ss. Cyril and Methodius University in Skopje and BOKU University in Vienna have participated in the series, while Brno University of Technology joined the steering group in 2013. Through this cooperation, WMHE has developed into a durable international forum for scientists, engineers and professionals working across the broad fields of water management and hydraulic engineering. The fundamental aim of the Symposium has remained unchanged: to encourage communication, exchange recent research results and professional experience, and strengthen cooperation among researchers and practitioners. Over successive editions, however, the programme has naturally evolved in response to changing scientific questions and engineering priorities.

Contributions to WMHE2026 reflect current trends in research: digitalization has moved from being an enabling tool to becoming an explicit area of research, with hydroinformatics, remote sensing and advanced monitoring receiving dedicated attention across disciplines. Contributions addressing green technologies, nature-based solutions, river and floodplain restoration, sustainable drainage, water retention and ecological considerations indicate an important transition to strengthening relationship between engineering and environmental objectives. Similarly, water supply, sewerage and treatment are increasingly approached as interconnected systems, while research into water and wastewater treatment is expanding toward questions of resource efficiency, reuse, recovery and circularity. Despite these advances, the Symposium also reminds us of the lasting importance of sound engineering fundamentals. More detailed data, more powerful computational tools and more sophisticated models are valuable only when supported by a rigorous understanding of physical processes, careful observation and engineering judgement. WMHE continues to provide a setting in which established knowledge and emerging approaches can meet, be critically examined and mutually strengthened.

We therefore hope that WMHE2026 will serve not only as a forum for presenting research results, but also that the discussions initiated here will continue well beyond the Symposium and contribute to future research, improved engineering practice and stronger professional cooperation. Above all, we hope that every participant leaves WMHE2026 with new knowledge, new professional connections and renewed motivation to advance water engineering in the service of safer, more resilient and more sustainable societies.

Organizing Committee

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KEYNOTE LECTURES

MITIGATION OF TYPICAL TORRENTIAL HAZARDS IN THE KRVAVEC AREA IN SLOVENIA

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Alpine regions are highly susceptible to torrential hazards, including flash floods, debris flows, and landslides, which pose significant risks to infrastructure and human safety. Risk reduction can be achieved through a combination of structural and non-structural measures, including grey, green, and hybrid infrastructure solutions. This contribution provides an overview of the mitigation measures implemented near the Krvavec ski resort in north-western Slovenia following an extreme debris flood in May 2018. The event caused severe soil erosion and sediment transport, resulting in substantial economic damage.

To support the design of mitigation measures, extensive field investigations, including geological and topographical surveys, were combined with numerical modelling approaches such as hydrological modelling and debris-flow simulations. The measures implemented include river engineering works on local streams, the construction of a large check dam, several smaller retention structures, and 16 flexible net barriers with an estimated total retention capacity of approximately 8,000 m³. In addition, a comprehensive monitoring system was established to improve the detection and assessment of future extreme events.

The effectiveness of these measures was tested during the extreme flood event of August 2023, which caused widespread damage across Slovenia. Field evidence and monitoring showed that the flexible net barriers successfully retained substantial volumes of sediment and protected downstream infrastructure despite the fact that the August 2023 rainfall return period exceeded 250 years. The monitoring system recorded significant impact loads on the barriers during the event. The installation of the barriers reduced erosion and sediment transport within the catchment and modified natural sedimentation patterns by trapping transported material, reducing flow velocities, and leading to sediment deposition.

Keywords: torrential hazards, debris flow, flexible net barriers, sediment retention, Krvavec (Slovenia)

FROM TURBULENT EVENTS TO PARTICLE RESPONSE: A DYNAMICAL FRAMEWORK FOR SEDIMENT TRANSPORT, SMART SENSING AND RESILIENCE

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Sediment transport has traditionally been approached through fluid-centred quantities such as shear stress, critical thresholds and bulk transport rates. While these concepts remain fundamental, sediment entrainment is inherently dynamic: particles respond to turbulent events whose magnitude, duration, temporal organisation and interaction with local bed geometry determine whether motion develops, ceases or progresses to full entrainment. Understanding this process therefore requires moving beyond the question of when a threshold is exceeded towards resolving how individual particles experience and respond to turbulent forcing.

This keynote traces the development of such a particle-centred perspective, from force-based descriptions of incipient motion towards impulse, energy and event-resolved approaches. Particular emphasis is placed on instrumented particles as Lagrangian sensing platforms capable of recording acceleration, rotation, orientation and impacts from within the moving object itself. These measurements reveal a richer picture of sediment dynamics, including rocking and pre-entrainment motion, transitions between transport modes, particle energetics, waiting times and the coupling between coherent turbulent structures and particle response.

The wider potential of this approach extends beyond sediment grains. Instrumented objects can provide new perspectives on ecological stability, scour protection and the resilience of hydraulic structures, while integration with computational modelling and machine learning may offer enhanced prediction for the sustainable management of rivers, habitats and infrastructure.

Keywords: sediment transport, smart sensing, particle dynamics, turbulence, resilience of hydraulic structures

COASTAL ADAPTATION: CONNECTING SCIENCE, COMMUNITIES AND ACTION

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Coastal communities face climate-related risks such as coastal flooding and erosion driven by sea-level rise and increased storminess. At the same time, many coastal areas are experiencing urbanisation and infrastructure development, which in turn increase the risks to coastal communities. Different adaptation strategies are used to reduce these risks. Hard engineering solutions have traditionally been used for coastal protection, particularly in more developed countries. Alternative strategies, such as nature-based solutions, coastal zone planning and accommodation approaches, are increasingly being considered instead of, or alongside, hard structures. Regardless of the chosen strategy, uncertainty around the timing, frequency and magnitude of coastal flooding and erosion, as well as complex interactions between different components of the coastal system, makes planning and implementing these strategies challenging. In this context, adaptive approaches to coastal management are increasingly being applied. This talk will introduce the concept of coastal adaptation. It will also introduce adaptation pathways, which are used as planning tools for decision-making under uncertain conditions where multiple options are available. It will raise fundamental questions about how we should adapt and who should shape the decisions that determine the futures of coastal communities. The talk will provide a brief overview of recent developments in coastal adaptation in England and the wider UK, considering both progress and ongoing challenges. It will then draw on examples from research conducted by the Coastal Collective at Lancaster University, which brings together researchers, practitioners and organisations working on pathways to coastal adaptation. The talk will argue that navigating uncertain coastal futures requires connections across scales and forms of knowledge: between scientific evidence and lived experience, between top-down policy and bottom-up action, and between understanding coastal change and imagining alternative futures.

The presentation will conclude by reflecting on the opportunities and challenges of building these connections, and on what a more participatory, place-based and forward-looking approach to coastal adaptation might mean for the future of coastal communities.

Keywords: Coastal adaptation, climate-related risks, coastal communities, participatory coastal management, coastal zone planning

ABSTRACTS

ANALYSIS OF TEMPERATURE AND PRECIPITATION PARAMETERS AND THEIR INFLUENCE ON DROUGHT OCCURRANCE IN OSIJEK

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The increase in the frequency of extreme hydrological events, such as droughts and floods, is a characteristic of climate change. Droughts, unlike floods, have a distinctly global character, and their increased duration and intensity have been confirmed across almost all regions of the world. Even though drought is defined as a period characterized by a lack of precipitation of sufficient duration and quantity to impact the hydrological balance, associated phenomena include high air temperatures, low air humidity, and prolonged periods of high solar radiation.

In this paper, several temperature and precipitation parameters for Osijek, a town in eastern Croatia, have been analyzed for the period 1900-2025. Over the observed 126-year period, trend calculations clearly show that temperatures are rising, as confirmed by all analyzed temperature parameters except for the number of tropical nights ($T_{min,\ daily}$>20 °C). Regarding precipitation, the number of days with lower precipitation (0.1, 1, and 10 mm) is decreasing, as is the seasonal precipitation amount, except in summer. On the other hand, the number of days with high precipitation (>20 mm) is slightly increasing. The influence of all calculated temperature and precipitation parameters will be analyzed on the drought index for Osijek. Since 2000, drought in the continental part of Croatia has occurred more often, with higher intensity and longer duration. This analysis will show which parameters, the ones regarding temperature or the precipitation ones, have a bigger influence on drought occurrence in Osijek.

Keywords: temperature, precipitation, drought, Osijek

COMPARATIVE ANALYSIS OF STATION-BASED AND CLIMATE MODEL DATA FOR FLOW MODELLING

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Water resources systems, such as reservoirs, are highly dependent on future water availability. Long term planning, particularly through mean monthly flow forecasting, provides the basis for decision-making related to water use and operational regimes. Since monthly streamflow is strongly influenced by climatic conditions (precipitation, temperature, etc.), it is expected that future climatic changes may substantially affect the water regime, especially through the occurrence of more frequent and intense precipitation events.

Therefore, it is important to assess the consistency between station observations and the outputs from different climate models under multiple climate scenarios for the key hydrological predictors, particularly precipitation and temperature. An already developed model for forecasting mean monthly flow for the Cetina River (Croatia) uses historical records of precipitation and temperature data from nearby meteorological stations. In the present study, the aim is to investigate the correspondence between station-based observations and climate-model outputs.

Available datasets include records from the hydrological station Vinalić, the main meteorological station Knin, the climatological station Sinj, and the precipitation gauge Vinalić (1951-2022), as well as outputs from three CMIP6 global climate models (HadGEM3, IPSL and MPI) under three Shared Socioeconomic Pathway scenarios (SSP126, SSP245 and SSP585) for the period 2015-2100. The climate-model outputs are used in their original spatial resolution without additional bias correction or statistical downscaling. All datasets are available at a daily temporal resolution.

The main objective is to evaluate the agreement between local (station-based) and spatial (model-derived) climatological data over their common period (2015-2022), as a foundation for subsequent application within a monthly flow modelling framework. For this purpose, station observations and climate-model outputs were compared using correlation, bias, and root mean square error for both original daily data and monthly aggregated data. Lagged-correlation analyses were performed using temporal shifts and spatial searches across all climate-model grid cells to identify the cells providing the highest agreement with station observations. To avoid information leakage and preserve an independent dataset for subsequent calibration and verification of the climate-to-station transfer methodology and the flow forecasting model, only the first 60 % of the common period was used for the initial analysis. The remaining 40 % was intentionally reserved for model calibration and independent verification.

The identified representative climate-model predictors will subsequently serve as replacements for, or augmentations to, station-based meteorological inputs in the existing monthly flow forecasting model for the Cetina River. This provides a framework for evaluating four alternative approaches to climate-informed flow forecasting: daily station-variable reconstruction, monthly station-variable reconstruction, representative grid-cell substitution, and direct climate-to-flow modelling, thereby supporting the application of the existing model under future climate scenarios.

Keywords: long term planning, mean monthly flow, precipitation, air temperature, climate scenarios

EARLY WARNING SYSTEM BASED ON PRE-SIMULATED SCENARIOS FOR COMPOUND FLOODING: APPLICATION TO THE RJEČINA RIVER, RIJEKA

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In densely populated low-lying estuarine and coastal areas, flooding usually occurs due to three primary drivers: high river discharges (fluvial), precipitation surface runoff (pluvial), and coastal oceanographic processes such as tides, wave action, storm surges, and relative mean sea level rise (coastal). When these drivers occur simultaneously or in close succession, their interaction can result in an event known as compound flooding. With climate change altering weather patterns and increasing mean sea levels, the risk of such events is expected to increase, highlighting the need for effective flood forecasting systems that support early warning systems (EWS) and decision support systems (DSS).

This study focuses on the lower course of the Rječina River, located in the northern Adriatic region of Rijeka, Croatia. For this area, high river discharges and extreme sea levels in the Adriatic Sea were identified as the primary drivers of compound flooding in the city centre. Projected changes in mean sea level due to climate change were also considered as an additional factor influencing compound flood hazard.

Instead of developing a fully integrated forecasting chain, a simplified approach was adopted to enable a fast-responsive EWS. The system is based on pre-simulated flood hazard scenarios, including flood extents, water depths, flow velocities, and flood severity, for selected annual exceedance probabilities (AEP). These scenarios are linked to observed or forecasted upstream river water levels and downstream sea levels. Because compound flooding in the study area is governed by the joint occurrence of these two boundary conditions, the main challenge was to develop an EWS that accounts for their combined effect. To address this, a set of representative upstream water level and downstream sea level pairs was defined, and corresponding flood simulations were performed. For any real-time combination of upstream water level and sea level, the expected flood characteristics are determined using two-dimensional bilinear interpolation between the four neighbouring simulated pairs, enabling rapid estimation of flood hazard without the need for additional hydrodynamic simulations. A decision matrix defining alert levels, along with a notification protocol and procedures for informing emergency services, forms a key component of the system and provides essential input for the future development of DSS.

The results demonstrate that the proposed simplified approach can provide a practical and efficient basis for a fast-responsive EWS for compound flooding in the lower course of the Rječina River in Rijeka. By linking pre-simulated flood scenarios with upstream water level and downstream sea level, the system enables rapid identification of potential flood conditions without the need for computationally intensive real-time modelling. This approach allows timely activation of alert levels and supports emergency response through clearly defined notification protocols and decision support inputs. The methodology represents a cost-effective and operationally feasible solution for improving flood preparedness in data-limited coastal urban catchments exposed to compound flooding, and it provides a flexible framework that can be further refined as additional hydrological and climate data become available.

Keywords: Rječina River, Compound Flooding, Flood Hazard Assessment, Early Warning System

HISTORICAL CHANGES IN FLOW RATES IN THE KLÁTOV BRANCH

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The history of the Klátov branch is different from other branches of the Danube in its area in Slovakia from Bratislava to Komárno. For many centuries, the Klátov branch was connected directly to the Danube River. Its location and connection to the Danube River can be found on historical maps in connection with the watercourse that is now called the Malý Dunaj.
The paper analyses the impact of these changes on the current state of flow and water quality after changes in land use over the past 100 years. The present study analyses selected sections of the stream and the influence of sediments on the flow regime in these sections. It evaluates historical and own measurements as well as changes in the landscape surrounding to the stream, which is today a national nature reserve and an element of the Natura 2000 area.
In the past, the water flow through the Klátovský branch was probably greater than today's flow through the Malý Dunaj River. This can be deduced based on the riverbed parameters such as the width of the riverbed and the depth of the water. The flow was very significant, especially during times of flood on the Danube River, which caused flooding of the villages through which the Klátov branch flows. Therefore, at the beginning of the 20th century, it was decided to dam it and water no longer flows directly into the Klátov branch.
The flow is maintained only by seepage through the bottom. Later, in the second half of the last century, drainage systems were built in the area and it was necessary to transport the water using melioration canals. One of them flowed into the Klátov branch near the village of Dunajský Klátov.
Later, after the construction of the waterworks on the Danube – Gabčíkovo hydropower station, it was necessary to gravity drain the seepage water through the landscape back into the Danube, but due to the differences in water levels, this is not possible right next to the hydroelectric power plant, and therefore the Gabcikovo-Topolniky canal was built, which brings water over a long route to the Klátov branch and subsequently to the Danube. It was observed that not only did the flow rate undergo a change, but the velocity of the flowing water also changed, resulting in a gradual transformation of both the cross-sectional and longitudinal shape of the channel.
All these changes had an impact on the hydrological regime of the Klátov branch and also on the quality of the water and of course on the formation of the quality of bottom sediments. The development of municipalities also reached the banks of the branch and the construction of road bridges changed the flow profile in several places.

Keywords: Klatov branch, flow rate, sediments, water quality, hydrological regime

EVALUATING THE SCS-CN METHOD IN THE PAZINČICA RIVER CATCHMENT (CROATIA): MEASURED EXTREMES VS. EVENT-BASED HYDROLOGICAL SIMULATIONS

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Design peak discharge is commonly derived from event-based rainfall–runoff simulations using the SCS Curve Number (CN) method under discrete Antecedent Moisture Condition (AMC I–III) scenarios, yet the validity of this framework is rarely tested against independent, long-term discharge observations. This study evaluates the SCS-CN/AMC framework in the Pazinčica River catchment, a small flysch catchment in Central Istria, Croatia, with a torrential flow regime, through a two-part diagnostic based on a sample of peaks-over-threshold (POT) discharge extremes at the Dubravica station (1972–2024). First, design peak discharges were simulated by a semi-distributed HEC-HMS model under AMC I, II and III design storms, with calibrated runoff-transformation parameters (CN, lag time, peak rate factor) and validated against the observed hydrographs of the most extreme events. Next, design peak discharges were compared against peak discharges estimated from measured flow at the Dubravica station using POT/GPD approach. The results show that POT/GPD discharge-frequency curve falls just below the HEC-HMS simulations under AMC II and above AMC I, which indicates that no single AMC-based CN reproduces the observed frequency distribution reliebly. Second, effective CN values calculated by direct inversion of the SCS-CN equation for all POT events showed that CN decreases systematically with increasing rainfall depth and maximum rainfall intensity, while showing no significant relationship with antecedent precipitation computed for cumulative observed rainfall across multiple aggregation windows. These results indicate that effective CN in this catchment is governed primarily by rainfall intensity rather than by antecedent moisture state, explaining why a discrete AMC I–III classification cannot simultaneously reproduce the flow behaviour captured by the analysis of measured discharges.

Keywords: SCS Curve Number (CN), Antecedent Moisture Conditions (AMC I–III), HEC-HMS rainfall-runoff modelling, Extreme value analysis, Mediterranean small catchment

COMPOUND FLOOD HAZARD ASSESSMENT IN THE ZRMANJA RIVER ESTUARY USING JOINT PROBABILITY ANALYSIS

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The Zrmanja River estuary in northern Dalmatia, Croatia, represents a hydrodynamically complex coastal system where the river enters the Novigrad Sea, a semi-enclosed basin connected to the Adriatic Sea through the narrow Novsko Ždrilo strait. This restricted exchange, combined with microtidal conditions and strong freshwater inflows from a karstic catchment, creates a setting particularly sensitive to the interaction between riverine and coastal processes. Under extreme conditions, cooccurrence of high river discharge and storm surge may lead to compound flooding along the lower Zrmanja River, particularly in the City of Obrovac.

This study presents a compound flood hazard assessment based on a joint probability framework that accounts for the statistical dependence between extreme river discharge and storm surge. A two-dimensional hydrodynamic model was developed using HEC-RAS 2D, covering the lower Zrmanja River reach and the entire Novigrad Sea basin, including its hydraulic connection to the Adriatic Sea. The model was used to simulate flood propagation, backwater effects, and inundation under combined upstream and downstream boundary conditions.

The statistical characterization of compound drivers was performed using a joint probability approach based on copula theory. Marginal extreme distributions of river discharge and storm surge were first estimated, and their dependence structure was modelled using copulas implemented through the MultiHazard statistical package. From the fitted joint distribution, design combinations corresponding to selected joint return periods were derived. These combinations were then used as boundary conditions in the hydrodynamic model to generate flood hazard maps, including spatial distributions of maximum water depths and inundation extents for each return period scenario.

The results demonstrate that neglecting the dependence between river discharge and storm surge can misrepresent flood hazard in semi-enclosed estuarine systems. By integrating bivariate extreme-value analysis with hydrodynamic modelling, the proposed framework provides a robust basis for assessing compound flood hazard for different return periods. The methodology is applicable to other microtidal coastal settings where fluvial and marine drivers interact under restricted exchange conditions.

Keywords: Compound flooding, joint probability analysis, copula modelling, HEC-RAS 2D, Zrmanja River estuary

BIOTECHNOLOGICAL POTENTIAL OF ALGAE FOR WASTEWATER TREATMENT

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The paper presents the possibility of using algae in wastewater treatment, with an emphasis on the removal of nutrients, specifically nitrogen and phosphorus. The basic properties of algae and the methods or mechanisms through which algae participate in wastewater treatment are explained. Additionally, an overview of the most commonly used systems and technologies today is provided, including open pond systems and photobioreactors (closed systems), highlighting the advantages and disadvantages of each option and assessing their practicality for industrial application. The potential use of biomass generated during the water treatment process is also considered. One of the greatest advantages of algal systems is the possibility of utilizing the resulting biomass, which can be used for biofuel production, as an animal feed supplement, in the pharmaceutical industry, or even in cosmetics. Case studies are presented in which algae are used for the treatment of specific wastewaters, with an overview of efficiency and costs.

Keywords: algae, wastewater, wastewater treatment, photobioreactors, open ponds

ADVANCED WASTEWATER TREATMENT USING SEWAGE SLUDGE–DERIVED BIOCHAR AS A CIRCULAR ADSORBENT MATERIAL

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This paper presents the initial phase of experimental investigations conducted within a newly established research project focused on advanced wastewater treatment using sewage sludge–derived biochar. The study explores the feasibility of using pristine biochar obtained through experimental semi-industrial sewage sludge gasification as a low-cost adsorbent for the removal of micropollutants, such as pharmaceuticals, heavy metals, and pesticides, as well as nutrients, which represent a growing concern in conventional wastewater treatment systems.

The research includes physicochemical characterization of the biochar and preliminary adsorption experiments performed under controlled laboratory conditions. The biochar is carbon-based (approximately 50%), which supports its potential suitability as an adsorbent. Removal efficiencies were evaluated through batch experiments to assess adsorption capacity and process behavior, employing single-component synthetic solutions under varying operational parameters, including pH, adsorbent dosage, initial pollutant concentration, and reaction time. Overall, high removal efficiencies were achieved (above 50%), with several target compounds exceeding 90%, highlighting the strong adsorption potential of the produced biochar even without further modification. The results indicate that sewage sludge–derived biochar may serve as an effective material in adsorption-based tertiary and quaternary wastewater treatment technologies, while simultaneously contributing to sustainable sewage sludge management and promoting the circular economy on multiple levels. These findings provide a foundation for further optimization and scale-up within the ongoing project.

Keywords: sewage sludge, gasification, biochar, adsorption, micropollutants

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The authors gratefully acknowledge INDELOOP d.o.o. for providing the biochar derived from sewage sludge gasification used in this research.

APPLICATION OF BIOCHAR FOR THE REMOVAL OF THE PHARMACEUTICAL ZIDOVUDINE FROM WASTEWATER

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Pharmaceuticals are biologically active substances encompassing a wide range of commonly used medical products, including antibiotics, antipyretics, anti-inflammatory drugs, analgesics, and many others, which are extensively applied in both human and veterinary medicine worldwide. Numerous studies have reported the presence of pharmaceutical residues in surface water, groundwater, treated and untreated wastewater, and other environmental matrices, often at trace concentrations.

Conventional wastewater treatment processes are often unable to completely remove antibiotics and other pharmaceutical residues, resulting in their discharge into natural water bodies and are often associated with high operational costs and significant energy demands. Therefore, there is a pressing need to explore alternative approaches that are not only effective but also economically viable and environmentally sustainable.

Biochar is a porous, carbon-rich material produced through the thermochemical conversion of organic biomass under limited or oxygen-free conditions. In this study, dried sludge was converted into biochar through pilot gasification process, and batch adsorption experiments were conducted to evaluate Zidovudine removal. Optimal Design (Response Surface Methodology) was used to study the effects of pH (3, 7, 9), initial concentrations of pharmaceutical Zidovudine (1, 10, and 20 mg/L), biochar mass (0.1, 0.5, and 1.0 g per 200 mL) and contact time (1, 6 and 24 h). Laboratory results showed a maximum removal efficiency of 65 % and an adsorption capacity of 2.94 mg/g. Optimal performance was achieved at low pH (3 – 4), higher biochar dosage (1 g/200 mL), and longer contact time (24 h), underscoring the key role of acidity in the adsorption process.

Keywords: Adsorption, Biochar, Response Surface Method, Sewage Sludge, Zidovudine

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This work was supported by the Croatian Science Foundation under the project number [HRZZ-UIP-2025-02-9907]: AdSorB – "*Advanced Wastewater Treatment by Repurposing Sewage Sludge Derived Biochar*".

The authors gratefully acknowledge INDELOOP d.o.o. for providing the biochar derived from sewage sludge gasification used in this research.

THE USE OF ULTRAFILTRATION IN WATER TREATMENT

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The Dúbrava group water supply system in Slovakia was built in connection with the construction of the Liptovská Mara Water Reservoir. The group water supply system was supplied with water from the Dúbrava water resource (capacity of about 40 L/s). The water resource included three springs (Brdáre, Močidlo and Škripeň). Škripeň is currently the only spring used for a drinking water supply, since it contains no antimony. Two other springs are contaminated with antimony.

A deposit of antimony ore is the main cause of the increased antimony concentrations in the springs of Močidlo (57 µg/L) and Brdáre (69 µg/L). Furthermore, a high concentration of antimony in water from mining activities as well as from rain falling on antimony-rich waste rock piles and a sludge-settling pond has led to higher concentrations of antimony in the relevant water resources.

Antimony is a toxic heavy metal with effects like those of arsenic and lead. Intoxication by antimony is not as severe as that from arsenic, since the antimony compounds are absorbed more slowly. The findings on the health aspects of certain heavy metals in drinking water are included in several publications (AWWA 1990; US EPA 1984). The World Health Organization and institutions dealing with the monitoring of carcinogenicity have not yet classified antimony as a carcinogen.

In Slovakia, the limit values are specified in the Decree of the Ministry of Health of the Slovak Republic No. 91/2023 Coll. The limit concentration for antimony is 10 µg/L. This limit value is in accordance EU Directive (2020/2184) of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption.

There are several technological methods for removing heavy metal in the water treatment process: precipitation, ion exchange, membrane processes, adsorption, electrochemical processes and biological methods.

The article deals with the removal of antimony from water using coagulation and ultrafiltration. The aim of the experiments is to compare the efficiency of removing antimony from water for iron coagulants (ferric sulphate, ferric chloride) or oxidizing agents (sodium hypochlorite, potassium permanganate), to monitor the agent doses, contact time with water, filtration rate and antimony concentration in raw water, and before and after ultrafiltration. The experiments will use a fully automated ultrafiltration device with a UA-640 membrane module (Microdyn-Nadir), with the material of membrane from polyacrylonitrile (PAN), diameter of pores 0,025 µm and membrane surface 16 m^2. To achieve the necessary contact time of water with the coagulant or oxidizing agent, a tubular reactor with a static stirrer (length > 6.0 m, volume 30 litres) will be used. The experiments will be carried out on the Dúbrava water resource.

Keywords: drinking water treatment, removal of antimony, coagulation, oxidation, ultrafiltration

WASTEWATER TREATMENT IN SMALL SETTLEMENTS USING THE TEHNIX BIOROTOR SYSTEM

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Water is a fundamental resource for life and sustainable development. Effective wastewater management is essential for protecting aquatic ecosystems and ensuring sustainable development. Untreated or inadequately treated municipal wastewater can lead to serious environmental impacts, including eutrophication, oxygen depletion, and disruption of ecological balance. Conventional centralized wastewater treatment systems are often economically and technically unsuitable for small and sparsely populated settlements, highlighting the need for decentralized solutions.

This paper presents the TEHNIX ECO INDUSTRY BIOROTOR SYSTEMS as an efficient on-site wastewater treatment technology designed for small communities. The system is based on the principle of a rotating biological contactor (RBC), where a partially submerged rotating drum provides a large surface area for biofilm growth. Microorganisms attached to the rotor surface degrade organic pollutants through aerobic biological processes.

The methodology includes analysis of long-term operational experience, performance data from installed systems, and evaluation of treatment efficiency based on key output parameters such as biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and suspended solids. The system demonstrates stable performance under varying hydraulic and biological loads with removal efficiencies exceeding 90% for BOD_5 and COD.

Results show that the BIOROTOR achieves high efficiency in secondary wastewater treatment, consistently meeting regulatory discharge standards. Additionally, the system offers potential for upgrading to tertiary treatment. Key advantages include low investment and operational costs, low energy consumption, minimal maintenance requirements, and no need for continuous supervision.

The TEHNIX ECO INDUSTRY BIOROTOR SYSTEMS represents a reliable, cost-effective, and environmentally sustainable solution for wastewater treatment in small settlements. Its adaptability, simplicity, and proven performance make it particularly suitable for decentralized applications where conventional systems are not viable.

Keywords: wastewater treatment, rotating biological contactor, decentralized purification systems, small settlements, biorotor

HYBRID ELECTROCOAGULATION–ADSORPTION TREATMENT OF AMMUNITION MANUFACTURING WASTEWATER: INFLUENCE OF PROCESS PARAMETERS ON COD, HEAVY METALS AND SULFATE REMOVAL

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Wastewater generated during ammunition manufacturing is characterized by a complex composition of pollutants, including heavy metals, sulphates, and organic contaminants, making its treatment a significant technological challenge. This study investigates the applicability of a hybrid treatment process combining electrocoagulation and adsorption for the treatment of industrial wastewater, with particular emphasis on the removal of sulphates, heavy metals, and organic load expressed as chemical oxygen demand (COD). The experimental investigation was conducted through several consecutive phases, including the selection of the most suitable adsorbent, optimization of the electrode configuration, and evaluation of the effects of current density and process sequence on the overall treatment performance. Adsorption experiments were carried out using granular activated carbon and two biochar materials, while different combinations of iron and aluminium electrodes were evaluated during the electrocoagulation stage. Process performance was assessed by determining physicochemical parameters, heavy metal concentrations using inductively coupled plasma optical emission spectrometry (ICP-OES), COD by photometric analysis, and sulphate concentrations by UV–Vis spectrophotometry. The results demonstrated that the combined electrocoagulation–adsorption process achieved highly efficient removal of heavy metals, with removal efficiencies exceeding 90%. The highest COD reduction, 42.86%, was achieved in the simultaneous electrocoagulation–adsorption process using GAC as the adsorbent and a combination of aluminium and graphite electrodes. In contrast, the highest sulphate removal, 46.31%, was obtained when electrocoagulation was applied prior to adsorption. An additional sequential experiment using a lead electrode further improved the treatment performance, achieving approximately 60% reduction of both sulphate concentration and COD value. Overall, the findings confirm that the hybrid electrocoagulation–adsorption process represents an effective and promising approach for the treatment of ammunition manufacturing wastewater and provides a sound basis for the further development and optimization of integrated wastewater treatment systems.

Keywords: wastewater, treatment, ammunition manufacturing, electrocoagulation, adsorption

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The views and opinions expressed are solely those of the author(s) and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

COMPARISON OF UNIVARIATE AND BIVARIATE APPROACHES TO DESIGN HYDROGRAPH DERIVATION IN CROATIAN AND SLOVENIAN CATCHMENTS

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The design hydrograph is one of the key inputs in the design of water management and hydraulic structures. It defines the design peak discharge, flood volume and duration of the flood wave. This study compares two approaches for defining a design hydrograph in gauged catchments: a simpler univariate approach based on the Typical Flood Hydrograph (TFH) method, and a more complex bivariate approach based on the joint analysis of peak discharge and flood volume.

In this study, when applying the TFH approach, the design flood hydrograph is derived using the flood frequency analysis based on the Annual Maximum (AM) method. The parameters of the selected probability distributions are obtained using the L-Moments method, and their goodness of fit is evaluated against the empirical frequency. A representative observed flood event is then selected, and its hydrograph is scaled to the design peak discharge and design flood volume using an amplification factor, resulting in the corresponding design hydrograph.

In the bivariate approach, the design hydrograph is defined through the joint analysis of peak discharge and flood volume. The dependance between these variables is modeled using copulas, which are then applied to derive bivariate return periods and the corresponding design combinations of discharge and volume. These combinations serve as the basis for constructing a synthetic design hydrograph (SDH).

The analysis is conducted for selected gauging stations in the Sava and Drava River basins in Croatia and Slovenia. The stations include: Kupljenovo (Krapina River), Farkašić (Kupa River), and Zagreb (Sava River) in Croatia, as well as Litija (Sava River) and Dravograd (Drava River) in Slovenia. Particular emphasis is placed on the application of copula-based bivariate analysis to catchments in Croatia and Slovenia, allowing a more realistic consideration of the dependence between peak discharge and flood volume.

The results highlight the advantages and limitations of both approaches in constructing design hydrograph. The study contributes to the development of a methodological framework for determining design hydrographs. The obtained results may serve as a basis for future classification of hydrograph types and for the application of machine learning methods to categorize different design hydrograph shapes.

Keywords: design hydrograph; Typical Flood Hydrograph (TFH); bivariate analysis; copulas; flood frequency analysis

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ASSESSMENT OF HYDROLOGICAL RISKS IN HORNAD RIVER BASIN

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The study examines land use changes in the Hornad river basin from 1990 to 2018 and their impact on surface runoff. Forest areas consistently dominated, slightly increasing by 2018, while arable land decreased. Built-up areas, particularly in industrial and transport sectors, expanded significantly. Hydrological analysis shows that surface runoff was highest in the early 1980s and 2001-2020, with the lowest recorded between 1981-2000. These findings highlight the evolving land use dynamics and their influence on watershed hydrology.

Keywords: climate change, hydrology, land use

TRENDS IN RIVER AND FLASH FLOOD EVENTS AND ASSOCIATED FATALITY INDICATORS IN EUROPE OVER THE PAST 50 YEARS

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Recent extreme events, including the 2021 Western Europe floods and the 2024 floods in Spain, rank among the most severe flood disasters in Europe over the past century, highlighting the need for a systematic assessment of long-term flood risk and impacts. In this study, we compile and harmonize records from two publicly available disaster databases, HANZE database and EM-DAT, to analyse temporal trends in river floods and flash floods across European countries.

We examine changes in (i) flood occurrence, (ii) reported fatalities, and (iii) normalized impact indicators, including fatalities per event, affected population per event, and mortality rates. The analysis is performed for the period of last 50 years and is disaggregated across major European climatic macro-regions to capture spatial heterogeneity in flood regimes and vulnerability.

Our results show a divergence between flood types: while river floods account for a larger share of affected populations, flash floods consistently exhibit higher fatality rates per event, indicating greater fatality despite their smaller spatial footprint. Temporal trend analysis suggests increasing trend in reported flood economic losses, accompanied by increasing flood events with fatalities.

We further demonstrate that uncertainty and inconsistencies in disaster databases, such as underreporting of affected populations or variability in fatality attribution, substantially influence derived mortality indicators. This underscores the critical need for rigorous data quality control and harmonization when assessing long-term flood risk and informing disaster risk reduction policies.

Overall, the study provides a comparative, data-driven perspective on the evolution of flood impacts in Europe, highlighting the disproportionate human risk posed by flash floods and the importance of improving disaster data reliability for robust risk assessment.

Keywords: flash floods, river floods, flood fatalities, long-term trends

OPTIONS FOR FLOOD PROTECTION OF THE ZÁHORSKÁ BYSTRICA URBAN AREA

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This study focuses on assessing the current state of flood protection in the Bratislava – Záhorská Bystrica district and its adjacent areas during 100-year flood events (Q100). The primary objective was to identify critical locations within the urban area and propose effective technical and nature-based measures to eliminate flood risks.

The HEC-RAS 2D mathematical model (v6.3.1), utilizing the shallow water approximation of Saint-Venant equations, was employed for water level analysis and flow simulation. The model was parameterized using a high-resolution digital elevation model (1x1 m) and hydrological data provided by the SHMU. Flood scenarios were simulated for the catchments of the Bystrický Brook and Salabov Jarok, including their mutual confluence.

Simulation results revealed insufficient capacity of key culverts, particularly on Vrbánska Street, where overtopping into residential zones occurs. To mitigate these risks, a system of four polders (retention basins) is proposed: three within the Salabov Jarok catchment and an upgrade of the existing sedimentation basin in the Bystrický Brook catchment. Additional measures include consolidation and retention check dams in the upper reaches to capture debris and sediment, as well as the installation of trash racks at culvert inlets.

The study confirms the necessity of implementing integrated flood risk management that combines technical structures with landscape elements designed for debris and sediment retention.

Keywords: flood protection, HEC-RAS 2D, Záhorská Bystrica, polder, Q100

THE ROLE OF RETENTION RESERVOIRS IN URBAN FLOOD PROTECTION IN THE KACZA RIVER BASIN IN GDYNIA, POLAND

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Technical methods are essential for mitigating urban flooding arising from land-use change and precipitation variability. This study investigates the role of retention reservoirs in reducing outflow in the Kacza River basin. The analysis is based on the extreme rainfall event of 14-15 July 2016, during which precipitation totals reached 83.2 mm in the downstream coastal zone and 133.2 mm in the upstream moraine hills, resulting in significant urban flooding. Hydrological simulations were conducted using the HEC-HMS model, while hydraulic floodplain mapping was performed using HEC-RAS. Four calculation scenarios were analysed: (1) the basin with two reservoirs operating in 2016; (2) a basin without reservoirs, representing pre-intervention conditions; (3) the basin with all currently existing reservoirs; and (4) a future scenario including existing and planned reservoirs in the catchment. All scenarios were forced using the same historical land-use land-cover map (2015) and rainfall to isolate the effect of retention infrastructure. Simulation results show that in the absence of reservoirs, the peak discharge at the basin outlet would have reached 52.7 m³/s. In contrast, the presence of the two operational reservoirs in 2016 reduced the peak flow to 40 m³/s, corresponding to a reduction of about 24.1 % and a noticeable delay in peak timing. The inclusion of all currently existing reservoirs further decreased peak discharge to 25 m³/s, while the future configuration with planned reservoirs reduced peak flow to approximately 17.3 m³/s, achieving a total peak reduction of nearly 67.2 % compared to the no-reservoir scenario. In addition to peak attenuation, reservoir systems increased the time to peak by 330 minutes, thereby improving runoff regulation. Similarly, the flood inundation area decreases from 0.30 km² in the scenario without reservoirs to 0.18 km² when all existing and planned reservoirs are included. The findings demonstrate the substantial hydrological effectiveness of retention reservoirs as structural measures for urban catchment management under extreme rainfall conditions. The scenario-based approach provides quantitative evidence to support strategic planning of retention capacity in rapidly urbanizing basins. Future research will incorporate nature-based solutions to enhance the catchment buffering system under land-use land-cover change and precipitation-driven extreme events.

Keywords: Flood mitigation, Gdynia, Kacza River, Retention reservoirs, Urban catchment

INFLUENCE OF DESIGN HYETOGRAPH CONSTRUCTION METHODS ON URBAN RUNOFF SIMULATION

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The temporal distribution of precipitation within a design storm significantly influences simulated runoff and hydraulic loading in urban drainage systems. Although intensity–duration–frequency (IDF) relationships define precipitation magnitude, the selection of the design hyetograph determines the temporal concentration of precipitation and thus the peak discharge response. This study investigates the sensitivity of an urban sewer system to different methods of constructing dimensionless design hyetographs.

Design storms were derived from local high-resolution precipitation records using two approaches: the Huff curves and the Method of Average Variability. For each method, representative dimensionless hyetographs were constructed and combined with design precipitation height corresponding to selected return periods. The resulting synthetic storms were applied as input to a numerical hydraulic model developed in the SWMM (Storm Water Management Model) software for a selected urban catchment in the city of Osijek, Croatia.

Model simulations were performed to evaluate differences in peak discharge, hydrograph shape and potential surcharge conditions within the sewer network. The results demonstrate that the choice of dimensionless hyetograph significantly affects predicted system response, particularly for short-duration, high-intensity storms. Hyetographs characterized by earlier precipitation concentration tend to generate higher and earlier peak flows, while those with delayed concentration can lead to sustained system loading and increased risk of surcharge in downstream sections.

The findings emphasize that the method used to construct the design hyetograph is not a neutral modelling choice but a critical factor influencing hydraulic performance assessment and infrastructure design. A transparent and locally derived selection of the temporal precipitation pattern is therefore essential for reliable urban drainage analysis.

Keywords: Design hyetograph, numerical model, Huff curves, Method of Average Variability, Urban floods

CORRECT ADOPTION OF THE TWO-DIMENSIONAL DISPERSION TENSOR FOR POLLUTANT PROPAGATION IN WIDE RIVERS

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This paper presents the problem of correctly determining the coordinates of the horizontal dispersion tensor in modelling pollutant transport in wide rivers with a distinct velocity profile. The aim of the study was to determine the influence of the actual, gradient velocity distribution on the values of the dispersion tensor elements and on the predicted shape and propagation of the pollutant plume. The analysis was based on data from tracer measurements taken in the estuarine section of the river. Numerical simulations were performed for a section of the Vistula River near Włocławek. The studied river section is characterized by a width exceeding 200 m and the presence of an island dividing the stream, which causes significant variation in the velocity field and the formation of zones with different flow dynamics. Based on the analysis of the statistical moments of the concentration distribution and the velocity profile, the coordinates of the dispersion tensor were determined: longitudinal D_{xx}, transverse D_{yy}, and conjugate components D_{xy}, D_{yx}. Numerical simulations of the reactive substance transport (without chemical reactions) were then performed using the two-dimensional advection-dispersion equation. The results obtained using the full dispersion tensor were compared with those of a simplified model, which adopted tensor coordinate values from measurements conducted in the coastal zone (for a drift velocity distribution). The results indicate that under conditions of a strong velocity gradient and flow around the island, adopting dispersion tensor coordinates for a drift velocity distribution leads to distortions of the predicted concentration distribution, particularly overestimating the exposure of coastal zones. Considering the tensor coordinates specific to the gradient distribution causes a change in the orientation of the plume's principal axis, greater asymmetry in its development, and a different estimate of the time it takes for pollutants to reach control cross-sections or the shore. It has been shown that in wide rivers with complex morphology, the use of a diagonal dispersion tensor may be insufficient, and incorrectly assumed dispersion coefficient values distort the results. Correct representation of transport anisotropy is a prerequisite for reliable forecasting of the effects of accidental discharges and for correct environmental risk assessment.

Keywords: migration in rivers**,** migration of pollutants in water, two-dimensional dispersion, mass dispersion, dispersion coefficients

URBAN AREAS AND GROUNDWATER FLOW ISSUES

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In urban areas the groundwater regime results both from natural conditions and by human interventions, namely by the construction of deep foundations of new residential and other buildings. The natural conditions are related to aquifer morphology often containing the network of historical "subsurface" water courses partly draining the areas.
Human activities are represented by a change of geological composition (anthropogenic geological layers), leakage from water supply pipes, pumping from water wells, obstruction of the subsurface flow by deep foundations and construction of deep engineering network collectors. These factors influence the groundwater flow regime, on contrary, groundwater flow affects a technical design of aforementioned structures and foundation techniques at the site.
Groundwater flow modelling is used for the assessment of the states before and after the construction of subsurface parts of new buildings. This enables both the evaluation of an impact of a structure on the groundwater regime in the locality and impact of groundwater on the subsurface structures (water pressure on the foundation joints, uplift forces, etc.). Special issue is the temporal change of the groundwater regime during floods when increase water stages in streams propagate to the floodplain and affect the groundwater regime in the areas along the streams. In river equipped by flood levees or floodwalls, the safety towards an internal erosion of the levee itself or of the subbase is crucial.
The issue has several aspects, out of which the most important ones are as follows:
(i) During the city development, new buildings are usually constructed with several subterranean floors with subsurface garages. Thus, subsurface parts of buildings frequently reach the groundwater level. Therefore, it is necessary to take into account groundwater effects on the newly proposed structure and a reverse influence of the new structure on the groundwater flow regime and an impact on existing structures.
(ii) In case of continuous line of flood protection, an “artificial” excess pressure occurs in the protected area as the increased flood level propagates into the aquifer and affects the structures in the protected area. In relation to permeability of the collector, the groundwater level advance can reach tens to hundreds of meters from the water course.
In conclusion, experience shows that the aspects mentioned above cannot be overlooked during the preparation of extensive investment and that it is always worth checking local conditions in the framework of the project elaboration through geological and hydrogeological surveys and through the use of interrelated hydraulic groundwater flow modelling to carry out conceptual proposal for possible measures. They have to guarantee a sufficient protection of structures themselves against unfavourable groundwater effects and to eliminate, in a suitable way, groundwater flow regime changes and a possible impact on the adjacent civil structures and environment.
In the paper, the groundwater flow issues in urban areas are listed and demonstrated on practical examples.

Keywords: groundwater flow, subsurface structures, urban areas, floods

APPLICATION OF THE ENTROPY THEORY IN A CASE OF THE MEANDER IN A COMPLEX MORPHODYNAMICS MEDIA

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Entropy theory, based on the principle of maximum entropy, is used to determine the velocity distribution across the cross-profile section relative to the maximum surface velocity. This method is reliable for the final result, which is the average flow value for the analysed watercourse profile. The presented research will analyse velocity distributions in the meander of the river Bednja in Croatia at the analysed location, Lovrentovec. It is expected that the results will differ from those for rectilinear flow, that is, in the direction of the water flow. The maximum velocity will be determined using a hydrometric wing, an Unmanned Aerial Vehicle (UAV), and a mobile phone (video-based surface velocity estimation). Reconstruction of the velocities across the cross-profile section will be performed using the Image Rastering procedure (image-based surface velocimetry), with support from the Python programming language. An additional difficulty is the changing geological structure of the meander relative to the existing sedimentary rocks that form the bottom and sides of the trough, running lengthwise along the watercourse at the analysed location. This research is important for understanding the properties of flow and velocity distributions, which affect the hydraulic and hydrological attributes of watercourses in general. This is particularly important for the sizing and construction of embankment regulation facilities, flood protection, and the sizing of other hydrotechnical facilities (hydropower plants, bulks, etc.).

Keywords: meander, flow, velocity, entropy, hydrometry

INNOVATIVE TREND ANALYSIS (ITA) OF GROUNDWATER QUALITY PARAMETERS AT THE BARTOLOVEC WELLFIELD (CROATIA)

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Groundwater is one of the most important sources of drinking water, especially in regions exposed to intensive agricultural and urban pressures, where long-term changes in water quality are increasingly evident. Continuous monitoring and analysis of groundwater quality are therefore essential for sustainable water resource management and timely identification of potential contamination processes. In this study, long-term trends in groundwater quality parameters at the Bartolovec wellfield in northern Croatia are analysed using the Innovative Trend Analysis (ITA) method. The analysis is based on a 30-year time series (1994–2023), which provides a robust basis for detecting temporal variations in groundwater quality. The selected parameters include nitrate concentration, chloride concentration, pH value, temperature, and turbidity, for which a sufficient number of samples is available to ensure reliable analysis. The ITA method is used as an advanced, highly sensitive approach to trend detection. Unlike conventional statistical approaches, such as linear regression analysis, the ITA method does not require strict assumptions regarding data distribution, serial correlation, or sample size, and enables a more detailed and visually interpretable assessment of trends. The analysis is performed on a time series of annual average values, providing insight into long-term changes in groundwater quality. Such an approach enables a more comprehensive understanding of the temporal dynamics of hydrochemical parameters in vulnerable aquifer systems. The expected outcomes of this research will contribute to an improved understanding of the evolution of groundwater quality over time and support the development of effective water protection and management strategies. The study further highlights the importance of applying innovative analytical methods to long-term environmental datasets, particularly amid increasing anthropogenic pressures and the need for sustainable groundwater resource management.

Keywords: groundwater quality, innovative trend analysis (ITA), long-term monitoring, wellfield, nitrates

TRANSBOUNDARY WATER COOPERATION BETWEEN EU MEMBER STATES AND THE THIRD COUNTRIES

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Transboundary water cooperation within the EU is subject to a highly harmonized legal regime dominated by the EU's Water Framework Directive (WFD). EU member states are also under a "best-effort" obligation to implement the objectives of the WFD vis-à-vis third countries in shared river basins. Consequently, the EC and EU member states have, over the past two decades, been consistently working to expand the application of the EU's water policy priorities and governance mechanisms to catchment areas spanning the EU's political borders. How far these efforts have succeeded, however, remains largely unknown. Project titled “Transboundary water cooperation between EU member States and third countries: governance resilience analysis and hydropolitical model-building” (TWCEU) will try to fill the gap by comparative analysis of the legal and institutional framework of cooperation in the relevant sub-basins, including the effectiveness of existing water management.

Project aims to map out the interactions between EU, national and international water policy and law in four river basins shared by EU and non-EU countries (the Rhône, the Rhine, the Po and the Danube).

In the first stage of project implementation, the focus is on the analysis of hydrological water management problems in the basins, specifically in sub-basins shared by EU and non-EU countries alike. All rivers with a catchment area > 1000 km² were extracted and associated with their respective sub-basins (HydroBASINS) together with direct transboundary catchment areas of the border river sections. Their geographical, hydrological and environmental characteristics and water management practices will be the starting point for the understanding of conflict and cooperation over shared rivers from an international relations, international law, and political science perspective.

Keywords: transboundary cooperation, third countries, water management

HYDROLOGICAL CHARACTERISTICS OF THE MEDVEDNICA MOUNTAIN SPRINGS

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Springs have great hydrological and ecological role, especially in the mountainous areas. During the period from 2020 to 2024, a total of 900 springs were mapped on the southern slopes of Medvednica Mountain Nature Park, which is several times more than previously assumed. Mapping was done through intensive field work during the whole period. At each site, discharge of the mapped springs was measured using the volumetric method. Based on the measured discharge and hydrological conditions at the time of measurement, spring discharge class was assigned for each spring using Meinzer's classification. All the data gathered in the field was organised in to a spring database using the ArcGIS 10.8. system. In addition to the field-collected data, each spring was joined with geomorphological and geological data of the area they were located, using the digital elevation model and Basic geological maps of Croatia. In general, springs were mapped on various slopes, elevations, and lithostratigraphic units.

Discharge classes were determined for 773 springs. Discharge category VIII (< 0.01 L/s) was the lowest found in the study area, and class IV (10-100 L/s) was the highest. Most of the springs (337) have discharges between 0.01 and 0.1 L/s (Meinzer's class VII), while class VI (0.1-1 L/s) was the second in number of springs (242). The springs have shown discharge class variability between, but also within certain lithostratigraphic units, as well as morphometric units.

Based on certain specifics, six springs were chosen for a two-year monitoring to compare the dynamics of their hydrological characteristics. Three springs were of class V (1-10 L/s) and three were of class VI (0.1-1 L/s). One pair of monitored springs is situated in the southwestern, karstic part of the research area, that consists mostly of Triassic carbonates. The four remaining springs chosen are situated in the central part of the research area, where various, less permeable metamorphic rocks dominate the area. About 40 volumetric discharge measurements were carried out on each spring in different periods of the year. The water level data logger was installed in the Jambrišakovo vrelo spring in the karstic part of the research area, since that was the only suitable spring for data logger placement. Using the volumetric discharge measurements, the discharge curve of the mentioned spring was created. Using the curve, a detailed discharge dynamic was obtained for the monitoring period, emphasizing the quick reaction of the spring discharge to precipitation.

Results of the monitoring have shown differences in discharge variability between springs, even in the case of neighbouring springs in the karstic area, as well as two neighbouring springs in the central part. Netopil's discharge variability classes were used to determine the variability of the spring discharge. The variability is calculated as a ratio between Q_{90} (discharge present 90 % of the time) and Q_{10} (discharge present 10 % of the time). From the six monitored springs, two were classified as extraordinarily unbalanced, in terms of their discharge variability. One Spring was classified as balanced, two were classified as well balanced, and one as extraordinarily balanced.

The results have shown that springs in the Medvednica mountain are numerous and show great hydrological diversity, which is the result of different (hydro)geological, geomorphological, climatological and other spatial factors. These findings can help in more successful water resources management and protection in the Nature Park.

Keywords: mountain springs**,** discharge variability, Medvednica mountain**,** water resources

A CASE STUDY TO TEST THE FEASIBILITY OF USING MANAGED AQUIFER RECHARGE IN KARST AREA

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Managed aquifer recharge is of utmost interest as a method to ensure enough water for public supply especially in the Mediterranean region in cases of increased demand for the tourism and reduced availability due to the impact of climate change. As a part of Blue Recharge Interreg project the Case study in south Istria was performed, testing the impact of the treated wastewater discharge into the Southern Istria karst aquifer, that is mostly abandoned for human consumption, but has potential for irrigation use.

Different sets of tests were performed at the newly constructed WWTP Loborika: tracer tests, monitoring underground water quality, wastewater quality and discharge field quantity and quality improvement.

For the tracer test two wells were drilled, application well, 35 m deep and control well, 100 m deep, 10 kg of uranin previously dissolved in water was introduced into the well using a funnel, rinsed with 40 m^3 of water. For monitoring purposes a measuring instruments with a data logger (fluorometer tip GGUN-FL30; Albillia Sàrl), were installed at the control well and one additional well, and manual sampling was performed on four additional locations to assess a groundwater movement in the area.

The other set of tests was focused on wastewater treatment and subsurface discharge optimisation. The analysis of the filtration properties of the natural soil from the Loborika drainage field were performed and the quality of the water filtered through the field was assessed. The collected soil material from the Loborika WWTP was analysed using a standard permeameter cell (inner diameter 100 mm). Conductivity of the sampled soil was measured with laboratory piezometers of different diameters using the EN ISO 17892-12 method. After preliminary laboratory testing Pilot test unit was installed at the site to compare efficacy of different compositions of filtration materials to improve treated water quality.

The tracer test results have shown the hydrogeological connection with the observation well, where a high concentration of tracer was persistent and a possible hydrogeological connection with the Tivoli well, with the first occurrence after 57 days, both confirming low apparent flow velocity of 0.08 cm/s. No tracers were found at the other four observation sites.

The filtration properties test places the soil from Loborika site in the class of very poorly permeable clay-clay materials according to Terzaghi-Peck and confirms its suitability for sealing layers, retention basins or protective barriers in karst areas. The filtration test has shown that the outlet water quality can be significantly improved with optimal composition of filtration column.

The result of the Case study is a toolkit for assessment whether and under what conditions wastewater plant effluent can be used for managed aquifer recharge.

Keywords: managed aquifer recharge, tracer test, soil permeability

STRATEGIC RECONNECTION OF FLOODPLAINS FOR IMPLEMENTING THE EU 2030 BIODIVERSITY STRATEGY IN LEVEE MANAGEMENT

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Flood levees have historically played a vital role in flood risk management, with more than half a million kilometers of such structures built worldwide. However, by disconnecting rivers from their natural floodplains, levees influenced natural water retention capacity and riverine ecosystems processes. The EU 2030 Biodiversity Strategy and the Nature Restoration Regulation call for the restoration of freshwater ecosystems, specifically aiming to revitalize at least 25,000 km of rivers by removing obsolete and redundant barriers, including non-functional sections of flood levees.

This study proposes a comprehensive three-step methodology to identify and evaluate opportunities for reconnecting floodplains with rivers. The first step involves a preliminary classification of the levee system to identify sections suitable for further analysis. This classification is based on four key criteria, such as flood protection effectiveness, financial implications of reconstructing or decommissioning, the technical condition of the structure, and any secondary functions the levee might serve, such as transportation or recreation. Each criterion is assigned a score and a weight, with flood protection and financial issues being the most significant factors in the decision-making process. Following the identification of suitable sections, the second step involves the specification of realistic management variants. These range from maintaining the current state to complete levee removal, partial removal, or decommissioning the levee from official records to allow for spontaneous ecological succession. The final step employs multicriterial optimization (MCDA) to select the optimal variant, integrating hydraulic modelling, cost-benefit analysis, and socio-economic, technical, and environmental considerations.

The methodology was demonstrated on a pilot localities along the Morava River in the Czech Republic representing typical land use characteristics and river morphology. The analysis identified specific levee reaches where the primary function was merely the protection of agricultural land, making them candidates for reconnection. The multicriterial evaluation indicated that in certain cases, the most effective approach is to leave the levee without maintenance and remove it from official water structure registries, thereby facilitating a gradual return to natural floodplain dynamics. This integrated approach provides a robust decision-support tool for water managers, authorities and stakeholders to balance public safety with the urgent need for ecological restoration as mandated by the Biodiversity 2030 requirements.

Keywords: Flood levee, floodplain reconnection, EU 2030 Biodiversity Strategy

CARTOGRAPHIC MICROZONATION OF NITRATE VULNERABILITY IN THE VARAŽDIN AQUIFER THROUGH INTEGRATION OF FIELD MEASUREMENTS, HISTORICAL TIME SERIES AND LAND COVER DATA

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The Varaždin aquifer is one of the most important drinking water resources in northwestern Croatia, which has been affected by persistently elevated nitrate concentrations over several decades. This long-term contamination has already led to the closure of one of the three major wellfields in the Varaždin area, underscoring the urgent need for a more precise and spatially differentiated assessment of nitrate vulnerability. This study proposes a methodology for nitrate vulnerability microzonation, with particular emphasis on advanced cartographic modelling and spatial data integration within a GIS framework. The approach is based on the systematic processing of multiannual nitrate concentration records from groundwater abstraction wells, complemented by recent field measurements in groundwater and surface water. Field-measured nitrate concentrations are georeferenced and mapped as point datasets, followed by spatial interpolation to generate continuous concentration surfaces. These cartographic outputs are quantitatively compared with long-term nitrate time series from wellfields, enabling the identification of persistent concentration hotspots, emerging risk areas, and temporal variability patterns in relation to hydrological conditions.

A central component of the methodology is the spatial overlay and cross-analysis of nitrate concentration maps with thematic environmental layers. These include the CORINE Land Cover dataset, which provides a harmonised land-use and land cover classification, and detailed maps of overlying cover deposits, incorporating lithological composition and thickness of protective strata above the aquifer. Through multi-criteria spatial analysis, correlations are evaluated between nitrate distribution, agricultural land-use intensity, and the hydrogeological protective function of superficial sediments. Particular attention is given to areas characterised by highly permeable deposits (e.g., gravel and sand) and reduced thickness of low-permeability cover layers, as these conditions facilitate accelerated vertical transport of nitrates toward the saturated zone. The integration of hydrogeological, pedological, and land-use parameters enables the delineation of initial microzones with increased intrinsic and specific vulnerability to nitrate contamination.

By combining environmental data science, GIS-based cartographic analysis, and targeted field verification, the study establishes a reproducible and scalable framework for nitrate vulnerability microzonation. The resulting spatially explicit outputs provide a scientifically sound basis for groundwater protection planning, optimisation of monitoring networks, implementation of good agricultural practices, and long-term safeguarding of drinking water resources, thereby contributing to environmental protection and public health.

Keywords: Varaždin aquifer, Nitrate vulnerability microzonation, GIS, CORINE Land Cover

Acknowledgement:
Part of this research was carried out within the Interreg Central Europe project CE0100184 „Management of urban water resources in Central Europe facing climate change MAURICE" and is additionally funded by the European Union – Next Generation EU through the project Development of a Methodology for Microzonation of Nitrate Vulnerability Using Artificial Intelligence and Multiple Data Sources (DIMRAN), project code: NPOO GFV-IP-006/2025.

A FRAMEWORK FOR URBAN CLIMATE RESILIENCE: REGULATION ELEMENTS FOR GROUNDWATER PROTECTION IN THE VARAŽDIN AQUIFER

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Water management of urban aquifers in highly permeable alluvial settings requires an integrated approach due to the increased exposure to combined pressures form land-use and climate change. Application of the Integrated Water Resources Management (IWRM) principles enhances the climate resilience of the Varaždin aquifer within the urban context.

The Varaždin aquifer is characterized by high hydraulic conductivity, strong interaction between surface water and groundwater, and documented nitrate and microbial contamination linked to agricultural and urban sources. The aquifer represents a strategically important drinking water resource for northwestern Croatia. Climate change, particularly the increasing frequency and intensity of extreme precipitation events and prolonged drought periods, enhances pollutant leaching, alters nitrate concentration dynamics, and increases hydraulic stress on urban drainage systems.

The study presented in this paper evaluates spatial planning regulation elements (RE) as instruments of IWRM based on a multi-criteria assessment framework assessing (i) potential for contaminant concentration reduction, (ii) contribution to climate resilience, such as hydraulic buffering and flood mitigation, (iii) implementation feasibility, and (iv) synergy with natural attenuation processes. The framework integrates hydrogeological indicators with regulatory and infrastructural parameters to connect planning instruments to measurable groundwater performance.

Land-use regulation, infrastructure measures, and ecosystem-based solutions are analysed to determine the different aspects of the RE's for building groundwater resilience. Results indicate that strictly enforced sanitary protection zones around abstraction sites provide the highest regulatory effectiveness, forming the structural backbone of groundwater protection. Wastewater network expansion and infrastructure upgrades in the water supply system with decentralized infiltration systems can significantly reduce point-source pressures while simultaneously enhancing flood mitigation capacity by reducing peak surface runoff.

By coupling hydraulic buffering with pollutant retention and urban heat mitigation, systemic adaptive capacity will be increased. Results confirm that urban IWRM must integrate spatial planning, technical infrastructure, and nature-based solutions within a coherent governance framework. In the Varaždin aquifer, RE's are embedded in statutory planning documents, supported by EU-funded investments and cross-sectoral coordination, representing a pathway for enhancing groundwater quality resilience under climate change. The scalability of these results supports the operationalization of IWRM principles in medium-sized European cities by connecting regulatory instruments to measurable hydrogeological performance and climate adaptation outcomes.

Keywords: IWRM, Regulation Elements, Climate Change Adaptation, Groundwater Protection

Acknowledgement:

This research was carried out within the Interreg Central Europe project CE0100184 „Management of urban water resources in Central Europe facing climate change MAURICE" and is additionally funded by the European Union – Next Generation EU through the project Development of a Methodology for Microzonation of Nitrate Vulnerability Using Artificial Intelligence and Multiple Data Sources (DIMRAN), project code: NPOO GFV-IP-006/2025.

PROPOSAL OF FISHPASSES BASED ON MONITORING

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This paper investigates the technology of fish attraction at fishway entrances, focusing on the interaction of factors like water flow, light, sound, oxygen, and bubble curtains. By examining the coupling effects of light with both internal (e.g., life stage, age) and external factors (e.g., water transparency, tide), the study aims to enhance fish migration efficiency. The research will provide engineering guidelines for optimizing fishway designs, reducing costs, and improving the effectiveness of existing structures.

Keywords: fishpass, monitoring, design

OPTIMIZATION OF THE MANNING´S ROUGHNESS COEFFICIENT VALUE FOR 1-D FISH PASS NUMERICAL MODELLING

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Nature-like fish passes, due to their irregular morphology and complex hydraulic conditions, require accurate hydraulic modeling based on sufficiently detailed geometric input data. Advances in photogrammetric surveying provide an efficient way to obtain high-resolution spatial data, potentially useful as a basis for hydraulic modeling. However, the influence of the level of detail of photogrammetric terrain data and the geometric representation of the channel on model calibration and accuracy in fish pass structures has not yet been sufficiently evaluated.

The investigated fish pass was surveyed using photogrammetric scanning to obtain a dense point cloud representing the channel morphology. From this dataset, terrain models with different raster resolutions were generated to represent varying levels of topographic detail. In addition to the geometric data derived from the photogrammetric survey, field measurements of water levels and discharge were conducted in the fish pass to provide reference data for model calibration.

Hydraulic simulations were performed in the software HEC-RAS using a one-dimensional steady non-uniform flow model. Several model configurations were prepared, differing in the level of detail of the underlying terrain raster and in the number and spacing of cross-sections representing the channel geometry. For each configuration, the model was calibrated by adjusting the roughness coefficient in order to reproduce the measured water surface profile. The resulting simulations were statistically compared with the observed data to evaluate the influence of geometric detail on model performance.

The study demonstrates that photogrammetric surveying represents a suitable and efficient source of geometric input data for hydraulic modeling of nature-like fish passes, while the level of geometric detail influences the calibration of the Manning roughness coefficient and overall model performance.

Keywords: roughness coefficient, topography, fish pass, numerical modeling

SOFTWARE TOOL FOR OPERATIONAL CONTROL OF THE GABČÍKOVO HYDROPOWER PLANT ON THE DANUBE: LINKING WATER FLOW SIMULATIONS AND ENERGY MANAGEMENT

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The Gabčíkovo Hydropower Plant (GHP) is the largest power plant in Slovakia in terms of generated electricity. The primary objective of its operational management is to optimise the utilisation of the hydroelectric potential of the Danube River to meet the required power output schedule (hydropeaking). At the same time, all other functions of the Gabčíkovo Project must be ensured, and the constraints resulting from its multipurpose character and the hierarchy of priorities for fulfilling its individual functions, as defined by the operating rules, must be respected. These functions include, for example, the safe conveyance of flood flows, ensuring water diversion, and maintaining navigation conditions in accordance with international regulations governing navigation on the Danube. This paper aims to describe a software tool developed at the Department of Hydraulic Engineering of the Faculty of Civil Engineering, Slovak University of Technology in Bratislava, designed for planning and operational management of the GHP in the environment of a liberalised electricity market. The tool ensures that all functions of the hydraulic structure are fulfilled while preventing any threat to navigation safety, particularly the deterioration of navigation channel parameters caused by the GHP's hydropeaking.

Keywords: the Gabčíkovo hydropower plant, hydropeaking, water flow simulation, navigation demands

SAFETY ASSESSMENT OF HYDRAULIC STRUCTURES USING RISK ANALYSIS

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The paper gives a comprehensive summary of the research carried out in the field of safety and risk analysis of natural and dam-break floods in the Department of Hydraulic Structures, at the Brno University of Technology. In the period until 2010 the prerequisites were created for the compilation of guidelines for the implementation of risk analysis in the field of protection against natural floods. In parallel, risk analysis of hydraulic structures, especially dams, was studied. In the period from 2008 to 2024, a number of tasks related to the implementation of risk analysis at water retaining structures was elaborated. These include:
(i) modelling dam failure due to overtopping and piping, study of the resistance of earth materials subject to flow, derivation of the dam break hydrograph,
(ii) internal erosion in soils, the study of the erodibility of sands and the process of backward erosion piping in embankments and their foundations,
(iii) assessment of impacts in the area of loss of human life during floods,
(iv) spatial analysis of hazard due to flooding and seepage using GIS,
(v) developing methodology for combining risk in the material sphere, loss of human life and operational impacts.
From the list of particular problems, two examples of risk based approach at the safety of hydraulic structures in the Czech Republic are shown and discussed, namely the assessment of the financial efficiency of emergency spillway rehabilitation at the dam Šance and the tolerability of losses of human lives when assessing flood protection in the city of Krnov.

Keywords: hydraulic structures, dam safety, flood protection, risk analysis, flood losses

COMPUTER-EFFICIENT CFD APPLICATION: ADAPTIVE DISCRETIZATION FOR 3D AIR-WATER BRIDGE FLOW WITH SCALE-RESOLVING SIMULATION

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Study deals with the application of three-dimensional scale-resolving simlation model of multiphase flow (air-water) through bridge with the implementation of adaptive discretization for computationally more efficient process. Method for adaptation of computational mesh for tracing free water surface, velocity field gradients and adaptation for no-slip wall boundary condition is presented. Simulation results were verified by experimental measurements using particle image velocimetry and image analysis of inlet (air) vortex formation.

Bridges (and transport infrastructure) are an obstruction to the natural run-off conditions in rivers and floodplains. When designing these structures, it is advisable to assess the hydraulic characteristics (capacity, velocities, etc.). Computational fluid dynamics (CFD) is imperative in the simulation of intricate multiphase flows (e.g., bridge flow) where the resolution of free surfaces, velocity gradients, and boundary layers is paramount. Achieving high levels of accuracy in three-dimensional (3D) simulations often necessitates the use of fine meshes, which can result in a substantial increase in computational costs. Industry standard methods rely on (global and local) incremental increasing the resolution of the computational domain, e.g., by multiplying the total number of cells in the area. It seems more efficient to use an adaptive mesh. Adaptive mesh refinement (AMR) is a technique that has been developed to optimize both accuracy and efficiency. This is achieved by dynamically refining the mesh in regions of high interest, such as sharp gradients or boundary layers, while coarsening it elsewhere. AMR has been demonstrated to be effective in a variety of CFD applications, including turbulent and multiphase flows. The present study employs adaptive discretization in a three-dimensional scale-resolving simulation (SRS) model for air-water bridge flow, with a focus on dynamic mesh adaptation to capture key flow features. This approach is validated by particle image velocimetry (PIV) and intake vortex image analysis.

PIV measurements were conducted in the Laboratory of Water Management Research (LVV) at Brno University of Technology (BUT). The basis is a plexiglass flume with a length of 4 m and interior width of 0.2 m. A plexiglass bridge deck is placed inside the flume. The PIV device consists of double-pulse laser with adjustable repetition rate from 0 to 15 Hz, wavelength 532 nm, maximum energy of 120 mJ and camera (resolution of 1600 × 1200 pixels, 60 mm lens). Computational model is based on finite volume method (FVM), pressure-based NITA (Non-iterative algorithm) with multiphase explicit volume of fluid (VOF) model (including surface tension). Turbulence spectrum is resolved using paradigm k-ω-based SRS model. A multi-layer averaging grid method was coded in Python to evaluate time-averaged values on a spatially and temporally varying computational mesh.

Key findings of the study include: computational cells count reduced by 87 % maintaining computational accuracy and stability, total computational time reduced by 75 %, easy-to-code and implement method in Ansys software, custom Python coded method for evaluating time-averaged results.

Keywords: CFD, adaptive mesh refinement, bridge flow, computer-efficiency, PIV

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UNCERTAINTY QUANTIFICATION OF WAVE TRANSMISSION OF PI-TYPE FLOATING BREAKWATERS

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This paper deals with the quantification of uncertainties in wave transmission for π-type floating breakwaters, increasingly applied in the protection of small harbors and marinas. The introduction explains the fundamental concepts of wave climate and the role of the transmission coefficient in assessing structural efficiency. The methodology is based on the application of existing calculation equations and numerical data processing using Sandia Dakota and Python. A total of 24 uncertainty quantification tests were carried out on models 4320BRK and 5320BRK, analyzing different wave, tidal, and geometric conditions. The results show that safety factors SF_{80} and SF_{95} increase in a nonlinear manner, with variations being more pronounced for higher quantiles. It was found that the relative depth parameter (d/L) has a stronger influence on safety factors compared to the width-to-draft ratio (w/d), while the transmission coefficient Kt demonstrates increased sensitivity in certain regions, while small sensitivity in others. It is concluded that the design of π-type breakwaters requires the application of higher safety factors to ensure functional reliability under conditions of pronounced nonlinearity.

Keywords: wave climate, floating breakwater, pontoon, transmission coefficient, safety factor, probabilistic analysis, uncertainty

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HIGH-RESOLUTION UAV LASER SCANNING OF THE CHANNEL MORPHOLOGY – COMPARISON WITH TRADITIONAL SURVEYING TECHNIQUES

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Traditionally, data describing channel morphology are collected through topographic surveys using total stations or RTK GNSS receivers. However, these methods have limitations, including coarse sampling densities and time-intensive field efforts. To overcome the limitations of traditional surveying, remote sensing technologies such as aerial laser scanning (ALS) or drone laser scanning (DLS) have been utilised to survey riverbed morphology.

The aim of the research on the Rye Island drainage channel system in Slovakia was to combine and compare traditional surveying (RTK GNSS) with DLS to obtain the channel bed morphology. An Unmanned Aerial Vehicle (UAV) DJI Matrice 300 RTK carrying an ultra-light Light Detection and Ranging (LiDAR) system of Slovak origin, Lidaretto, was used to obtain data describing the morphology of the channels Vojka-Kračany (A VII) and Šuľany-Jurová (B VII). The said channels are artificially fed with water originating as a seepage through the dykes of the Gabčíkovo supply channel. It is therefore a clear water with groundwater quality. The processed LiDAR data covering the entire channel area were then compared with point data measured at several cross-sections using RTK GNSS. The results show that in clear, shallow water, DLS achieved performance comparable to that of RTK GNSS. The mean absolute error calculated for cross-sections varies from 0,05 – 0,45 meters. The differences in results are mainly in profiles with a thick layer of bottom fine sediments.

Keywords: drainage channels, riverbed morphology, UAV, LiDAR, DLS

JADRO AS A LIVING LAB: INTEGRATING LOW-COST DRIFTERS WITH SYSTEM-BASED ASSESSMENT IN EDUCATION AND MONITORING

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Transitional water systems are characterized by strong spatial and temporal variability, requiring monitoring approaches that extend beyond traditional fixed-point measurements. This study presents the Jadro estuary as a living laboratory for integrating low-cost Lagrangian drifters with system-based assessment within an engineering education and monitoring framework.

The proposed approach combines drifter-based observations with system-based assessment tools commonly used in water resources engineering, including flow-duration analysis, pressure interpretation, status review, and conceptual synthesis of the transitional system. In parallel, field measurements using in situ sensors (e.g. conductivity–temperature–depth and fluorometric probes) provide supporting information on vertical structure and water quality conditions.

A key component of the framework is the iterative development of modular, low-cost drifters, designed to capture surface transport dynamics and spatial variability. The approach is implemented through student-led and research-oriented activities, linking device development, field deployment, and system interpretation within a unified educational setting.

While drifters do not provide direct estimates of pollutant loads, they complement system-based analyses by revealing transport pathways, mixing behaviour, and fine-scale spatial structures that are not captured by conventional monitoring approaches alone. Initial applications demonstrate the value of combining dynamic observations with established assessment methods in a transitional river–estuary system.

The results highlight the potential of using a living laboratory approach to support adaptive monitoring, improve system understanding, and strengthen the connection between education and practice in water management. The framework is transferable to similar transitional environments facing complex hydrological and water quality pressures.

Keywords: transitional waters, estuarine systems, Lagrangian drifters, water quality, adaptive monitoring

ADVANCING THE TEMPORAL DYNAMICS ANALYSIS OF THE BULAŽ SPRING CATCHMENT WATER BALANCE WITH GLOBAL MODERATE RESOLUTION SOIL MOISTURE DATASETS

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Highly heterogenous and vulnerable, karst springs with the underlying karst aquifers are critical to water supply in Adriatic Sea coastal region. Estimating the availability of water that can meet the increasing demand for potable water is essential but complex and often difficult task. Researchers are frequently confronted with the lack of data hence preliminary water budget investigations were usually conducted using the various empirical methods e.g., Turc (1954) and Langbein (1949) methods that require minimum input data, such as precipitation and air temperature. Over the past decades, advances in remote sensing technology enabled data collection using Earth observation satellites and overcoming the data availability gap, including in water budget estimation. Copernicus Land Monitoring Service (CLMS) and ERA5 Land derived from the ERA5 ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis offer long time series (CLMS for period 2021-today, ERA5 Land for period 1950-today) of spatial distribution of soil moisture data at various temporal and spatial resolutions. Bulaž Spring, located in the northern Istria with catchment area spanning over 105 km^2 serves as the secondary water source in the water supply system. The paper describes the approach to analysing monthly dynamics of water balance in the soil-atmosphere system based on the modified Palmer's two-layer soil moisture model and using the monthly meteorological ground observations and satellite-derived soil water observations. Strong correlation between satellite-derived average monthly soil water and observed total discharges indicate strong hydrological connection between the parameters. Comparison of estimated (Palmer's) and measured runoff coefficients also indicate strong correlation although estimations are overestimated, depending on a month of the year. Interrelationship between estimated groundwater recharge and the observed spring discharges is used to demonstrate monthly storage/release dynamics of the underlying aquifer: water is usually stored during winter months and released during spring and summer. Those preliminary results are in accordance with the existing knowledge of the catchment dynamics, and validate the existing hypothesis. However, further development of the research that focuses on further leveraging the connection between the ground measurements and remotely sensed data is needed to improve our understanding of quantitative relationship between the water balance components in the catchment.

Keywords: Copernicus Land Monitoring Service (CLMS), ERA5 Land, soil-atmosphere water balance, Palmer's two-layer soil moisture model, Bulaž Spring

DETECTION OF DROUGHT EVENTS IN THE DRWĘCA RIVER BASIN USING STANDARDIZED INDICES AND SATELLITE DATA

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The aim of this study is to identify temporal and spatial variations in meteorological and hydrological drought in the Drwęca River basin during the hydrological years 1990–2024. A Standardized Precipitation Index (SPI) was used to assess meteorological drought; this index was calculated based on monthly average precipitation for 14 meteorological stations located in the Drwęca River basin. Hydrological drought, in turn, was characterized based on a Standardized Runoff Index (SRI), which was calculated using the values of average monthly flows for 6 hydrological stations located on the Drwęca River. The obtained SPI and SRI values were calculated for various accumulation periods, i.e., 1, 3, 6, 9, and 12 months. The identified drought periods were correlated with the Normalized Difference Vegetation Index (NDVI). The obtained NDVI values did not simply reflect meteorological and hydrological drought. However, the spatial co-occurrence of meteorological and hydrological drought with drought defined based on the NDVI was demonstrated. The study presents a new approach to identifying drought characterized by SPI, SRI, and NDVI based on the based on the bivariate choropleth map method, which can indicate the actual locations of drought.

Keywords: meteorological drought, hydrological drought, Standardized Precipitation Index (SPI), Standardized Runoff Index (SPI), Normalized Difference Vegetation Index (NDVI), Drwęca River, Poland

FLOOD RISK ASSESSMENT AND HYDRAULIC CAPACITY ANALYSIS OF THE UNGAUGED ROKALOVO KARST CATCHMENT

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Hydrological analysis of ungauged karst catchments represents a significant challenge for urban planning and infrastructure safety, particularly in Mediterranean regions characterized by rapid responses to intense precipitation. This paper examines the Rokalovo stream catchment, for which historical measurements are unavailable, with the aim of defining flood risks for existing and future critical utility infrastructure. The focus of the work is on providing pragmatic engineering solutions by integrating the SCS (NRCS) method and Manning's equation. The results indicate that local, partial interventions are insufficient. Instead, it is necessary to adopt a holistic catchment management approach, emphasizing the importance of integrated regulation and the strategic use of retention areas to ensure the long-term resilience of the urban environment and vital infrastructure systems.

Keywords: ungauged karst catchments, Rokalovo stream, infrastructure protection, parametric sensitivity, holistic management

EVALUATION OF REANALYSIS AND CLIMATE PRODUCTS FOR WIND FORCING OF A MID-ADRIATIC NUMERICAL WAVE MODEL

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Accurate atmospheric forcing is essential for reliable numerical wave modelling in semi-enclosed basins with complex island-mainland geometry such as the mid-Adriatic area of coastal Croatia. Multiple reanalysis and climate products provide wind fields of varying spatial and temporal resolution, yet their performance as forcing for regional wave simulations requires systematic evaluation. The goal of this study is to assess selected products (ERA5, CERRA, ICON-DREAM, MERIDA and AdriaClim) as wind forcing for a high-resolution numerical wave model of the Croatian mid-Adriatic area. Wave simulations were performed using the spectral wave model SWAN, implemented on an unstructured computational grid covering the coastal-island system and validated against buoy wave measurements. Solution verification was first conducted by simulating the most severe recorded storm event using ERA5 forcing. Three mesh configurations of varying cell sizes and two directional resolutions were tested to quantify numerical sensitivity to spatial and spectral discretization. Model calibration was subsequently carried out by adjusting the Janssen whitecapping coefficient using several months of measured wave data. The calibration procedure was applied for each wind forcing dataset. Model performance was evaluated using standard statistical indicators for significant wave height and selected spectral parameters. Preliminary results indicate that both mesh refinement and directional resolution have little influence on model results for the tested storm event below a cell area of 100 000 m^2. Two wind datasets that produced best agreement with the measurements were selected for extended-period simulations to further assess their applicability. The findings underline the importance of careful model development when applying reanalysis and climate products as wind forcing for regional SWAN-based modelling.

Keywords: numerical wave model, SWAN, wind forcing, atmospheric reanalysis products, Adriatic Sea

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FROM STORMWATER TO WELLBEING: NATURE-BASED SOLUTIONS FOR URBAN WATER MANAGEMENT AND THERMAL COMFORT – EUPOLIS BGD

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Nature-based solutions (NBS), as a form of blue-green infrastructure, play a key role in advancing sustainable water management, urban climate resilience, and environmental protection. In addition to regulating stormwater and supporting ecosystem functions, NBS contribute to microclimate regulation and improved thermal comfort. This study evaluates the performance of integrated NBS interventions implemented at a pilot site in Belgrade, Serbia, with a focus on their contribution to sustainable urban water management and climate resilience.

The analysed system includes a multifunctional pocket park with a stormwater biofilter, vegetated areas (trees and shrubs for air pollution abatement), and vertical green elements. A monitoring framework was established before, during, and after construction, integrating environmental observations with microclimatic modelling. Field measurements of air temperature and humidity were collected using distributed sensors, while microclimatic effects were assessed using the ENVI-met model. Simulations were performed for a representative "typical summer day," defined using long-term climatic data and local observations. The analysis focused on air temperature, Potential Air Temperature (PAT), Physiological Equivalent Temperature (PET), and Universal Thermal Climate Index (UTCI), capturing both physical and perceived impacts of NBS. The study also considers the role of vegetated systems in regulating surface–atmosphere interactions, including evapotranspiration and moisture retention, which are directly linked to sustainable water use and urban hydrological processes.

The implemented NBS interventions maintained airflow patterns while creating localized cooling zones, particularly in areas with dense vegetation associated with the biofilter system. These zones exhibited significant reductions in thermal stress indicators due to shading and evapotranspiration processes linked to water retention and vegetation. At the site scale, aggregated results show substantial reductions in thermal stress, with peak daytime (14:00) reductions of −3.3°C in PAT, −16°C in PET, and −10.4°C in UTCI, exceeding predefined performance targets. The results indicate that water-related processes within the vegetated area (soil moisture retention and evapotranspiration) play a substantial role in enhancing cooling performance and improving outdoor usability of the space throughout the day.

The findings demonstrate that integrated NBS can simultaneously support sustainable water management and improve urban climate resilience by coupling hydrological processes with microclimate regulation. Stormwater biofilters and vegetated systems contribute not only to water retention and potential pollutant mitigation but also to significant reductions in heat stress through evapotranspiration and shading. These results highlight the importance of designing multifunctional green infrastructure that integrates water management and thermal comfort objectives, particularly in the context of climate change and increasing urban heat and flood risks.

Keywords: nature-based solutions, urban water management, health and wellbeing, thermal comfort

WATER RETENTION MEASURES IN THE TURANY NAD ONDAVOU VILLAGE

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Paper deals with the proposal of water retention measures in the village Turany nad Ondavou. From an urban planning point of view, the measures are designed in such a way that it creates the conditions for the controlled retention of rainwater from the reconstructed area of the parking lot and pedestrian communication or recreation zone, due to which the water will be returned to the water cycle back to nature. A green permeable to semi-permeable paved area will be created in the central part of the village, which will give the space a new dimension and replace the drab asphalt surface with a green "island" in the central part of the village, before the main entrance to the building and the transition between the streets, when it will functionally connect them.

Keywords: rainwater, hydrology, water retention

REVITALIZATION OF A DRAVA RIVER SIDE BRANCH USING 2D NUMERICAL MODELLING

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River side branches within regulated floodplains often experience reduced connectivity and disturbed hydraulic and sediment balance, particularly during low-flow periods. This study addresses the revitalization of the Podravska Moslavina side branch of the Drava River. This river section is characterized by the presence of a sill at the side branch inlet, which prevents inflow for approximately 35% of the year, leading to limited flow conveyance and sediment transport.

The aim of this study is to demonstrate that alternative design solutions can improve flow conditions and restore a more natural velocity distribution. The analysis is based on two-dimensional hydraulic modelling using HEC-RAS. Following model calibration for representative low- and high-flow conditions, two groups of measures were investigated: lowering of the inlet sill and channel excavation to achieve the desired longitudinal bed slope.

Results indicate that the proposed measures improve hydraulic conditions, particularly under low-flow scenarios, by increasing flow conveyance and promoting a more natural velocity distribution along the side branch.

The study highlights the importance of adapting restoration measures to site-specific hydraulic conditions and demonstrates the applicability of numerical modelling in the design of river restoration interventions.

Keywords: revitalization, river side branch, numerical 2D model, sill, sand bar, flow conveyance

NATURE-BASED SOLUTION FOR CLIMATE CHANGE ADAPTATION CASE STUDY IN SLOVAKIA

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The goal of the contribution is to present the possibility of improving and accomplishing the overall objectives of a former WACO project proposal. The project was a result of the Dutch water board and the Slovak Water Management Enterprise branch in the eastern part of Slovakia, and concerned the reduction of the flooding intensity in the area surrounded by the Ondava and Trnávka rivers. This region is part of the Bodrog River basin (Fig.1).

The improvement of the WACO project consists of digitalisation of the whole area of interest, improving water control structures, enlarging the water storage capacity of the project area from a flooding point of view, as well as drought mitigation possibilities in conditions of climate change. Based on the Trnávka drainage basin reconnaissance, own measurements in situ, and study literature relating thereto, a proposal of several technical measures for safe run-off in the Trnávka River bed has been elaborated and consequently evaluated from a hydraulic point of view. The whole research is a part of nature-based solutions for climate change adaptation in frame of the EU-financed LIFE Strategic Nature and Integrated Projects in Slovakia.



Fig.1. Illustration of the pilot area of interest.

Keywords: Adaptation to climate change, nature-based solutions, drought and flood protection measures proposal

INTEGRATING HYDRODYNAMIC HABITAT MODELLING AND NATURE-BASED SOLUTIONS FOR THE RESTORATION OF THE NOSKOVAČKA BARA SIDE-ARM

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Noskovačka Bara, a former side arm of the Drava River located in Virovitica-Podravina County (Croatia), represents an important floodplain water body within the UNESCO Transboundary Biosphere Reserve Mura, Drava, Danube (TBR MDD). and the Natura 2000 network. Long-term hydrological disconnection from the main river watercourse, progressive sedimentation and altered groundwater dynamics have resulted in very poor ecological status and reduced habitat functionality. Within the SWIMM project (Sustainable Water and Integrated Management of Fish Migration and their Habitats in the Danube River Basin and NW Black Sea), the site has been designated as Reference Site RS4.1 to demonstrate nature-based restoration measures aimed to re-establish hydrological connectivity and to improve conditions for native fish communities.

The research integrates ecohydrological assessment, hydromorphological analysis and hydrodynamic fish habitat modelling to support evidence-based restoration design. Baseline investigations included bathymetric survey, water level and temperature monitoring, flow observations, sediment characterization, and assessment of aquatic and riparian vegetation and fish. These datasets were combined with historical information and species-specific habitat requirements to define reference conditions and restoration targets. The proposed measures focus on partial reconnection of surface and groundwater pathways with the Drava River, selective removal of excess fine sediment, channel reshaping, and the creation of diverse habitats, such as shallow spawning grounds and deeper pools that serve as low-velocity refugia.

Scenario analyses and simplified hydraulic calculations indicate that the planned interventions increase inundation duration, stabilize the water regime and maintain adequate water depths during low-flow periods. Model results suggest a significant potential for improving the availability of spawning and nursery habitats, particularly for rheophilic and limnophilic species such as *Aspius aspius* and *Romanogobio vladykovi*. The restored side arm is expected to provide suitable conditions for supportive stocking with locally cultivated fish.

The Noskovačka Bara pilot demonstrates how oxbow and floodplain wetland restoration can serve as an effective nature-based solution for strengthening fish migration corridors and improving ecological status in the Drava River floodplain. The presented methodology offers a transferable framework for planning and designing the restoration of similar degraded side arms across the Danube River Basin.

Keywords: Noskovačka Bara, oxbow restoration, ecohydrology, fish habitat modelling, nature-based solutions

NATURE-BASED SOLUTIONS IN THE WATER SECTOR IN SERBIA AND THE EU: FROM REGULATORY ALIGNMENT TO IMPLEMENTATION CHALLENGES

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Nature-based solutions (NbS) have become a central concept in European water and climate policy, particularly through their integration into the Water Framework Directive, the Floods Directive, and the EU adaptation agenda. In parallel, Serbia is aligning its water and environmental acquis under Chapter 27 (Environment and climate change), which is part of Cluster 4 - Green Agenda and Sustainable Connectivity in the revised EU enlargement methodology, supported by substantial EU technical and financial assistance in the water sector. This study examines the extent to which this regulatory convergence has translated into the systematic use of NbS in Serbian water and flood risk management. The analysis follows a three-pillar framework. First, key EU water, flood risk and climate documents are compared with Serbian laws, strategies and plans to assess the explicit and implicit integration of NbS or functionally equivalent concepts. Second, quantitative and qualitative indicators characterise the structural context for implementation, including wastewater service coverage, treatment levels, water body status and the presence of NbS or natural water retention measures in flood risk management plans. Third, institutional and implementation aspects are assessed through national NbS and climate adaptation reports, project documentation and pilot initiatives. Preliminary results indicate substantial policy alignment but a pronounced implementation gap, with Serbian investments still dominated by grey infrastructure. The study identifies institutional fragmentation, lack of technical standards and project-level risk aversion as key barriers and outlines actionable measures to embed NbS in planning and investment.

Keywords: Nature-based solutions, water sector, flood risk management, European Union, Serbia, environmental policy, implementation gap

THE IMPACT OF WASTE CAR TIRES ON THE AQUATIC ENVIRONMENT AND THE POTENTIAL OF RECYCLING INTO NEW CONSTRUCTION PRODUCTS

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Waste automobile tires pose a major environmental problem due to the large quantities generated daily, uncontrolled disposal in the environment, and their slow degradation. The release of hazardous substances into the environment, especially when tires are in contact with precipitation and leachate, together with the presence of various potentially harmful compounds in their composition, classifies waste tires as hazardous waste. Improper disposal and prolonged exposure to atmospheric conditions cause mechanical wear and rubber degradation, leading to the formation of fine particles and the gradual release of certain chemical compounds. When in contact with precipitation and leachate, these constituents and particles can be leached and transported into soil, surface waters, and sediments, making waste tires a relevant source of pollution in the context of aquatic environment protection. At the same time, waste tires constitute a valuable secondary raw material, as their processing yields rubber granulate, steel cords, and textile fibers suitable for producing new products. Recycled tire rubber is used in construction both as an additive to specific materials and as a primary component. In this way, the amount of waste is reduced, the burden on landfills is eased, and the demand for primary raw materials decreases, which also contributes to lower CO_2 emissions. Research will provide insight into the impacts of waste tires on the aquatic environment. In addition, the research will demonstrate the application of waste tires in new products, i.e., soundproofing panels, asphalt additives, concrete and asphalt additives, road equipment, roof coverings,... Only such an integrated approach, combining the reduction of environmental risk, efficient resource use, and verified safety of new products, can truly transform waste tires from hazardous waste into a reliable and sustainable resource.

Keywords: waste tires, aquatic environment, recycled rubber, secondary raw material, waste recovery

COMPARATIVE HYDRAULIC ANALYSIS AND OPTIMISATION OF THE WATER SUPPLY SYSTEM IN A RESIDENTIAL AND TOURIST AREA

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Seasonal fluctuations in water consumption present a significant challenge in planning and managing water supply systems in tourist-intensive urban areas. This paper analyses the hydraulic behaviour and optimisation of the water supply system in Novo Naselje (City of Poreč), with emphasis on the comparative evaluation of water tank and pumping station layouts and their implications for efficient water management.

Based on demographic and tourist projections for a 30-year design period, relevant water quantities were determined, including average daily, maximum daily and maximum hourly consumption, as well as fire and safety reserves. Input parameters for the dimensioning of water towers, pumping stations and pipeline networks were defined, taking into account the marked increase in load during the summer months.

Five system variants were developed. Three variants are based on the gravitational inflow of water to the water tank, with different water tank layouts and elevations (WT1, WT2 and WT3) analysed. In each variant, the operational, fire-fighting, and safety volumes were determined, water level oscillations and the influence of the water tank position on pressure and velocity distribution in the network were analysed. Additionally, two variants of pumping inflow (PS1 and PS2) with different positions and configurations of pumping stations were developed.

Hydraulic calculations were performed using the WaterCAD V8i and Urbano Hydra software packages. Operating pressures, velocities and flows were analysed for different pipe materials (cast iron, PVC and steel) and for scenarios with varying numbers of simultaneous fires. Comparison of the results from both models showed a high level of agreement, confirming the reliability of the numerical approach.

The results indicate that the water tank layout has a crucial impact on the stability of pressures and hydraulic balance of the network, while the choice of pumping station configuration significantly affects energy efficiency and security of supply. In the context of water management, the analysis enables identification of the optimal variant with regard to reliability, operational flexibility and system resistance to peak loads. Integrated hydraulic modelling has proven to be an effective tool for decision support in planning and managing water supply systems under conditions of climatic and seasonal variability.

Keywords: hydraulic analysis, water supply system, numerical modelling, water tank, pumping station

HYDRAULIC ANALYSIS AND OPTIMISATION OF AN ANNULAR WATER SUPPLY SYSTEM IN AN URBAN AREA

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The planning and optimisation of urban water supply systems require an integrated approach that encompasses hydraulic reliability, energy efficiency and security of supply under emergency conditions. This paper presents a variant hydraulic analysis of a section of the ring water supply system in the City of Vinkovci, aiming to determine the optimal placement of the water tank, reservoir and pumping stations within the existing regional system of Eastern Slavonia.

The analysis is based on defined relevant water demands for residential, tourist and industrial consumers, including average daily, maximum daily and maximum hourly consumption, as well as fire-fighting requirements, the system's own needs and water losses. Three system variants are developed. In the first and second variants, water is pumped to a 30 m high water tank, from which it is distributed by gravity to consumers: the variants differ in the placement of the water tank and the location of the pumping station. In the third variant, water flows by gravity into a low-level reservoir, behind which a pumping station is located to ensure the necessary operating pressures in the network.

The hydraulic analysis was conducted using the WaterCAD V8i software package, with modelling of a ring network and consideration of different pipe materials (cast iron, steel and PVC). Flows, velocities, and operating pressures at characteristic nodes and sections of the network were evaluated. Special attention was given to extraordinary load scenarios: in the first variant, one fire was analysed; in the second, two simultaneous fires; and in the third, two fires with an additional load from an industrial consumer.

The results show that all considered variants meet the technical criteria for permissible velocities and pressures, but there are differences in pressure distribution and energy efficiency. The variants with a water tank provide stable gravitational distribution, while the variant with a low-level reservoir and pumping station offers greater operational flexibility and more precise pressure control, particularly during night-time operation by using a pressure reducing valve. A comparative verification of the results in the Urbano Hydra software package confirmed the reliability of the numerical model.

In the context of water management, the variant analysis contributes to rational infrastructure investment planning, optimisation of pumping station operation and increased system resilience to peak and extraordinary loads. Integrated hydraulic modelling has proven to be an effective tool for supporting decision-making in the management of regional and urban water supply systems.

Keywords: hydraulic modelling, ring water supply system, reservoir layout, pumping station, water resources management

POROUS ASPHALT AS A FLOOD RESILIENCE SOLUTION: COUPLED SURFACE-SUBSURFACE WATER FLOW MODELLING IN POROUS ASPHALTS

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The formation of surface water layers on pavements is a primary cause of aquaplaning, leading to loss of tire–road contact, reduced braking efficiency, and increased accident risk, particularly in low-slope road sections. Porous asphalt represents an engineering solution that enables rapid infiltration, temporary storage, and controlled drainage of stormwater, thereby reducing surface runoff and improving traffic safety. In addition to mitigating aquaplaning risk, porous asphalt enhances skid resistance under wet conditions, reduces splash and spray, and contributes to more stable vehicle handling during rainfall events. Despite these advantages, existing modelling approaches often oversimplify subsurface drainage processes. This study, developed within the RESAFE project, introduces a physically based modelling framework for assessing the role of porous asphalt in (urban) flood resilience and traffic safety.

A coupled surface–subsurface flow model was developed, integrating the Richards equation for subsurface flow and the diffusion wave approximation for surface flow. The model captures dynamic interactions between infiltration, storage, and overland flow through a unified formulation. Nonlinear flow relationships are linearized using Taylor series expansion, enabling efficient, non-iterative numerical solutions. Model parameters are defined through Brooks–Corey relationships for water retention and hydraulic conductivity and calibrated using laboratory experiments. The experimental validation was conducted in a controlled open-channel facility (2 m length, 0.1 m width, adjustable slope) fully lined with a 7 cm thick porous asphalt layer. The setup allows only subsurface drainage at the downstream boundary while preventing surface outflow, thereby isolating infiltration processes. A controlled inflow was applied at the upstream boundary, while cumulative drainage discharge and surface water depth were continuously monitored. The modelling framework reproduces these conditions and is further extendable to two-dimensional domains for application to real road geometries and urban drainage systems.

The model shows strong agreement with experimental observations for both drained outflow and surface water depth dynamics ($R^2 > 0.95$), which confirms high predictive accuracy. Calibration results indicate effective porosity of approximately 0.15 and high saturated hydraulic conductivity (~2.5 mm/s), confirming the rapid drainage capacity of porous asphalt. These properties directly translate into reduced surface water accumulation, lower water film thickness, and faster dissipation of ponded water, which are critical factors in preventing aquaplaning. By enabling vertical infiltration even in near-flat sections, porous asphalt significantly reduces the persistence and spatial extent of hazardous water layers. Additionally, the delay and attenuation of runoff contribute to reduced peak flows in urban drainage systems, supporting flood resilience under intense rainfall conditions.

Future work will extend the model to two-dimensional applications and assess system-level impacts on urban drainage networks and combined sewer systems.

Keywords: porous asphalt, (sub)surface flow, road drainage, numerical modeling

USING MULTI-YEAR PHYTOPLANKTON DATA TO PRIORITISE FRESHWATER LAKES FOR TARGETED CYANOTOXIN MONITORING

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Cyanobacterial blooms present an increasing challenge for freshwater management, as they can produce harmful cyanotoxins that threaten ecosystem health, drinking water safety, and recreational use. Efficient monitoring is therefore essential, especially in systems where resources for detailed toxin analysis are limited.

This study uses multi-year phytoplankton monitoring data from various freshwater lakes to support a risk-based approach to cyanotoxin monitoring. Cyanobacterial biomass data were evaluated across multiple sampling seasons, and taxa were categorised according to their ability to produce cyanotoxins. This enabled comparison of lakes in terms of total cyanobacterial biomass, the proportion of toxic taxa, and the diversity of toxin-producing species.

Clear differences were observed among lakes, with some systems consistently showing higher proportions of potentially toxic cyanobacteria, greater biomass, and a wider range of toxin-producing taxa. Other lakes showed lower and more stable conditions, indicating reduced potential risk.

Results from this study provide a practical framework for prioritising lakes for further investigation. Lakes identified as high-risk will be selected for advanced cyanotoxin analysis using LC-MS/MS, enabling confirmation of toxin presence and supporting more targeted water quality management.

By linking routine monitoring data with risk-based decision-making, this approach facilitates more efficient resource allocation and enhances the effectiveness of cyanotoxin monitoring programmes through a scientifically based method.

Keywords: cyanobacterial blooms, cyanotoxin risk assessment, freshwater lake monitoring, phytoplankton community analysis, water quality management

HYDROLOGICAL MODEL CALIBRATION USING SWAT-CUP

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Model calibration can be done manually, when user alters calibration parameters, or by using specific calibration software. This paper presents results of SWAT model calibration and validation in the case of the Sill River catchment in Austria. Model calibration was performed using the sequential uncertainty fitting 2 (SUFI-2) algorithms of the SWAT Calibration Uncertainty Programs (SWAT-CUP). The algorithm in SWAT-CUP uses a Latin hypercube sampling method to calculate the 2.5% and 97.5% levels of a given parameter's cumulative distribution to get the 95% of the data (95PPU). Two factors describing the quality of the fit between the calculated and observed data (in this example, streamflow) are mandatory: the P-factor and R-factor. Several investigations tackled the problem of SWAT-CUP calibration in snowmelt-influenced mountainous basins, where particularly the Nash-Sutcliffe Efficiency (NSE) and Pearson's coefficient of determination (R^2) were found as effective indicators of goodness of fit. According to prior investigations in similar regions, a specific set of calibration parameters important for model performance was identified. A total of three stages of calibration were performed where the selected model statistics, namely, R^2 and NSE, were increased from 0.51 and 0.17 to 0.93 and 0.90, respectively, for the calibration period, and 0.91 and 0.84 for the validation period. It was effectively shown that a thought-out selection of calibration parameters and the respective physically valid ranges can increase model performance in complex snowmelt-influenced mountainous basins.

Keywords: hydrological modelling; SWAT; snowmelt; mountainous catchment; model calibration; Sill River

NUMERICAL ASSESSMENT OF AN IMPROVED HYDRODYNAMIC VORTEX SEPARATOR FOR STORMWATER TREATMENT

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Urbanization and climate change have significantly increased the volume and degraded the quality of stormwater entering receiving water bodies. Hydrodynamic vortex separators (HDVS) are effective devices for removing suspended solids from urban runoff, but their performance depends heavily on internal geometric configuration. This paper presents a numerical assessment of an HDVS design to evaluate its hydrodynamic characteristics and particle capture efficiency. Three-dimensional CFD simulations were performed using the Reynolds Stress Model (RSM) for turbulence closure and a Eulerian-Eulerian approach for multiphase flow. The proposed geometry was evaluated based on velocity distribution, tangential flow profile, and dispersed phase volume fraction. Quantitative analysis indicates a theoretical hydraulic residence time of 6.6 s and a calculated separation efficiency of 87.4% for 100 µm particles, with a mass balance closure error below 0.5%. The design achieves effective flow stabilization in the settling zone and high phase separation, providing a numerical basis for designing compact HDVS units for sustainable urban water management.

Keywords: computational fluid dynamics, Reynolds Stress Model, multiphase flow, stormwater treatment, separation efficiency

MODELLING OF SNOWMELT USING SWAT IN THE CASE OF THE UPPER DRAVA CATCHMENTS

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The SWAT (Soil Water Assessment Tool) is a physically based, semi-distributed, watershed simulation model initially developed for comprehensive modelling of the impacts of management practices on water yield, sediment yield, crop growth, and agricultural chemical yields in large, ungagged basins. SWAT has also been shown to be an effective tool for snowmelt modelling; however, intensive data collection and data file creation efforts are mandatory. ArcSWAT was developed as a GIS (Geographic Information System) add-on to simplify the user interface for SWAT model development and the process of extracting parameter values and necessary input data from map layers and databases.

The hydrologic processes calculated in the model are precipitation, interception, surface runoff, soil and root zone infiltration, evapotranspiration, soil and snow evaporation and groundwater flow. In SWAT, the modelling domain is delineated into subbasins, and later, based on unique Land Use/Land Cover (LULC), soil characteristics and digital elevation model (DEM) into Hydrologic Response Units (HRU). The water content of any HRU is represented as soil water content ΔSW which is calculated based on the precipitation P, runoff Q, evapotranspiration ET, deep percolation DP, return flow QR, with all units being represented as height of water in mm.

Snowpack accumulation and snow in general, in SWAT, are considered as Snow Water Equivalent (SWE) of the snowpack, which denotes the amount of melted water in mm from a given amount of snow. SWE gets increased with snowfall (precipitation treated as snow), while being reduced via snowmelt and snow evaporation. Snow accumulation and the precipitation type depend on the average air temperature and catchment characteristics. Since in mountainous basins the network of meteorological gauging stations is often scarce, SWAT uses a lapse rate method in order to account for precipitation amount and air temperature changes with elevation change. Snowmelt is calculated by the degree-day method, where the melting coefficient of snow is calculated based on time (day of the year) and maximum and minimum melting factors.

This paper provides detailed insights into the snow melting and accumulation processes within SWAT while emphasising potential drawbacks of the method. The pilot area are the headwaters of the Drava River basin in the Italian and Austrian Alps.

Keywords: hydrological model; SWAT; snowmelt; snow water equivalent; mountainous catchments; Drava River

DISCREPANCIES BETWEEN AN UPDATED 1000-YEAR DESIGN HYDROGRAPH AND RECONSTRUCTED HISTORICAL FLOOD EVENTS

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Design flood hydrographs are a fundamental input for the design and assessment of the flood safety of hydraulic structures. In small catchments, however, their estimation may be subject to substantial uncertainty, particularly where hydrological records are limited, and the catchment response is rapid to short-duration intense rainfall. This paper analyses the Lozorno II reservoir on the Suchý Stream and compares the updated design hydrograph Q_{1000} provided by the Slovak Hydrometeorological Institute (SHMI) with two documented historical flood events that occurred in July 1999 and September 2024.
Because direct inflows into the reservoir are not measured, the inflow hydrographs for both flood events had to be reconstructed indirectly from the observed water levels in the reservoir and the hydraulic characteristics of the outlet structures. The reconstruction of the inflow hydrographs was based on a reverse volumetric balance of the reservoir. The calculation used measured reservoir water levels, an updated reservoir storage curve, and the rating curves of the outlet structures, namely the ungated safety spillway and the bottom outlets. This approach made it possible to estimate the inflow hydrographs indirectly from the recorded water-level development in the reservoir and the corresponding outflows.
The peak discharge of the updated SHMI Q_{1000} design hydrograph is 17.2 $m^3 s^{-1}$, while the peak discharge of the reconstructed hydrograph of the 1999 flood was approximately 110 $m^3 s^{-1}$, and the 2024 flood, according to the available record, had a maximum calculated hourly inflow of 35.33 $m^3 s^{-1}$. However, the peak segment of the 2024 flood event is affected by uncertainty due to a failure of measurements at the hydraulic structure during the flood. Despite this limitation, the volumetric balance estimation indicates that the reconstructed parameters of both documented events, particularly the peak discharge and flood volume, exceed the parameters of the updated SHMI Q_{1000} design hydrograph.
The results confirm the need for verification of the design hydrological data against real extreme hydrological events, especially for small reservoirs with limited flood storage and rapid catchment response to intense rainfall. Such retrospective analyses provide an important basis for evaluating flood safety, outlet capacity, and operational rules under extreme hydrological loading.

Keywords: flood hydrograph, reverse inflow calculation, reservoir volumetric balance, flood wave routing, dam safety

FLOOD HAZARD CHANGES ACROSS THE DANUBE RIVER BASIN UNDER CLIMATE CHANGE

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The Danube River Basin expands across 19 countries (making it the most international basin of the world) and contains the living places of approximately 79 million inhabitants speaking eleven different major languages. Many of these people live and work in areas threatened by river floods, but there are still challenges in dealing with this hazard jointly. Language borders, political blocks and the heterogeneity of economic conditions are barriers to better coordination. More basin-wide research and communication about actual and future river flood hazards could play an important role in raising common problem awareness and joint action.

Our contribution – funded by the EU HORIZON project DIRECTED (grant no. 101073978) and supported by the Croatian Science Foundation through the SERIOUS project (HRZZ-IP-2024-05-1497) – is the further development and application of PIK's Danube Model. Basically, a combination of the eco-hydrological model SWIM and the hydrodynamical model CaMa-Flood, it is capable of calculating river water stages and flood heights for ten-thousands of subcatchments from daily weather inputs. Using bias-adjusted ISIMIP CMIP6 climate scenario data we produced respective flood projections for all major branches of the Danube river system under SSP 370 and 585 emission scenarios.

To illustrate the peculiarities of the model set-up we are going to show some results obtained in the process of calibration. A levee module recently developed for CaMa-Flood made a huge difference especially in level areas of the Carpathian basin; flood events were simulated more than 1 m higher and in better agreement with gauge measurements if levees were enabled. The celerity of flood waves is controlled by roughness parameters of riverbed and floodplain in CaMa-Flood which could be optimized, and another fine-tuning involved the crop rotations on agricultural areas in SWIM whose composition modifies the seasonality of evapotranspiration and hence river runoff.

The principal result are maps of the river system with each river reach coloured after the average return intervals expected for floods at the end of the century which are currently assigned 100-year return intervals. The two scenario maps for SSP 370 and 585, respectively, show shifts in both directions: In many locations current 100-year floods are projected to occur over three times more or less frequently. Trends of shortening return periods however dominate both scenarios – river flood hazards are likely to increase under climate change. Although 600 model years had been used for the analysis, the spatial patterns modulating the general trend differ significantly between the two scenarios. This indicates high uncertainty in the projections and in the estimation of extreme value distributions.

The results call for caution regarding continuous maintenance and improvement of flood defences and the long-term reliability of currently available flood hazard maps. Coordinated efforts should be taken to better estimate and react to altering river flood hazards across borders.

Keywords: Danube River Basin, Flood hazard, CaMa-Flood, SWIM, Climate Change

IMPACT OF PRIMARY PRECIPITATION DATA PROCESSING ON DIMENSIONLESS HYETOGRAPHS

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Primary precipitation data processing plays a crucial role in the construction of dimensionless design hyetographs used in urban drainage analysis. The definition of independent precipitation events and the application of precipitation height thresholds directly influence statistics and the temporal distribution of precipitation within events. This study investigates the impact of precipitation event separation and threshold selection on dimensionless hyetographs derived using both the Huff curves and the Method of Average Variability (hereinafter MAV).

High-resolution (5-minute) precipitation data from Čepin/Osijek meteorological station in Croatia, covering a 10-year period, were analysed, and precipitation events were separated using two approaches: an autocorrelation-based method (hereinafter AC) and a statistical method based on the Kolmogorov–Smirnov and Poisson tests with the Kernel Density Estimation method of function smoothing (hereinafter the KDE method). In addition, precipitation height thresholds were applied to evaluate their influence on event selection and hyetograph shape. For each processing variant, dimensionless hyetographs were constructed using both the Huff and MAV methods.

Results indicate that the choice of event separation method significantly affects the duration and total height of precipitation events, which consequently alters the shape of derived dimensionless hyetographs. The AC method generally leads to longer events and more pronounced late-peak structures, while the KDE method preserves shorter and more concentrated precipitation patterns. The application of thresholds reduces the influence of weak events and increases the temporal concentration of precipitation, particularly for moderate threshold values. Although both Huff and MAV approaches capture dominant precipitation patterns, their sensitivity to primary processing differs, emphasising the need for transparent and methodologically consistent event definition in design applications.

The findings highlight that primary precipitation data processing is not merely a technical preprocessing step but a decisive factor in defining design storm structure for urban drainage systems.

Keywords: Precipitation data processing, Huff curves, Method of Average Variability, Urban drainage

ANALYSIS OF GAUGING STATIONS WITH ZERO FLOW OCCURRENCE IN THE YEAR IN THE STREAMS OF SLOVAKIA BETWEEN 1993 AND 2022

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Under natural conditions, we can find streams with permanent, intermittent or ephemeral flow. However, zero flow can occur in all types of streams throughout the year. This study aims to present the number of gauging stations at which the first zero-flow of the year occurred in Slovakian streams between 1993 and 2022. Data on zero-flow occurrences were analyzed using the Hydrological Yearbook of Surface Waters for each year. All gauging stations for each year were considered in the analysis, including those with flow manipulation. In the gauging station, the yearly minimum discharge of ≤0.001 m^3/s was considered a zero-flow occurrence. Due to the limited availability of free data, only the first occurrence of zero flow was analyzed. The first zero-flow occurrence was recorded in each month of the year, with the highest number of occurrences in the summer months. The minimum number of occurrences was at one gauging station (0.25%) in a particular year. This occurred several times, including in years with high precipitation. The highest number of gauging stations with zero-flow (25 stations, 6.23%) was in 2022, which was evaluated as a meteorologically dry year.

Keywords: zero-flow, streams, temporal occurrence

THE EFFECT OF SUBMERGED SILL ON THE MORPHODYNAMIC RESPONSE OF ARTIFICIAL POCKET GRAVEL BEACHES

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Artificial gravel beaches have become an increasingly common engineering solution along the eastern Adriatic coast due to growing tourism demands and the need to expand the recreational capacity of coastal areas. Although these beaches provide important recreational and coastal protection functions, their long-term stability remains a challenge because storm-induced sediment transport can lead to profile deformation and permanent material losses. Consequently, understanding the interaction between beach geometry, wave conditions, and coastal structures is essential for improving beach design and long-term sustainability.

This study investigates the influence of submerged sill geometry and beach-face slope on the morphodynamic response of artificial gravel beaches under storm conditions characteristic of the eastern Adriatic. The research combines systematic field monitoring with process based numerical modelling using the XBeach-Gravel model. Field measurements collected at Ploče Beach in Rijeka, Croatia, including UAV-derived morphodynamic data, were used for calibration and validation of the numerical model. Following validation, a series of simulations were performed using idealized beach profiles with different slopes and submerged sill crest depths, and reference configurations without a submerged sill. The results demonstrated that increasing beach slope leads to greater sediment mobility and larger material losses in both configurations, with and without a submerged sill. However, the introduction of a submerged sill consistently reduced cross-shore sediment transport and retained a larger proportion of sediment within the active beach profile, resulting in a more stable morphodynamic response.

Additionally, a newly introduced dimensionless beach parameter, combining beach geometry and wave characteristics, successfully described the relationship between relative beach length and sediment dislocation. The results indicated that submerged sill effectiveness is not constant but depends on the interaction between wave conditions and beach geometry, with greater effectiveness observed under more energetic wave conditions.

The study provides engineering based guidance for estimating expected sediment dislocation and evaluating the morphodynamic and economic justification for submerged sill implementation under wave conditions characteristic of the eastern Adriatic. The obtained findings contribute to the development of more stable and sustainable artificial gravel beach designs, and improved coastal management strategies.

Keywords: artificial gravel beaches, submerged sill, morphodynamics, sediment transport, XBeach-Gravel

POSSIBILITIES OF WATER RESOURCES USE FROM DRAINAGE CANALS ALONG RESERVOIRS ON THE DRAVA RIVER, CROATIA

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Drainage canals constructed along the hydropower reservoirs of the Drava River constitute a critical component of the regional water management system. They play a fundamental role in controlling seepage, maintaining embankment stability, and regulating interactions between groundwater and surface water bodies. Despite their operational significance, the hydrological dynamics, water quality characteristics, and potential for secondary water use of these canals have received limited scientific attention. In the context of increasing hydrological variability associated with climate change, a comprehensive understanding of their function within integrated water management frameworks has become increasingly important.

This study examines the hydrological functioning, hydrogeological connectivity, and water quality of drainage canals within the integrated hydropower reservoir system of the Drava River in northern Croatia, encompassing the Varaždin, Čakovec, and Dubrava reservoirs, with detailed analyses focused on the Dubrava reservoir. Field measurements, laboratory analyses, and historical operational data were employed to characterize flow regimes, physical and chemical parameters, nutrient concentrations, heavy and toxic metals, microbiological indicators, and sediment composition.

The findings demonstrate strong hydraulic connectivity between the reservoirs, the alluvial aquifer, and the drainage canal network, indicating that canal water is predominantly groundwater-derived and significantly influenced by reservoir operation. Physical and chemical parameters generally exhibit stable conditions, but pronounced microbiological contamination was identified in specific canal sections. This factor limits the suitability of drainage water for irrigation of edible crops and for direct human use. Relatively stable flow regimes and existing hydraulic infrastructure support the feasibility of limited hydropower production, ecological enhancement, and selected non-consumptive uses.

Overall, drainage canals function as a redistributed component of the integrated groundwater–reservoir system rather than as an independent water resource. Their sustainable management therefore requires careful consideration of hydrogeological processes, contamination pathways, and operational constraints within the broader hydropower system.

Keywords: Drava River; hydropower reservoirs; drainage canals; groundwater–surface water interaction; water quality

125 YEARS OF REGULATION OF THE SAVA RIVER IN ZAGREB - AN UNFINISHED STORY

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The city of Zagreb was formed on the slopes of Medvednica in the early Middle Ages, which, at the time, provided the city with protection from the floods of the Sava river. Centuries later, the city expanded southward to, and beyond, the riverbank.

The regulation of the Sava river began with regulatory works on the river Sava in 1899. That is when the Sava started losing the characteristics of a natural waterway. The current state of the Sava within the Zagreb county is the result of protecting the county from the river's floodwaters. The documents from 1969 and 1982 developed a system of protection against flooding that to this day hasn't been finalised nor does it fulfil the project idea.

Due to the recent morphological and climate changes, there is a larger amount of water flowing in high-flow conditions through Zagreb than planned, which increases the vulnerability of downstream areas. Additionally, during low-flow periods, the discharge of the Sava river through Zagreb falls below the necessary levels for sustainable water usage. To this day, through an array of strategic and spatial plans, it has been proposed to fix the problem of significant longitudinal slopes of the Sava river in the city with hydropower utilization, i.e. by building small hydropower plants. However, these plans don't provide a satisfactory concept of solutions to the problem of low water, which is becoming more pronounced. Furthermore, from the water management perspective, the Sava is a permanent urban planning issue, which has for the past century been handled exclusively by the sectoral approach without agreement or consent from all involved professions.

The paper gives a review of projects from the last 50 years presenting their advantages and flaws from a water management point of view with an overview of interesting urban design suggestions for the inclusion of the river into the city's life.

In conclusion, it is undeniably crucial to begin the process of re-urbanisation, revitalisation, and re-naturalisation of the river in the city's area using integrated water resources management in line with urban development.

Keywords: regulation, re-naturalisation, flood protection, low water, r. Sava

FLOW SIMULATION IN CONSTRUCTED WETLANDS: HORIZONTAL VS. VERTICAL SUBSTRATES

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Constructed wetlands are widely used for wastewater treatment due to their efficiency and low operational costs. Accurate modelling of flow behavior is essential to predict system performance and to identify potential challenges in physical model implementation.

This study investigates the hydraulic behavior of a small-scale constructed wetland by simulating both horizontal and vertical substrate arrangements in software GeoStudio. Each model consists of five layers: gravel, sand, activated carbon, sand, and gravel, each with specific hydraulic conductivities and porosities.

Steady-state groundwater flow simulations were performed to determine outlet discharge and hydraulic retention times (HRT) for different substrate configurations.

Results indicate that both horizontal and vertical substrate arrangements can achieve the target hydraulic retention time of approximately four days. However, different hydraulic conductivities are required for each configuration to reach the same HRT.

The horizontal arrangement requires a higher hydraulic conductivity of 5×10^{-4} m/s in the activated carbon layer, while the vertical arrangement achieves the same retention time with a lower conductivity of 4×10^{-5} m/s. This difference reflects how substrate orientation affects flow paths and overall hydraulic behaviour.

These findings highlight that substrate arrangement significantly influences the system's hydraulic characteristics and the selection of layer-specific properties. Numerical modelling provides valuable insights for predicting flow behavior, optimizing design parameters, and informing physical model implementation to ensure consistent retention times.

Keywords: activated carbon, constructed wetlands, flow simulation, HRT, substrate

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SONO-ELECTROCOAGULATION FOR SIMULTANEOUS SELENIUM AND STRONTIUM REMOVAL IN A MULTI-STAGE REACTOR

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This study evaluates ultrasound-assisted electrocoagulation (sono-EC) for simultaneous selenium (Se) and strontium (Sr) removal in a multi-stage reactor. A D-optimal response surface design (24 randomized runs) was used to quantify the effects of current (5–25 A), treatment time (5–25 min), ultrasound power (150–450 W), electrode material (Al/Fe), and pH regime (no adjustment vs. maximum pH range achieved by upstream electrochemical pH modulation). Removal efficiencies for Se (Y1) and Sr (Y2) were determined at the end of treatment. Se and Sr concentrations were measured by ICP-OES after filtration and acidification, and cavitation intensity was verified by cavimetry.

Se removal was high under most conditions (>95%) and was best described by a reduced quadratic model ($R^2 \approx 0.98$), dominated by treatment time and pH regime, with additional contributions from current, ultrasound power, electrode material, and their interactions. Sr removal was more sensitive to operating conditions and followed a reduced two-factor interaction model ($R^2 \approx 0.97$), where pH regime was the key factor, followed by time, current, and electrode material. Ultrasound did not act as a consistently significant main effect for Sr, but improved performance mainly through interactions with pH and time, indicating process intensification when pH is not optimized. Overall, sono-EC increased process robustness, while pH control remained critical for high Sr removal.

Keywords: selenium, strontium, sonoelectrocoagulation, response surface methodology

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COMPARATIVE EVALUATION OF ELECTROOXIDATION, ULTRASOUND, AND OZONATION FOR THE INACTIVATION OF *ESCHERICHIA COLI* AND TOTAL COLIFORMS

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The presence of faecal indicator bacteria in surface water represents an important environmental and public health issue, highlighting the need for effective disinfection strategies. This study evaluated three disinfection technologies: electrooxidation (EO) with graphite electrodes, ultrasound (US), and ozonation, over a 15-minute treatment period. The efficiency of each technology was tested at three dose levels: EO at 1 A, 5 A and 10 A of electric current; US at 20%, 60% and 100% of power; and ozonation at 1 g/h, 5 g/h and 10 g/h of O_3. Experiments were conducted with lake water spiked with environmentally isolated *E. Coli*. Bacterial enumeration was performed using the automated TECTA B4 system. Efficacy was assessed through log reduction and inactivation efficiency, benchmarked against untreated controls.

The results showed a clear dependence of bacterial inactivation on both treatment intensity and contact time. Among the tested technologies, ozonation and EO at the highest applied doses achieved the best disinfection performance after 15 min of treatment. EO achieved 96.44% inactivation of *E. coli* and 99.09% inactivation of total coliforms, corresponding to 1.45 and 2.04 log reduction, respectively. Ozonation was the most effective treatment, achieving 99.00% inactivation of *E. coli* and 99.50% inactivation of total coliforms, corresponding to 2.00 and 2.30 log reduction, respectively. In contrast, US showed substantially lower efficiency under the tested conditions. Even at maximum power, it achieved 60.36% inactivation of *E. coli* and 74.78% inactivation of total coliforms after 15 min, corresponding to only 0.40 and 0.60 log reduction, respectively. Overall, ozonation proved to be the most effective disinfection method, followed by EO, while ultrasound showed limited standalone potential for rapid microbial inactivation.

Keywords: disinfection, ultrasound, electrooxidation, ozone, *Escherichia coli*

HYDRAULIC DESIGN OF DETACHED GROYNES FOR MORPHODYNAMIC DEVELOPMENT OF DRAVA RIVER

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River groynes are structures used to maintain navigability conditions in rivers while supporting river ecosystems in such a way that they do not have a firm connecting point with river banks. These structures affect the flow velocity and sediment transport patterns, which are crucial for morphological changes in the riverbed through erosion and sedimentation processes. Groynes locally increase the flow velocity and shear stress, consequently initiating erosion of the riverbed nest to the opposite bank. To quantify the effect of groynes on the flow velocity and sediment transport, 2D numerical model can be used, often aiming to optimize the functionality of groynes regarding their position in the river, size and spacing. The goal of optimization is to induce local changes in the riverbed, in a way that does not cause excessive erosion and does not disturb the global sediment balance in the riverbed. Detached groynes are a subtype developed to support river ecosystems in such a way that they do not have a firm connection to riverbanks. They enable a parallel flow of water between the groyne and the bank which physically separates the sandbar created by sediment deposition behind the groyne. The aim of this study is to analyse the efficiency of the group of detached groynes on the flow velocity field through varied length, angle in relation to the bank and spacing. The case study area is a channelised section of the Drava River from rkm 0 to rkm 12. To evaluate the functionality of the groynes, the numerical model HEC-RAS 2D was used, calibrated for characteristic flow conditions: low navigable water level and mean flow.

Keywords: detached groynes, morphodynamics, shear stress, erosion, HEC-RAS

GEOSTATISTICAL MODELLING OF SPATIAL DISTRIBUTION OF GROUNDWATER QUALITY PARAMETERS AT THE BARTOLOVEC WELLFIELD (CROATIA)

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Groundwater quality is characterized by significant spatial variability resulting from complex interactions between hydrogeological conditions and anthropogenic influences. Understanding these spatial patterns is essential for effective groundwater management, particularly in vulnerable alluvial aquifers that supply drinking water. In recent years, geostatistical methods have become an important tool for analysing and visualising the spatial distribution of hydrochemical parameters. This study presents the application of geostatistical interpolation methods to assess the spatial distribution of groundwater quality parameters in the Bartolovec wellfield area in northern Croatia. The analysis is based on a ten-year time series (2014–2023), from which average values were calculated and used as input for spatial modelling. The parameters analyzed include nitrate concentration, chloride concentration, pH value, temperature, and turbidity, for which sufficient data are available to ensure a reliable analysis. Spatial distribution models are developed using several interpolation techniques, including kriging, inverse distance to a power, minimum curvature, polynomial regression, and nearest neighbour methods. The geostatistical processing is performed using Surfer software, enabling the generation of spatial distribution maps and isoline representations for each parameter. Since different interpolation methods can produce significantly different spatial patterns from the same dataset, their comparative application provides a more comprehensive understanding of groundwater quality variability. The best interpolation model was then identified through cross-validation using the RMSE criterion. The methodology enables estimation of parameter values at unsampled locations and identification of zones with elevated concentrations, which may indicate point sources of pollution. The results of this research are expected to provide insights into spatial patterns of groundwater quality and support the identification of critical zones, thereby contributing to more effective groundwater protection and management.

Keywords: groundwater quality, geostatistics, spatial variability, interpolation, kriging

WATER QUALITY ANALYSIS IN THE ORLJAVA RIVER BASIN AREA

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Water is a non-renewable resource that is the foundation of life, as well as the origin and development of all living beings, therefore, it can be described as the liquid of life. It is also an integral part of every segment of human activity, and is considered an irreplaceable resource in households, agriculture and the economy. Globalization and technological progress are becoming important for social development, but their progress leads to increased consumption of clean water and the generation of growing quantities of wastewater contaminated with various organic and inorganic substances. Ensuring and adequate supply of drinking water today represents one of the greatest global challenges.

The availability of water in Croatia is considered highly sufficient, but its spatial and annual distribution can be assessed as unfavourable. Environmental changes caused by natural phenomena, as well as human activities, threaten water quality. The research area of this study is the Orljava river basin, from which four out of ten monitoring stations will be analysed, selected based on the availability of the longest data series (2001 to 2024). Based on the collected data for observed stations, water quality assessments are also carried out with a focus on nutrients – nitrates, total nitrogen and total phosphorus – in accordance with the Regulation on Water quality standards.

The homogeneity of the data series is examined using the RAPS method. Based on the obtained results, sub-periods and characteristics are analysed. At the same time, conclusions are drawn, along with plans for the future that include measures for improving water quality.

Keywords: the river Orljava basin, water quality, RAPS method

METHODOLOGY FOR WHOLESALE WATER PRICING BETWEEN PUBLIC WATER UTILITIES IN CROATIA: LEGAL FRAMEWORK AND COST ALLOCATION

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The increasing interconnection of public water supply systems in the Republic of Croatia has resulted in a growing number of contractual relationships in which one public water utility supplies drinking water to another. While retail water tariffs are strictly regulated, the methodology for determining wholesale water prices between utilities has historically been insufficiently defined. This regulatory ambiguity has led to prolonged court proceedings and inconsistent expert assessments, particularly regarding cost allocation, accounting for water losses, depreciation of infrastructure, and inclusion of indirect expenses.

In several judicial disputes, the parties engaged private legal entities to prepare cost assessments for wholesale water pricing. However, these analyses frequently relied on approximations and scientifically insufficiently substantiated quantifications, lacking a clear causal relationship between specific cost components and the actual supply route to the receiving utility. Such methodological inconsistencies contributed to further legal uncertainty and conflicting interpretations of admissible cost elements. This paper develops a structured methodological framework for determining wholesale water prices based on the analysis of three court expert assessments conducted between 2013 and 2019 in disputes between supplying and purchasing utilities. An analytical-comparative approach was applied to examine cost structures, allocation keys, and the impact of the legislative transition from the former Water Act to the Water Services Act.

The results indicate that the decisive methodological principle is the precise definition of the “supply route” as the physical and functional boundary for cost allocation. Only costs directly attributable to water abstraction, treatment, and transmission through the main pipeline to the point of delivery may be included in the wholesale price. Losses occurring within the supplier’s secondary distribution network cannot be allocated to the receiving utility. Special attention is given to water conditioning processes, which vary across Croatia depending on hydrogeological characteristics of aquifers and raw water quality. Depreciation of historically financed infrastructure requires careful treatment to prevent fictitious cost inflation, particularly where assets were constructed through public contributions and are already fully amortized.

The objective of the paper is to standardize the methodology for determining wholesale water prices and to clearly define admissible cost components in inter-utility transactions. The proposed framework enhances transparency, scientific rigor, and legal certainty, while preventing cross-subsidization between service areas and ensuring cost-reflective pricing principles.

Keywords: wholesale water price, water utilities, water losses, Water Services Act (Croatia)

CALIBRATION OF ANALYTICAL MODELS FOR WAVE PREDICTION

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This paper analyzes the possibility of applying empirical formulas for wave estimation in the area of the Rijeka Bay, with a focus on verifying the reliability of using the revised SPM (1984) model, which provides significant wave heights and wave periods. The research was carried out on the basis of data obtained from measurements by the DATAWELL Waverider DWR MKIII wave buoy, located near the Port of Rijeka, and ERA5 reanalysis records for the period 2009–2011. After quality control and synchronization of the data, the input parameters were defined for use in the revised SPM (1984) model. Input variable comprise of wind speed, storm duration, fetch lengths, and the values of the correction factors R_L and R_T. The obtained results showed that the basic model systematically underestimates the measured values, with the largest deviations observed in cases of higher waves and shorter fetch. The best agreement between the measured and calculated values was obtained by applying the factor R_T = 1,1, while further improvement of the results can be achieved by a simple calibration correction. The conducted analysis showed that the revised SPM (1984) model, with certain corrections, provides satisfactory estimates of wave characteristics in the investigated area. However, due to its simplified approach and certain limitations, the application of such a model is recommended for basic analyses and simpler tasks.

Keywords: wave prediction; significant wave lenght; calibration; SPM (1984); fetch

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CROSS-SCALE ANALYSIS OF PRECIPITATION DATA FROM HIGH AND LOW TEMPORAL RESOLUTION DATASETS

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Hyetographs form the basis for runoff analysis, flood protection, and generally the design of infrastructure exposed to extreme precipitation. Traditionally, they are derived from historical meteorological data by applying statistical methods to maximum annual precipitation or peak-over-threshold precipitation for defined durations (e.g. 5, 10, 15, …, 60, 120, …, 1440 minutes). Primary analysis, extraction of intensities from rain gauge records, provides foundation for secondary analysis and the construction of intensity-duration-frequency (IDF) curves, which are essential starting points for hyetograph creation and engineering design. This approach assumes that the statistical properties of precipitation remain stationary over time.

The assumption of stationarity is highly questionable, as the climate is defined as the 30-year average state of the atmosphere, and climate change can significantly affect hyetographs. Rising global air temperatures increase the atmosphere's capacity to retain water vapor, leading to more intense and frequent extreme precipitation events. In addition, local climate characteristics and spatial variability influence the distribution and intensity of precipitation. Consequently, detailed analysis of historical, current, and future meteorological and climatological data is required to assess the influence of changing climate conditions on precipitation relevant for IDF curves and hyetograph construction, and thus on hydrological and engineering design.

Available data include daily precipitation (1970-2024) and 5-minute precipitation (2016-2024) from the main meteorological station Osijek-Čepin (Croatia), spatial ERA5 reanalyzed hourly data from meteorological prognostic models (1940-2025), and daily spatial climate scenario data covering the area of interest (2015-2100) from three different scenarios and three different models. These datasets differ in both spatial resolution (local - station; global - reanalysis and climate models) and temporal resolution (from 5 minutes to 1 hour and 1 day).

The analysis focuses on differences among summary statistics (monthly precipitation), differences among precipitation episodes and obtained intensities, relationships between high and low temporal and spatial resolution datasets, and analysis of consistency of existing IDF curves and data on disposition. Thus, the objective is to explore temporal variability and cross-scale relationships between precipitation extremes, and to discuss their potential implications for the interpretation and application of IDF curves under changing climate conditions.

Keywords: precipitation analysis, intensity, temporal resolution, IDF curves

QUANTIFYING WIND CONTRIBUTION TO WATER EXCHANGE IN MARINAS USING AN IMPROVED ANALYTICAL FORMULATION

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Efficient water exchange in marinas is essential for maintaining acceptable water quality, particularly in semi-enclosed basins within microtidal environments. In these conditions, wind is an important but often insufficiently quantified driver of water renewal. Although its influence is often considered secondary over longer time scales, wind can play a dominant role in short-term exchange processes. This study aims to quantify the contribution of wind to water exchange in marinas, with particular emphasis on its impact over short time scales, by combining tracer-based analysis with an improved analytical formulation of exchange time.

Water exchange is assessed using the e-folding time, defined as the period required for the spatially averaged tracer concentration within the marina basin to decrease to 1/e (≈37%) of its initial value. This metric allows consistent comparison of exchange efficiency across different forcing conditions and temporal scales. The proposed methodology extends the classical tidal prism approach by incorporating wind-driven processes as an additional mechanism influencing water exchange in marinas. The baseline analytical model was first validated against numerical simulations under tidal forcing alone, showing strong agreement and confirming its reliability. The improved formulation introduces a wind-induced exchange term, parameterized through a calibration coefficient that accounts for wind speed, direction, and marina geometry, including the size and positioning of openings. To ensure general applicability, density variations were neglected, and the return flow factor was assumed negligible, based on numerical evidence of reduced recirculation under wind forcing. The model further considers only characteristic wind directions that effectively enhance exchange by aligning with the marina geometry and entrance orientation. This approach enables a simplified yet physically consistent quantification of both tidal and wind-driven contributions to water exchange.

The analytical results were compared with three-dimensional hydrodynamic simulations performed using the MIKE 3 FM model, which resolves flow circulation and tracer transport in complex marina geometries. The analysis was carried out on a hypothetical marina configuration to systematically isolate the influence of wind under controlled conditions. Agreement between the analytical and numerical approaches was evaluated using statistical performance indicators, including RMSE and the coefficient of determination (R^2). The results show that wind can significantly reduce e-folding time during short-term events, particularly under moderate to strong winds aligned with marina openings or culvert systems. The analytical model shows good agreement with numerical simulations, confirming its capability to capture wind-driven exchange processes and its applicability as a simplified tool for assessing water renewal under varying wind conditions.

The proposed methodology provides a practical framework for quantifying wind contribution to water exchange and supports the design and optimization of marina layouts. The findings contribute to a better understanding of water renewal dynamics and offer guidance for improving environmental performance in marina design.

Keywords: wind, water exchange, e-folding time, improved analytical formulation

COMPREHENSIVE EVALUATION OF DIFFERENT FLOOD MITIGATION STRATEGIES COMBINING HYDROLOGICAL EFFECTIVNESS, SOCIAL PERSPECTIVE AND ECONOMIC ASSESSMENT

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Climate-driven increases in flood frequency and magnitude are intensifying the demand for comprehensive flood mitigation strategies that are both effective and socially acceptable while offering additional co-benefits such as ecosystem services. Flood mitigation measures include grey infrastructure, nature-based solutions (NbS), and hybrid approaches. Although NbS measures are promoted by European and global policy agendas, their uptake is often slowed by uncertainties and barriers related to performance, feasibility, public acceptance, and funding. Our recent research illustrates these challenges across several dimensions. In the scope of the research project "Evaluation of hazard-mitigating hybrid infrastructure under climate change scenarios" we conducted public perception survey, hydrological evaluation and economic assessment of several flood risk mitigation measures.

Public perception study was conducted in Slovenia, Czechia, and the Netherlands and showed significant differences in how green (NbS), grey, and hybrid measures are viewed in terms of effectiveness, feasibility, and acceptability by the general public and three expert groups. Grey measures such as dams are generally perceived as more effective and acceptable, though more difficult to implement, with views varying by country, age, and income. Target-group analysis in Slovenia further indicates that researchers tend to rate NbS measures more positively than engineers or agricultural advisors.

Hydrological modelling that was performed in the Gradaščica catchment demonstrated that wetlands provide only modest peak-flow reductions, whereas retention polders and dams achieve substantially larger effects. Economic assessments mirror these findings, with classical engineering flood protection measures outperforming green measures in cost-effectiveness. However, wetlands can provide a large number of co-benefits. At the same time, other NbS measures such as urban greenery can potentially reduce runoff at smaller spatial scales during low and medium-intensity rainfall, though their performance declines with event magnitude and spatial scale.

A complementary review of European and global funding calls and projects showed that the growing prominence of NbS in policy discourse increasingly shapes funding opportunities. While this framing can facilitate access to resources and stimulate research, overly broad use of the NbS label may obscure effectiveness assessments and sideline other viable flood mitigation options.

Overall, despite strong policy support, NbS continue to face divergent public and stakeholder perceptions, variable hydrological performance, and mixed economic viability across spatial scales. At the same time, the expanding use of the NbS label within the research community that is often driven by funding structures may limit the clarity needed for transparent and effective implementation of different flood protection measures.

Keywords: flood mitigation, nature-based solutions, grey infrastructure, hybrid measures, interdisciplinary evaluation

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