



Conference Report

Abstracts of the 9th International Electronic Conference on Water Science [†]

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Abstract

Building on the success of its predecessors, the 9th International Electronic Conference on Water Sciences (ECWS-9) has been hosted entirely online. The conference aims to explore pivotal advancements in water sciences amidst environmental change. Researchers and practitioners are invited to contribute across a spectrum of critical topics, from hydrological processes, water resources management, and ecohydrology to urban water systems, agricultural water use, wastewater reuse, and the application of remote sensing and artificial intelligence. Special attention will be given to extreme hydro-meteorological events, water policy, and the impacts of climate change.

Keywords: water quality; ecohydrology; hydrology; water resources management and policy; floods; droughts; water and wastewater treatment

1. Hydrological Processes and Modelling

1.1. Recession Flow Dynamics in Karst Basins: Comparing Basin-Specific and Universal Approaches Under Anthropogenic Influences

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In an era of increasing water scarcity, understanding the recession flow dynamics of karst aquifers is critical for conserving the water supplies on which millions rely. We use the coefficient k from the power-law connection between discharge and time (with fixed exponent α) to generate effective solutions for real-world water difficulties. This study provides a comprehensive evaluation of recession flow dynamics across Croatian karst basins, utilizing an innovative dual-method framework that combines: (1) basin-specific parameter derivation using the Brutsaert-Nieber constant time step method, and (2) systematic assessment of universal recession constants' predictive performance under anthropogenic influences. Our findings show three key facts that have significant significance for karst water management. First, the Brutsaert-Nieber technique excels at capturing the distinctive dual-drainage behavior of karst systems, accurately reflecting both rapid conduit flow and slower matrix drainage processes. Second, a comparative study reveals that universal parameters are useful and valid for theoretical benchmarking but have major limitations in



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anthropogenically modified basins, where water withdrawals and land-use changes disrupt natural recession patterns. Third, the analysis identifies different indications of human effect on recession curves, with managed systems consistently deviating from theoretical assumptions at multiple temporal scales. Overall, these findings are particularly important for karst systems under increasing anthropogenic stress, and the scientific methodology has transferable relevance for similar ecosystems worldwide.

1.2. Modelling Climate Change Impacts on Hydrological Processes and Water Balance in the Cervaro River Basin (Italy) Using SWAT+

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Mediterranean agroecosystems are increasingly exposed to climate variability and prolonged droughts, threatening water availability and the long-term sustainability of agricultural production. Understanding how climate change may reshape the hydrological dynamics of river catchments is therefore essential to support the development of long-term adaptation strategies.

This study investigates the Cervaro river basin, a key grain-producing area in southern Italy, with the aim of quantifying the impacts of climate change on catchment-scale hydrological processes and water balance components. The Soil and Water Assessment Tool (SWAT+) model will be applied to simulate the main hydrological fluxes across the basin.

Model calibration and validation will be performed using observed river discharge data and satellite-derived actual evapotranspiration estimates in order to accurately represent the current hydrological conditions of the basin, which will serve as the reference baseline.

Future projections will be assessed through a comparative analysis between the baseline and two future climate scenarios. The first scenario, based on RCP4.5 projections, represents an intermediate mitigation pathway assuming stabilization of greenhouse gas emissions. The second scenario, based on RCP8.5 projections, represents a high-emission trajectory assuming continued growth in emissions and a marked increase in temperatures and extreme events.

High-resolution climate model data will be used to drive hydrological simulations under both scenarios, enabling a systematic evaluation of potential changes in precipitation, evapotranspiration, runoff, and other water balance components. The results will provide a quantitative basis for understanding climate-driven shifts in water availability in Mediterranean agricultural systems and inform the development of future strategies for sustainable water resource management.

1.3. A National-Scale IDF-Based Design Storm Hyetograph Inventory: Applying the Catchment2Storm Tool in Greece

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We present an automated Python-based tool called Catchment2Storm that generates design storm hyetographs directly from watershed shapefiles, using the official Greek gridded IDF parameters (“ombrian parameters”) provided by the Ministry of Environment. We apply it to an indicative watershed, and at the national scale (~11,000 sub-catchments), providing an inventory of design storms.

The tool overlays a user-defined catchment shapefile onto the national IDF grid, which is publicly available from the Greek Ministry of Environment. Then, the IDF grid cells that intersect the user's catchment are identified. For each intersected polygon (sub-catchment), the script calculates its area and relative contribution to the total catchment, extracting the corresponding IDF parameters. Intensity and Precipitation depth are computed for each sub-area over a user-selected storm duration, return period, and time interval. The storm is reduced spatially using the Area-Reduction-Coefficient Φ , and is temporally rearranged using the Alternating Block Method (ABM), resulting in a ready-to-use hyetograph.

The output includes a hyetograph plot, Excel summaries, and rainfall input tables formatted for direct use for HEC-HMS and HEC-RAS. We showcase how this tool can be also used for multiple catchments: We have applied it to all Greek sub-catchments ($N = 10,773$), using a batch-run approach in Python, which also summarizes key metrics for different hyetographs.

The developed Catchment2Storm tool has been developed in Python, and we are considering its commercial use. All materials are stored in a private Github repository (<https://github.com/Alamanos11/Catchment2Storm>), including step-by-step guidance on running the tool, single-or-multiple catchments, summarizing key results' metrics, and mapping them, even in the case of missing values.

Catchment2Storm streamlines the process of generating design storms by automating geospatial analysis and storm synthesis directly from national IDF data, at any catchment or scale, providing accurate, model-ready hyetographs in seconds.

1.4. Accuracy Assessment of ERA5-LAND, TPMFD, and CDMet Meteorological Datasets in the Yarlung Zangbo River Basin

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The Yarlung Zangbo River Basin, located in the southeastern Qinghai–Tibet Plateau, is an important transboundary river system in China. The basin features dramatic topographic relief, forming a unique vertical climate spectrum. To evaluate the accuracy of temperature, air pressure, wind speed, and relative humidity from three reanalysis datasets (ERA5-LAND, TPMFD, and CDMet), the ground observations at three sites in that basin (including Nam Co, Mount Qomolangma, and Southeast Tibet Alpine site) are selected as the references. Results show that each dataset has distinct advantages. TPMFD demonstrates the highest consistency for temperature at both daily and monthly scales, with R^2 values generally above 0.9 and relatively low RMSE, respectively. CDMet performs best in representing relative humidity, with R^2 of 0.53 and RMSE of 10.8%, respectively. CDMet performs relatively better in representing wind speed compared to the other two products; however, due to the strong influence of complex terrain, it still exhibits substantial errors and uncertainties. The coefficients of determination (R^2) at the three sites are 0.1825, 0.1043, and 0.0514, indicating poor agreement with observations. ERA5-LAND shows the best performance in atmospheric pressure, with R^2 values of 0.9148, 0.8339, and 0.9429 at the three sites, demonstrating high consistency and reliability. These findings provide an important reference for selecting appropriate meteorological reanalysis datasets in hydrological and ecological studies across the Tibetan Plateau and other high-altitude regions.

1.5. Climate Variability and Land-Use Dynamics: Implications for Groundwater Recharge in the Motril–Salobreña Coastal Aquifer (MSCA), Spain

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Climate and land-use change significantly impact the hydrological cycle and water resources. Accordingly, assessing groundwater recharge under varying climatic conditions and land use/land cover (LULC) is crucial for effective integrated water resource management and the development of robust adaptation strategies. Such evaluations are indispensable for the sustainable management of water systems, supporting the long-term resilience of both human and ecological water demands. Therefore, this research work emphasizes the influence of climate change and land-use dynamics on groundwater recharge of the Motril Salobreña coastal aquifer over the period 1980–2020, using a hydrological model, the WetSpass model. Four scenarios were used in the present study. Scenarios 1 and 2 examine the influence of climate variability, while Scenarios 3 and 4 analyze the impact of land-use/land-cover (LULC) change on the groundwater recharge.

The climate results of the study area indicated a decrease in precipitation of approximately 2% and an increase in temperature of 2%, and evapotranspiration of 4% from 1980–2000 period to 2001–2020 period. Land-use/cover results showed that the agriculture and orchard were the dominant land-use types in 2000 and 2020. Agriculture land decreased 15% from 2000 to 2020. Conversely, the building zone and orchard land increased 10% and 3%, respectively. Because of all these environmental changes, the amount of the groundwater recharge varied in the study area, where the annual average groundwater recharge was approximately 212, 197, 206 and 174 mm in scenarios 1, 2, 3 and 4, respectively.

In conclusion, the findings of this study indicate that annual groundwater recharge in the study area during the 1980–2020 period decreased by approximately 7% due to climate variability and by around 16% as a result of land use/land cover (LULC) change. In addition, the study results shown that recharge from irrigation is much more important than that from precipitation, leading to an error of approximately 67% if it is overlooked. This comprehensive analysis is vital for sustainable water resource management in the study area.

1.6. Croatian Karst River Flows: Insights from Hurst Exponent Analysis

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This study investigates long-term persistence in the daily water levels of the Čabranka and Kupa rivers in Croatia using Hurst exponent analysis. Daily water level data, spanning several decades for each river, were analyzed to determine the Hurst exponent (H) and assess the presence of long-range dependence. The analysis employed Hurst–Kolmogorov (HK) dynamics and climacogram analysis, established methods for identifying long-range dependence in time series data. Climacograms were constructed to visually assess the scaling behavior of the variance, and linear regression was applied to estimate the Hurst exponent (H) within a range of time scales (10–100 days) to ensure statistical robustness.

Results reveal significant long-term persistence in both river systems, with Hurst exponents (H) consistently exceeding 0.5, a threshold indicating the presence of long-range dependence. High coefficients of determination (R^2) support the reliability of the linear fits. Potential contributing factors to this observed persistence, including climatic influences (e.g., rainfall patterns, snowmelt), geological characteristics of the river basins, and the impact of human activities (e.g., dam operations, water withdrawals), are discussed.

The implications of these findings are substantial for water resource management in the region. The presence of long-term persistence necessitates the incorporation of this characteristic into hydrological models to improve forecasting accuracy and inform sustainable water management strategies. Further research will focus on investigating the relative contributions of various factors to the observed persistence and developing improved hydrological models that explicitly account for long-range dependence. This enhanced understanding will allow for more robust and reliable water resource management strategies in the face of increasing climate variability and human pressures on these vital water resources.

1.7. Developing a Coupled Surface–Subsurface Flow Model for High-Mountain Watersheds Using the Finite Element Method: Preliminary Results

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Mountain and high-mountain watersheds are headwaters of major rivers worldwide. Although they have smaller sizes, these catchments offer significant hydropower potential, transform considerable amounts of snow into runoff, provide water for specific mountain ecosystems, and could also be viewed as climate change indicators. Hence, continuous research on this topic is important either in the form of field investigations or computational modelling of natural processes.

In this study, a coupled distributed surface–subsurface flow model of the watershed runoff formation was implemented. For the surface flow, the zero-inertia/diffusive-wave hydrodynamic model was used. For the subsurface flow, the Boussinesq model for saturated flow in porous media was used. Using these models, a two-dimensional transient differential problem was set, consisting of a system of two nonlinear advection partial differential equations. The functions of the solutions for both models are the flow thicknesses (also called flow heights). To improve the numerical stability of the solutions and to use convenient time steps, an implicit scheme was used for the time domain. For the irregular geometries of the real-world watersheds, the Galerkin finite element method was employed. Because of the nonlinear and advective nature of the system, stabilization terms were added to the numerical scheme. These were a streamline–upwind Petrov–Galerkin (SUPG) term and spurious-oscillations-at-layers diminishing (SOLD) term.

Numerical experiments, each one with a simulation time of one hydrological year, were conducted for an example of a high-mountain watershed. The input meteorological data was obtained from stations and was spatially and temporally distributed. The computed river discharge values were compared with the measured ones, and the results were acceptable, although with defects.

Physically based distributed hydrological models are useful, e.g., in the determination of effective areal values of some physical variables, estimation of results of different what-if scenarios, runoff forecasting, etc. Further studies can improve the numerical approaches used in this field.

1.8. Forecasting Climate-Driven River Flow Extremes and Variability in the Deduru Oya Basin, Sri Lanka

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The Deduru Oya Basin (DOB) is the sixth-largest river basin in Sri Lanka, and it faces significant flooding during the monsoon season and prolonged droughts during dry periods, making accurate forecasting of future river flow essential for effective water resource management and hydraulic structure design. To assess future river flow in the DOB, a rainfall–runoff model was developed, integrating HEC-HMS for basin routing and HEC-ResSim for reservoir simulation, calibrated against observed data. The integrated model was simulated using bias-corrected future rainfall data derived from the CNRM-CM6-1 Global Climate Model, across two carbon emission scenarios (SSP2-4.5 and SSP5-8.5) and three timeframes: Near Future (2025–2040), Middle Future (2041–2070), and Far Future (2071–2100). The implications of climate change on river flow were assessed through box plot comparisons, General Extreme Value analysis for flood events, and Flow Duration Curve (FDC) analysis within the three timeframes and two SSPs. Projections suggest that the DOB may experience modest increases in flow, ranging from 4% to 12% for the two SSPs. However, our analysis indicates that historical 50-year flood events could occur every 25 years under an extreme climate scenario. Furthermore, the FDC analysis reveals a significant decline in base flow under both scenarios, which is likely to be exacerbated during drought conditions. This decline could have detrimental effects on agricultural sustainability and groundwater recharge. These findings underscore the urgent need to improve flood and drought preparedness in the future.

1.9. How Can Modelling Assist Decision-Making in Flood Management and the Implementation of Prevention Measures? The Case Study of Hauts-De-France

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Faced with increasingly severe climate change, some areas are having to cope with more extreme natural events. This was particularly true of the floods that hit the Hauts-de-France region (France), and more specifically the Pas-de-Calais department, in 2023.

Our study is part of an approach to prevent erosion and flooding in this region, with the aim of assessing the impact of sedimentation on bank erosion, but also to see how the implementation of new developments such as controlled flood zones could limit water stagnation. After analysing the characteristics of the areas concerned, peak flood flows for return periods of 10, 20, 50 and 100 years were estimated using hydrological and hydraulic modelling tools. Thanks to these simulations, we can identify areas prone to flooding on several sections of each catchment area.

The methodological approach includes statistical analysis of rainfall data using Hyfran-Plus software, extraction of geometric data from the hydrological network via ArcGIS, hydrological modelling to simulate rainfall-runoff transformation using HEC-HMS, and hydraulic studies to delineate and map eroded areas using 2D modelling with HEC-RAS, integrating the geometric and hydraulic data needed to simulate current conditions in the event of flooding.

The results of this hydrological modelling made it possible to estimate the peak flows specific to each area studied, providing key information for the design of structures to

protect against natural hazards. The hydraulic modelling highlights several sensitive areas along watercourses with a high risk of overflow and erosion.

These results not only identify areas at risk, but also guide preventive measures, such as reinforcing riverbanks, installing retention basins and updating hazard maps for local authorities.

1.10. Hydrodynamic Modeling of Circulation Patterns in Amazonian Rivers and Estuaries Around Belém, Brazil

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Hydrodynamic models are essential for understanding water bodies' circulation, and they complement studies regarding pollutant transport, especially concerning estuarine and river systems, e.g., the ones surrounding the city of Belém in northern Brazil. Hydrodynamic simulations were developed, using Guamá river (GR), Guajará bay (GB), and Pará river estuary (PRE), to assess circulation patterns under high (HD) and low river discharge (LD) and along tidal cycles. The simulations were run in Delft3D-FM, using an unstructured grid with resolutions from 1,000,000 to 40 m². Bathymetry was interpolated from observed data, while Manning's roughness ranged from 0.020 to 0.039. Tidal boundaries were provided by the TPXO 7.2 Inverse Tidel Model—PRE mouth—and in situ observations—Breves Strait—while discharge boundaries were applied to the Guamá, Acará, Tocantins and Moju rivers, supplied with values estimated from historical records of the Brazilian National Waters Agency. Model validation, based on Pearson's coefficient, NSE, and pRMSE, indicated efficient performance. Under HD, PRE showed higher velocities on the lower estuary during flood tides and on the higher estuary during the ebb, with persistent upstream flux driven by the Tocantins river discharge. In GB and GR, velocities ranged between 0.5 and 1.0 m/s during flood tide, with a low-dynamics zone in GR, near Belém, due to opposing flows from GB and GR, which disappeared throughout the ebb. Under LD, PRE's patterns remained similar, though velocities slightly increased on the higher estuary during flood and on the lower estuary during ebb. In GB, velocities peaked during flood along the left margin due to a deep channel, while low-dynamic zones disappeared. Overall, PRE exhibited stable circulation whilst GR and GB differed between season and tidal cycles. These findings can highlight critical zones for pollutant retention and dispersion, providing a basis for water quality assessments in the region.

1.11. Impacts of Hydrological Dimensionality Reduction in Stochastic Energy Modeling of Interconnected Power Systems

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In modeling interconnected electric power systems, the role of input parameters is crucial. For example, when considering the flow series that define the hydrological state of hydroelectric plants, these inputs can directly influence operational economic value and cause variations in generator dispatch to satisfy demand. This study focuses on evaluating the reduction in the dimensionality of the stochastic state space using a CEGH (Correlations in Gaussian Space with Histogram) synthesizer to generate hydrological data. Using advanced electrical modeling techniques, the medium-term modeling of a real inter-

connected system is analyzed. This system includes wind, solar, and thermal generators, along with four hydroelectric plants and CEGH inputs. Regarding the serial synthesizer, the variation fields are assessed by reducing the state from six to three. Variations in the states are considered with initial ranges such as low (5–10%), medium (30–45%), and high (60–85%), enabling the identification of trend changes and the development of a robust variation matrix. This research develops indicators to assign weights to the simulated cases using the open-source, freely available SimSEE platform. These indicators facilitate the identification of economic impacts resulting from the operating policies derived from the case matrix, with resulting sample variations in MUSD ranging from 4% to 15% in operating costs. Additionally, statistical analysis shows differences in computational costs: cases without reduction require approximately 122 h of modeling, whereas applying the serial analysis synthesizer reduces this to 2–6 h, demonstrating significant time savings. Furthermore, the study proposes indicators to assess the flexibility of generators under these hydrological variations.

1.12. Integrated Assessment of Water-Induced Soil Erosion Risk Using Topographic Wetness and Stream Power Indices in the Idemili Drainage Area, Southeastern Nigeria

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Introduction: Soil erosion is a major land degradation problem in southeastern Nigeria. The Idemili drainage area is one of the most degraded landscapes in the country. This study evaluated the spatial variability of water-induced soil erosion risk in the Idemili watershed. The aim was to identify erosion hotspots, understand the role of key drivers, and provide insights for targeted and sustainable land management practices.

Methods: A GIS-based terrain modelling approach was employed, based on a 10 m resolution Copernicus DEM. Three hydrologically informed indices were computed: Slope, Stream Power Index (SPI) and Topographic Wetness Index (TWI). Spatial analysis in ArcGIS Pro 3.4 involved terrain preprocessing, index computation, reclassification to standardised classes and weighted overlay fusion into a single erosion risk map (Very Low to Very High). Model validation was based on field-surveyed gully erosion points, collected in the field using GPS.

Results: The spatial variability of erosion risk was high, with more than 47% of the watershed being characterised by moderately steep to steep slopes, with a high correspondence to observed gully occurrence. The erosion risk map categorised 34.2% of the watershed into High- and Very High-risk regions, forming a distinct belt in the central/southeastern part of the study area. Validation showed that the model performs well, with about 58.3% of observed gullies being located within the High- and Very High-risk regions and a further 20.8% in the Moderate-risk category, with only 20.9% in the Low-/Very Low-risk category.

Conclusions: The integration of SPI, TWI and slope presented a reliable geospatial approach to assess soil erosion risk in the data-scarce tropical environment under study, with the results demonstrating a strong spatial relationship between high-risk areas, steep slopes, hydrological convergence and gully erosion occurrence. The method provided a valuable tool to prioritise erosion control interventions, specifically in the upland and valley convergence areas of Idemili.

1.13. Integration of Geological and Hydrological Parameters Through a Bayesian Framework to Estimate Flood Likelihood: A Case Study of the Ottawa River Basin, Canada

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Flood risk quantification in large-scale watersheds poses a persistent challenge due to the nonlinear interactions among geological, hydrometeorological, and anthropogenic variables. Conventional deterministic models often lack the flexibility to incorporate uncertainty and interdependencies inherent in such systems. This study introduces a Bayesian probabilistic modeling framework to evaluate flood occurrence probability by systematically integrating multi-source data and expert knowledge. A Bayesian network (BN) was constructed to capture the conditional dependencies among key flood-driving variables, including antecedent soil permeability, rainfall intensity–duration–frequency (IDF), land use/land cover, and slope and drainage density. The structure of the BN was informed by an understanding of hydrological processes and refined using a combination of mutual information and structure learning algorithms. The model was applied to the Ottawa River watershed in Eastern Canada, a region frequently impacted by spring floods due to snowmelt and rainfall interactions. Historical flood events, streamflow records, and spatially distributed physiographic data were used to calibrate and validate the model. Sensitivity analysis demonstrated that antecedent permeability and extreme precipitation indices exhibited the highest influence on flood occurrence. The probabilistic output of the BN allowed scenario-based flood likelihood assessments, highlighting critical thresholds in contributing variables. Compared to conventional empirical models, the proposed Bayesian approach reduced dimensionality, explicitly quantified uncertainty, and provided probabilistic predictions aligned with observed patterns. The framework is particularly well-suited to data-sparse regions and supports risk-informed floodplain management under a changing climate.

1.14. Multicriteria Analysis Supported by Geographic Information Systems and Hydraulic Modelling for Flood Protection in Riparian Regions

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Flood hazard and risk management in riverine environments requires the integration of advanced simulation tools with decision-making methods to support the selection of effective and sustainable protection measures. This study investigates and proposes a sequential framework that combines modern tools for flood hazard simulation, such as Geographic Information Systems (GISs) and hydraulic models, with multicriteria decision-making methods for evaluating flood protection structures in flood-prone areas. GISs are employed to extract critical information from digital elevation models (e.g., river cross sections), which serve as inputs to 1D hydraulic models. The resulting flood simulations, generated for different return periods, are subsequently used to score five evaluation criteria: implementation cost, societal impacts, environmental impact, technical feasibility, and implementation schedule. These criteria are then analyzed using the Analytic Hierarchy Process (AHP) for each return period. Thereafter, the framework provides a ranking of four flood protection alternatives identified as the most suitable for the case study area: (a) reinforcement of existing embankments, (b) widening of the riverbed, (c) underground conduits, and (d) construction of a bypass channel. The findings identify

the optimal measure under the current criterion weights, while also demonstrating that, under extreme environmental scenarios, the ranking of alternatives may vary. Overall, the proposed methodology offers a transferable approach that can be applied to any inhabited riverine environment.

1.15. Numerical Modeling and Hydrodynamic Characterization of an Eastern Amazon Estuary Under Macrotidal Forcing

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Delft3D-FM model was implemented to analyze the hydrodynamics of the Mojuim and Mocajuba estuaries, the Pará River mouth, and part of the Atlantic Ocean. The model domain extended ~150 km along the coast and up to 140 km inland, incorporating wind, tides, river discharges, and bathymetry. Data from the Costa Norte Project (2017) and the Amazon Coastal Observatory (OCA) supported the simulations, which were validated against in situ tide and discharge measurements. Calibration, carried out at four tidal stations and two discharge points, showed excellent performance. Tidal adjustment presented RMSE 10%, strong positive correlation ($r > 0.9$), and satisfactory efficiency ($NSE > 0.85$), ensuring over 90% model confidence. For river discharge, although RMSE exceeded 15%, Pearson (>0.9) and NSE (>0.60) indices confirmed consistent behavior between observed and simulated data. The results revealed macrotidal influence up to 50 km inside the estuaries, with amplitudes ranging from 6 m at the mouth to 4.5 m upstream. The system showed positive asymmetry, with flood lasting ~5 h and ebb ~7 h. Pará River transport exhibited bidirectional flow on the Amazon Continental Shelf, ranging from $-400,000 \text{ m}^3 \cdot \text{s}^{-1}$ (flood) to $600,000 \text{ m}^3 \cdot \text{s}^{-1}$ (ebb), with the river plume propagating eastward along the Eastern Amazon coast, corroborating previous observations. In the Mojuim and Mocajuba estuaries, positive discharge ($\sim 63 \text{ m}^3 \cdot \text{s}^{-1}$) predominated, consistent with historical records and indicating stable outflow during ebb. These results highlight the strong interaction between tides and river discharge in the Amazon estuary, emphasizing asymmetry processes, bidirectional flow, and eastward propagation of the river plume along the eastern coast. The study advances the understanding of Amazon coastal dynamics and reinforces numerical modeling as a strategic tool for environmental monitoring and management of riverine and estuarine systems.

1.16. Physicochemical Modeling of the Redistribution of Uranium Chemical Forms in the Natural–Technogenic System of a Nuclear Fuel Cycle Enterprise’s Tailings Storage Facility

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The object of this study is the tailings storage facility (TSF) for low-level radioactive waste at the Novosibirsk Chemical Concentrates Plant (NCCP) and the adjacent territory. Liquid low-level waste is discharged via a pipeline into the TSF impoundment. The impoundment is confined by a filtration-type embankment dam constructed from local soils containing uranium ore sludge. Water infiltrates through the walls and base of the impoundment, becoming enriched with radionuclides, and subsequently enters groundwater and surface watercourses.

Investigation of the speciation of radioactive elements is essential for improving the radioecological situation through the development of measures to reduce their migration intensity.

Water samples were collected during the summer season from 6 surface water points and 3 groundwater points from wells at a depth of 7–9 m. The concentrations of cations were determined using ICP AES and ICP MS. Hydrogeochemical modeling was performed using the “HCh” software package. All studies were carried out at the Analytical Center for multi-elemental and isotope research of the Siberian Branch of the Russian Academy of Sciences in 2023–2024.

Physicochemical modeling revealed the speciation of uranium: under oxidizing conditions in surface waters, precipitation of calcium uranate and uranophane occurs, while in subsurface waters characterized by more reducing conditions, uranium oxide precipitates. Additionally, modeling results indicate that uranium is present in aqueous complexes as dicarbonatouranyl and tricarbonatouranyl species.

The calculation results demonstrated that the geochemical conditions of the environment (pH and Eh), along with the uranium concentration controlled by dilution processes, are the primary factors governing the redistribution of uranium in the system with increasing distance from the tailings storage facility. The obtained results contribute to understanding the current radioecological situation in the vicinity of the NCCP low-level radioactive waste tailings storage facility.

1.17. Short-Term River Discharge Forecasting Using an XGBoost-Based Regression Model

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Accurate discharge forecasting is important for effective river basin management, flood control, and water resource planning. In this study, an XGBoost-based multi-output regression approach is developed and evaluated to forecast river discharge up to six hours ahead using historical discharge data and engineered temporal features. The study outlet is located near Hurricane Mills, Tennessee (USGS monitoring site 03603000). Hourly discharge data from 2016 to 2024 were preprocessed by imputing missing values, resampling at regular intervals, and dividing into training (2016–2020) and validation (2020–2024) datasets. Feature engineering included lagged discharges, hourly differences, 24-h differences, and time features such as hour of day. The XGBoost model was trained in a multi-output stepwise manner, with each horizon being predicted by a separate regressor and assessed according to a set of statistical metrics. Results show that the model achieved excellent predictive performance, with mean absolute error (MAE) increasing gradually from 0.99 m³/s for predictions 1 h ahead to 4.79 m³/s for predictions 6 h ahead. The root mean square error (RMSE) was in the same range between 4.44 m³/s and 21.06 m³/s, while the mean absolute percentage error (MAPE) was below 3% for all lead times, reflecting the model strength in capturing both short- and medium-term discharge dynamics. Also, efficiency statistics of Kling–Gupta Efficiency (KGE > 0.99 for the first three steps), Nash–Sutcliffe Efficiency (NSE > 0.99 for 1 h ahead and 0.98–0.99 for subsequent steps), and R² values close to unity point towards very good correspondence between predicted and observed flows. Analysis of feature importance revealed that recent discharge lags and short-term discharge differences were the most predictive features, which reflected the importance of recent flow history in prediction. Overall, the proposed XGBoost-based framework provides outstanding accuracy for short-term discharge forecasting and provides an efficient data-driven approach to hydrological decision support systems in river basins.

1.18. Spatial and Temporal Changes of Major Elements in Surface Water in Arieș River Catchment, Western România

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The Arieș River is a middle-sized water stream, located in the NW of Romania, near to a mining area (in the middle basin) and an industrial facility (in the lower basin). Due to its geographic location and its significance in the Mureș–Tisza Basin, the Arieș River has a major impact on its emissary quality. Therefore, the dynamics of hydrochemical major parameters of surface waters sampled from a selected sector of Arieș River were analyzed. A total of 12 different water quality parameters (HCO_3^- , Cl^- , F^- , NO_2^- , NO_3^- , SO_4^{2-} , PO_4^{3-} , Ca, Mg, Na, K, Fe) from 10 surface water sampling points situated in different locations along the water stream, collected in 4 different seasons in 2020, were analyzed in a laboratory. The findings indicated that the water samples were more contaminated in the mining area, compared to the samples near the industrial facility. The highest Na (19.2 mg/L), Mg (13.7 mg/L), K (14.7 mg/L), and Ca (314 mg/L) concentrations were obtained near a copper mining facility. The Piper and Durov diagrams classified the waters into the Mg-HCO_3^- and Ca-Cl^- types. It was noticed that there is no clear temporal variability in the major water quality parameters, indicating that natural processes have no major impact on the water quality. Past and present mining and industrial activities have an impact on the water chemistry, altering the quality of the Arieș River. Thus, pollution prevention and curation treatments are required before water use.

1.19. Three-Dimensional Lake Modeling in the Volga Basin Reservoirs

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Numerical modeling of inland water bodies is an important tool for understanding their role in local ecosystems and the climate system. While one-dimensional lake models are widely used in geophysical applications due to their efficiency, they have limited ability to describe horizontal processes and basin-scale circulation. In cases of large reservoirs and lakes with complex morphometry, three-dimensional approaches can provide additional insights.

A three-dimensional thermohydrodynamics model with turbulence closure, ice dynamics, and biogeochemical modules for oxygen and methane was applied to several reservoirs in the Volga Basin, including the Rybinsk, Mozhaysk, and Gorky reservoirs. Simulations were forced with in situ data and ERA5-Land reanalysis and evaluated against field observations collected in different years.

The simulations reproduce observed seasonal thermal stratification, mixing, and ice cover, as well as spatial heterogeneity of temperature fields related to reservoir morphometry. Model results show generally good agreement with available profiles and freeze–thaw timing. The use of a three-dimensional framework makes it possible to investigate circulation patterns and horizontal heterogeneity, which may be important for understanding mixing processes and biogeochemical regimes in large inland waters.

These examples illustrate the usefulness of 3D modeling as a complementary approach to widely used 1D lake schemes in studies of hydrophysics and limnology.

2. Urban Water Modelling and Management

2.1. Analysis of Sustainable Solutions for Stormwater Management in Vulnerable Urban Areas: Case Study in Monteverde, Montería, Colombia

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Rapid urban expansion in Montería, Córdoba, Colombia, has led to significant challenges in stormwater management, especially in neighborhoods that lack adequate drainage infrastructure. This study evaluates the preliminary feasibility of implementing Sustainable Urban Drainage Systems in the Monteverde neighborhood, an area that is frequently affected by severe flooding during rainfall events. Using the Storm Water Management Model (SWMM), three intervention scenarios were simulated: (1) implementation of floodable tree pits, (2) installation of stormwater storage tanks, and (3) a combination of both. The simulations were based on a designed storm with a 10-year return period. The results showed that scenario 2 (storage tanks) achieved the most effective performance, with reductions in peak flow ranging from 10% to 34% at all discharge points in the system. In scenario 1 (floodable tree pits), the reduction was negligible, less than 1%, due to the limited infiltration capacity of local soils and the available green space. Scenario 3, which combined both types, showed cumulative improvements but did not significantly outperform scenario 2. In addition, the tanks demonstrated better hydraulic performance in critical sub-basins where high runoff volumes were observed. These findings indicate that while SUDSs can contribute to urban resilience, their efficiency depends heavily on site-specific conditions. The study provides technical evidence supporting the inclusion of storage tanks as a viable SUDS strategy in Montería's stormwater planning.

2.2. Economic and Environmental Benefits of Reusing Thermal Energy from Pool Water

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Public swimming pools play an essential role in promoting health and physical activity; however, they are also among the most resource- and energy-intensive municipal facilities. High consumption of water, electricity, and thermal energy results in elevated operational costs, creating a demand for sustainable and cost-effective technological solutions.

This study presents a novel heat recovery method that captures waste heat from swimming pool circulation pumps. Instead of releasing this heat into technical rooms, the system transfers it to the pool water to preheat the recirculation stream. This process both cools the pumps and recovers thermal energy, thus increasing energy efficiency, reducing heat emissions in technical areas, and lowering dependence on external energy

sources. A case study examined 34 pumps with a combined installed power of 700 kW, operating 10 h daily for 3520 h annually. The total electrical energy consumption was estimated at 2464 MWh per year. Depending on recovery efficiency, between 1725 MWh (70%) and 2341 MWh (95%) of thermal energy can be reused annually within the facility. Economic analysis showed that larger pumps achieved payback in under two years, with an average payback period of about three years across all units. The environmental assessment indicated a reduction in CO₂ emissions of 1240 to 1680 tonnes per year, according to the national grid emission factor.

The novelty of this research lies in the systematic integration of hydraulic and thermal energy management in swimming pool facilities, where pump-generated heat has not previously been exploited as a recoverable energy source. The findings demonstrate that significant operational savings and environmental benefits can be achieved with relatively low investment costs, providing a scalable framework for sustainable technical installations in public swimming pools and other water-intensive buildings.

2.3. Enhancing Urban Stormwater Management Through Green Infrastructure: A Case Study of Terre Haute

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This study investigates cost-effective, low-impact strategies for improving stormwater management in urban environments, using the City of Terre Haute, Indiana, as a case study. The primary novelty lies in its integrative, multidisciplinary approach combining stakeholder interviews, water quality sampling, and urban green space assessments to evaluate how existing public infrastructure, particularly parks, can be leveraged for stormwater control without major new construction.

Our methodology involved three interconnected components. First, we conducted interviews with municipal engineers and faculty at Rose-Hulman Institute of Technology (RHIT) to identify existing stormwater management challenges and limitations in staffing and maintenance capacity. These insights informed us of the selection of sampling locations and the focus of site inspections. Second, stormwater runoff samples were collected from both green (e.g., vegetated swales, permeable surfaces) and grey infrastructure (e.g., impervious roads and parking lots) on City of Terre Haute and RHIT's campus following a rain event. Comparative analysis of runoff quality showed lower pollutant levels from green infrastructure sites. Third, we performed field inspections at public parks and nature centers throughout Terre Haute, evaluating physical features such as drainage pathways, vegetation, infrastructure condition, and visible signs of pollution. These observations confirmed that many public green spaces are already serving, albeit informally, as stormwater catchment zones.

The key finding of this research is that existing urban parks and green spaces can be retrofitted to function as intentional stormwater infrastructure through minor upgrades such as vegetative buffers, improved grading, or expanded infiltration areas requiring minimal financial or operational burden. This passive, decentralized strategy aligns with the city's limited capacity for large-scale infrastructure investment and provides a sustainable, scalable model for similar mid-sized communities.

2.4. Historical Evolution and Software Selection Criteria for Transient Hydraulic Analysis with Hydro-Pneumatic Protection

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The analysis of hydraulic transients has progressed substantially over the past three centuries, from early formulations by Newton and Euler to modern numerical models. This work presents a historical synthesis of key theoretical developments in transient flow modelling, including the Method of Characteristics and simplifications such as the Rigid Water Column Model (RWCM).

Building on this foundation, a structured evaluation matrix was developed to support the selection of simulation software for pressurised systems with hydro-pneumatic protection. This method combines technical, operational, and resource-based criteria to assess several software packages and guide engineers in choosing tools suited to complex water networks.

Using this matrix, the ALLIEVI software was selected to simulate a real-world case study with both RWCM and the Elastic Water Column Method (EWCM). Results show that RWCM can reduce computation time by over 70% compared to EWCM, with acceptable accuracy when protective devices are present. However, in unprotected systems, it may underestimate critical conditions.

To complement the simulations, a Coarse Tree machine learning model was trained on the results. It successfully classified risk conditions such as overpressure or sub-atmospheric events, achieving up to 100% accuracy in elastic model scenarios.

These findings offer practical guidance for engineers operating under design or computational constraints and identify scenarios where simplified models remain reliable.

2.5. Hydrological and Pollutant Response of a Ceramic Roof: Implications for Stormwater Reuse

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Urbanization has significantly intensified surface runoff and degraded urban water quality, particularly in developing countries. Rainwater harvesting (RWH) systems represent a sustainable approach to stormwater management by mitigating runoff volumes, reducing dependency on potable water, and addressing diffuse pollution. In Brazil, ceramic-tiled roofs are among the most prevalent in residential areas; however, their hydrological behavior and pollutant wash-off dynamics remain underexplored.

This study aims to evaluate both quantitative and qualitative runoff parameters for a conventional ceramic-tiled roof under real-world rainfall conditions. A pilot roof with a

25° slope was monitored across 38 rainfall events. Hydrological performance was assessed using two methods: the SCS-Curve Number (CN) model and direct estimation of the runoff coefficient (C). The results showed high runoff generation, with an average C of 0.89 (median 0.93), strongly influenced by rainfall depth. The average CN was 99.5. Out of 712 mm of cumulative rainfall, only 7% was retained.

Water quality was evaluated during 26 events through two complementary analyses. First, runoff samples were collected every 17 min during the first hour of each event. Kruskal–Wallis tests revealed significant temporal variation in electrical conductivity (EC), suggesting early mobilization of dissolved pollutants. Second, the occurrence of the first flush was assessed by fitting a first-order exponential decay model to pollutant concentrations. Events with $R^2 > 0.90$ were classified as first flush occurrences for EC and total organic carbon (TOC).

These findings emphasize the substantial runoff potential of ceramic-tiled roofs and the dynamic nature of early pollutant wash-off. This study highlights the importance of site-specific hydrological and water quality calibration to improve urban drainage modeling. Future work will focus on extending these models to optimize RWH system design and pollutant retention strategies, promoting more efficient and resilient urban water management in subtropical environments.

2.6. Integrating Vulnerability Assessment and Urban Water Modeling for Resilient Management of Aqueduct Failures

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Urban water supply systems are increasingly vulnerable to natural hazards and climate-induced disruptions, demanding robust strategies to ensure reliable service. This study builds upon a multi-indicator vulnerability assessment framework previously developed for the Fiumefreddo aqueduct and combines it with dynamic urban water distribution modeling to quantify the impacts of landslide-induced pipeline failures on Messina's water supply network.

Scenario-based simulations revealed that a major aqueduct failure could reduce system-wide service reliability by up to 35%, deplete critical storage tanks within 9–12 h, and directly impact water availability for approximately 75% of the residential population. This research further demonstrates that implementing targeted management interventions, specifically increasing storage capacity by 20% and leakage reduction, can reduce the affected population by half and extend buffer times for storage depletion by up to 24 h. Source diversification also proved effective, limiting peak water deficits during disruptions.

These findings deliver clear, quantitative measures of vulnerability and resilience, supporting urban water managers and policymakers in prioritizing physical upgrades and emergency procedures. By identifying and comparing the effectiveness of different interventions, this work supplies actionable guidance for enhancing the sustainability and resilience of urban water supply systems facing growing environmental and climatic pressures.

2.7. Non-Revenue Water (NRW) and Leakage Management: Global KPIs and Modelling Challenges

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The water distribution system is a critical infrastructure for achieving Sustainable Development Goal 6, yet global inefficiencies remain due to high levels of Non-Revenue Water (NRW). This term refers to water that is lost before it reaches the consumer, primarily due to physical leaks, metering inaccuracies, or unauthorized consumption. Global NRW averages 29.5%, with extremes ranging from 4% in Singapore to 83% in Armenia. These losses equate to over 126 billion cubic meters annually, undermining both economic performance and water security in the face of climate change.

This study conducts a global assessment of NRW using two key performance indicators: the NRW percentage and the leak flow index (L/s/km). Drawing from international databases and reports, the analysis categorizes countries and continents according to infrastructure conditions and efficiency thresholds. The review also evaluates conventional hydraulic models and compares them with dynamic approaches such as the Rigid Water Column Model (RWCM), which accounts for transient pressure effects during operations.

Our findings show that 76.6% of countries exceed the 25% NRW threshold that is deemed economically inefficient, and 25% report values above 40%. Leak indices range widely, from 0.002 to 4.93 L/s/km, and correlate strongly with ageing infrastructure and inadequate pressure control. RWCM-based simulations reveal that standard Extended Period Simulation (EPS) models may underestimate leakage by 18–55% due to their inability to capture inertial effects.

Reducing NRW by one-third could supply 800 million people annually and generate savings of up to USD 13 billion. The proposed integration of RWCM with machine learning involves using time series generated by dynamic hydraulic simulations as training data for predictive models that estimate leakage behaviour under varying operational conditions. This hybrid approach offers a promising pathway to design smarter interventions, optimise pressure management, and enhance the resilience of water distribution networks.

2.8. Transient Leakage Estimation in Pressure-Reducing Valves: A Comparative Assessment Using RWCM and EPS Models

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Accurately estimating leakage volumes during valve operations remains a challenge in hydraulic modeling of water distribution networks (WDNs). Conventional simulation approaches, such as Extended Period Simulation (EPS), rely on quasi-steady-state assumptions, neglecting inertial effects during rapid valve maneuvers. This study proposes a novel methodology based on the Rigid Water Column Model (RWCM) to evaluate leakage behavior under transient conditions induced by valve operations.

A comparative analysis was conducted between the EPS and RWCM frameworks, examining multiple valve configurations under different operational scenarios. The models were tested in a real-world WDN, focusing on leakage volume predictions, instantaneous

leakage rates, and non-revenue water (NRW) variations during both fast and gradual valve closures.

The results indicate that EPS consistently underestimates leakage volumes—by up to 50%—in short-duration events. In contrast, RWCM accounts for transient pressure dynamics, capturing leakage peaks and oscillatory effects with higher precision. Specific valve designs exhibited significant deviations in the leakage volumes between models, with transient-sensitive simulations revealing substantially higher NRW fluctuations.

This study demonstrates the value of integrating inertial effects into hydraulic models for improved leakage assessment, particularly in dynamic operational scenarios. These insights can enhance digital twin applications and inform decision-making for network management. The findings emphasize the need for model selection aligned with system dynamics and valve-specific hydraulic responses.

2.9. Unsupervised Timely Detection of Leaks in Water Network DMAs Using a Robust Regression Ensemble Method

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Leakage in water distribution networks (WDNs) threatens water conservation and supply reliability, making timely leak detection essential for effective localization and remediation. However, limited labeled leak events associated with DMA-level measurements hinder the use of supervised learning methods. Unsupervised anomaly detection methods based on a single machine learning model and single anomaly scores, while label-independent, often suffer from imbalanced trade-offs between sensitivity and specificity, resulting in false alarms or delayed detections. This study proposes a robust approach based on an ensemble of regression models, for detecting newly emerging leakages at the DMA level, even under conditions where background leakage is present in the broader network. We estimate DMA-wise water supply patterns from net consumption using an ensemble of regression models—Random Forest, Support Vector Regression, XGBoost, and Multi-Layer Perceptron—trained on one year of hourly smart meter data that was preprocessed to correct for newly emerging leaks, while preserving the effects of steady background leakage. Discrepancies between predicted and actual supply are evaluated using Pearson's correlation, Z-score, and Kendall-Tau, combined via majority voting to produce a regression model-corresponding leak decision, which is then aggregated using weights proportional to each regression model's prediction accuracy. A leakage event is confirmed when this confidence score exceeds a threshold, optimized by varying the threshold within a predefined range and selecting the value that maximizes classification accuracy based on the area under the ROC curve (AUC). The proposed method detects leaks within 8–12 h of onset. Simulated leak scenarios of varying severity achieved 90% accuracy, while validation on historical leaks from a Danish utility reached 98%. Compared to an Isolation Forest baseline, the method improves accuracy by 31% on simulated and 39% on real-world data. These results highlight the potential of smart meter-driven ensemble analytics for rapid and reliable leak detection, supporting global water sustainability.

3. River, Lake and Groundwater Hydraulics, Quality and Vulnerability

3.1. Assessment of the Quality and Acquisition of Groundwater Mineralization in the Mbour Fatick Area, Central–Western Senegal

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Water resource management is one of the major global challenges today, both in terms of agricultural and industrial activities and direct consumption by the population. Access to drinking water is a major priority in the Mbour Fatick area (central–western Senegal), where groundwater resources, the only ones available, are subject to severe climatic and anthropogenic pressures. Several aquifers contain significant groundwater quantities, but the quality does not meet consumption standards due to deterioration caused by natural and/or anthropogenic processes. This work aims to update knowledge on the chemical quality of groundwater. Its main objective is to assess changes in groundwater chemistry, identify the processes responsible for mineralization, and determine the suitability of the water for consumption. The study was based on the results of physicochemical analyses of 42 samples collected during two campaigns conducted in September 2019 (22 wells and 20 boreholes) and May–June 2023 (20 wells and 15 boreholes), as well as data from SARR's work in 1982. The methodological approach used to achieve these objectives incorporates both hydro-geochemistry and multivariate statistical analysis. The results obtained show that pH values range from 6.89 to 8.2, indicating that the waters are neutral to basic. Geochemical analysis shows that water–rock interaction (dissolution and alteration of carbonate and silicate minerals), ion exchange, and evaporation are the main processes regulating the water chemistry. A comparative study of fluoride and chloride ion concentrations between different datasets shows significant spatial and temporal variation. Hierarchical cluster analyses (HCA) revealed the presence of two water groups: highly mineralized waters and moderately mineralized alkaline waters with dominant facies of the mixed Cl-type and mixed HCO₃-type, respectively. Calculation of Total Health Index (THI) for fluoride indicates that the health risk is very high, especially in children, with a high probability of diseases such as dental and bone fluorosis.

3.2. Assessment of Physicochemical Characteristics of River Landzun and River Umaru in Bida, Niger State, Nigeria

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Access to clean and safe drinking water is critical for the health and well-being of any community. In Bida, Niger State, the quality of surface water sources is increasingly threatened by anthropogenic activities such as open defecation and the washing of clothes, motorcycles, and utensils directly in the rivers, as well as surface runoff from surrounding areas. This study compares the potability of water from River Landzun and River Umaru, with the objective of identifying potential pollution sources and evaluating water quality

based on key physicochemical parameters. Samples were collected from each river at locations of use within the community. The physicochemical properties were analyzed, and the results were compared against the Nigerian Standard for Drinking Water Quality (NSDWQ) and World Health Organization (WHO) guidelines. The findings revealed that most parameters in both rivers were not within the permissible limits for potable water. Specifically, turbidity ranged from 31.4 to 58.1 NTU, TSS from 180 to 340 mg/L, TDS from 230 to 602 mg/L, BOD from 23 to 28 mg/L, and DO from 3.10 to 5.20 mg/L. However, hardness levels (30 to 100 mg/L), color (10 Hazen), and taste were within acceptable standards. These results indicate that the water in both rivers is not safe for direct human consumption. The study recommends regular monitoring of river water quality, improved public awareness, and the implementation of sustainable waste management and environmentally friendly practices.

3.3. A Comparative Physical Assessment of Intensified Global Flood Susceptibility Assessing Global Flood Susceptibility Through Multi-Parameter Integration

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Floods remain among the most destructive natural hazards, and their frequency, intensity, and spatial distribution are being profoundly reshaped under the influence of climate change. Despite their global significance, comprehensive physical assessments of changing flood susceptibility at a planetary scale remain limited, with most studies constrained to regional or basin-level analyses. In this study, we present the first global comparative evaluation of flood vulnerability using multiple assessment methodologies designed to capture both the spatial complexity and the physical drivers of flood risk. By analyzing 5105 historical flood events in conjunction with nine critical biophysical parameters—encompassing topography, terrain indices, precipitation regimes, vegetation cover, and soil characteristics—we reveal that approximately one-quarter of the Earth's land surface currently exhibits high to very high flood susceptibility. Spatial heterogeneity is evident, with susceptibility concentrated in large river basins and densely populated alluvial plains.

Our multi-model comparison highlights the superior performance of machine learning approaches, particularly the Random Forest model (AUC = 0.85), which effectively captures nonlinear interactions between precipitation variability, terrain morphology, and land surface features. Key flood-prone regions identified include the Yangtze, Indus, Ganges-Brahmaputra, and Amazon basins, where compound drivers converge to intensify vulnerability. This research provides a high-precision, physically grounded assessment of global flood susceptibility, demonstrating how shifting precipitation regimes interact with terrestrial landscapes to create emergent patterns of flood risk. The findings offer valuable spatial intelligence for climate adaptation planning, water resource management, and disaster preparedness, especially in regions where traditional hydrological monitoring and infrastructure remain insufficient.

3.4. An Early Warning Indicator of Hydrological Drought for Enhancing Reservoir Operation Rules

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Hydrological droughts, when combined with mismanagement of reservoir water resources, can lead to severe shortages. Reliable early warning of hydrological droughts can support improved monthly operation of upstream reservoirs. In this study, we evaluated an early-warning approach that integrates local rainfall with modeled soil moisture from the DREAM rainfall–runoff model, applied to the Camastra river basin upstream of the Camastra dam in Basilicata, Southern Italy. The performance of the proposed approach was tested against streamflow data derived by an inverse reservoir water balance.

Monthly soil moisture data were averaged over 1-, 3-, and 6-month periods and standardized per calendar month using a beta cumulative distribution function. When the Shapiro–Wilk test did not reject normality ($p > 0.05$), the data were further transformed into Z-scores via probit mapping, producing a series of Soil Moisture Index (SMI) values. A Joint Drought Index (JDI) was then computed by combining the Standardized Precipitation Index at a 6-month aggregation time scale (SPI-6) and SMI- k ($k = 1, 3, 6$) through a bivariate Gaussian copula. The predictive skill of JDI was evaluated against hydrological drought events defined by Standardized Streamflow Index (SFI) thresholds (≤ 0 , ≤ -1 , ≤ -1.5 , ≤ -2) using ROC/AUC with 12-month block-bootstrap 95% confidence intervals, testing lead times at $k = 0$ –3 months and benchmarking against SPI-6 alone.

Cross-correlation analysis revealed a coherent propagation chain: SPI-6 $\rightarrow$ SMI-6 peaked near a 1-month lead ($r \approx 0.85$ – 0.87), while SMI-6 $\rightarrow$ SFI peaked at a 0-month lead ($r \approx 0.75$). Consistently, JDI-6 showed predictive skill at lead times of 0 and 1 month. Compared to SPI-6 alone, JDI generally matched or slightly outperformed it, particularly at $k = 1$, demonstrating the added value of soil moisture information.

These results indicate that JDI can provide reliable short-term (0–1 month) hydrological drought warnings, particularly when direct inflow data are unavailable, thereby supporting timely operational decisions for water-supply management.

3.5. Antimicrobial Resistance Pollution Dynamics and Ecotoxicological Impacts on Zebrafish from Untreated Wastewater in Urban Rivers

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Antimicrobial resistance (AMR) is a silent pandemic, rising sharply worldwide and having particularly severe impacts in low- and middle-income countries (LMICs). This is largely driven by rapid urbanization and the lack of adequate wastewater treatment infrastructure, resulting in the direct discharge of untreated wastewater into urban rivers and thereby contributing to the spread of AMR. However, the extent, fate, transport, and ecotoxicological implications of AMR pollution in these urban environments remain scarce. This study quantified taxonomic and antibiotic resistance genes (ARGs), resistant and sensitive bacteria, and environmental conditions in the Musi River that runs through Hyderabad, a

city containing the largest manufacturers of pharmaceutical products. Furthermore, a total of 25-point sources were identified, wastewater inputs were estimated, and a hydraulic model was developed to study the rapid fluctuations in river flow and pollution concentrations along the river stretch passing through the city. The ecotoxic effects of polluted river water on zebrafish larvae were also assessed. Our findings revealed increasing, though spatially variable, concentrations in ARGs along the river through the dry season, and stronger discrete point source and flow dilution dynamics in the wet season. The riverbed sediment stores far higher concentrations of ARGs than the water column, especially in the dry season, and has more dynamic interaction with the river during the wet season. The river modeling indicated that approximately 60% of the flow in the city stretch comprises untreated wastewater. Moreover, the observed lethal and sub-lethal ecotoxic effects on zebrafish larvae underscore the environmental and biological risks associated with sewage pollution. This study highlights the urgent need for expanding wastewater treatment capacity to reduce raw discharges and mitigate AMR risks, an issue of growing concern across the urban rivers of LMICs.

3.6. Assessment of Groundwater Vulnerability Using the DRASTIC Method in the Transboundary Coastal Aquifer Between Albania and Montenegro: Focus on Lake Sasko and the Pentari Plain

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This study, carried out in the framework of the MedProgramme Project, applies the DRASTIC model to assess the intrinsic vulnerability of the transboundary coastal aquifer shared by Albania and Montenegro, with particular emphasis on the Lake Sasko area and the Pentari Plain. The DRASTIC method, an acronym representing Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and hydraulic Conductivity, was used to generate a vulnerability map based on hydrogeological and environmental parameters. The region is characterized by complex hydrogeological settings, where the interaction between shallow alluvial aquifers, karst systems, and surface water bodies such as Lake Sasko plays a significant role in groundwater dynamics.

Results indicate moderate to high vulnerability in the studied areas, particularly around the Pentari Plain (Albania) and the western margins of Lake Sasko (Montenegro). These zones exhibit shallow water tables, permeable soils, and high recharge potential, which enhance the susceptibility of the aquifer to contamination from agricultural runoff and human activities. The DRASTIC index values range from 120 to 185, corresponding to moderate to high vulnerability classes. The findings highlight the need for targeted land-use planning, pollution prevention strategies, and enhanced transboundary cooperation to safeguard the groundwater resources in this ecologically sensitive and geopolitically important region. This study provides a scientific basis for sustainable water resource man-

agement and supports ongoing efforts to harmonize environmental monitoring frameworks across national borders.

3.7. Bacterial Transport in Contaminated Groundwater: Column Experiments and Public Health Implications in Nigeria

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Contaminated drinking water poses significant environmental health risks, particularly in developing countries like Nigeria, where inadequate treatment and microbial pollution of groundwater remain major challenges. This study investigates bacterial movement in contaminated groundwater using column experiments to assess filtration efficiency under varying conditions.

Sewage samples were collected, and bacterial isolates (*Escherichia coli*, a rod-shaped bacterium, and *Staphylococcus aureus*, a coccoid bacterium) were selected based on biochemical characterization and morphology. A laboratory-scale column system was packed with sterile sand of different particle sizes (600 µm, 425 µm, 212 µm, and 150 µm) and depths (10 cm, 20 cm, 40 cm, and 50 cm). Bacterial suspensions were injected into the column, followed by intermittent sterile water elution. Effluent samples were collected and analyzed microbiologically to determine bacterial retention.

Results showed that bacterial recovery decreased with increasing sand depth and decreasing particle size. The highest retention occurred at 50 cm depth with 150 µm sand, while the lowest retention was observed at 10 cm with 600 µm sand. Sequential elution further reduced bacterial loads, with the first eluent containing the highest concentration and the fifth the least. Statistical analysis confirmed a significant negative correlation between bacterial recovery and sand depth ($p < 0.05$). *E. coli* exhibited greater mobility than *S. aureus*, suggesting shape-dependent transport behavior.

These findings imply that bacteria from septic tanks and pit latrines can migrate through subsurface layers, reaching groundwater sources and posing fecal–oral disease risks. Since aquifer remediation is often impractical, preventive measures, such as proper waste disposal and optimized well placement, are critical for safeguarding groundwater quality. This study underscores the need for improved water management policies in Nigeria to mitigate public health threats from microbial contamination.

3.8. Disinfection of Water for Human Consumption in Rural Communities of Peru Using a UV-C LED Prototype

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Currently, significant challenges exist regarding both the quantity and quality of water, especially in rural areas of Peru, where access to potable water is limited. This study aims to address these issues by implementing a UVC-LED system for the disinfection of water intended for human consumption in rural Peruvian communities. The research was conducted in three stages: (1) characterization of the microbiological status of water from the rural district of Querulpa Chico, Aplao; (2) development of a disinfection prototype based on UVC-LED technology; and (3) application of this UVC-LED system to disinfect

water used for human consumption in the study area. Preliminary results from the microbiological analysis revealed that water consumed by the population of Querulpa Chico is contaminated with total coliforms. Specifically, measurements at two sampling points reported 3 and 4 Most Probable Number (MPN) units, respectively. These values exceed the regulatory limit of 0 MPN for potable water. Regarding the disinfection system, tracer tests and mathematical model indicated a retention time of 240 s. The system employs 17 UVC-LEDs, each with an optical output power of 11.5 mW. Disinfection trials using water samples from Querulpa Chico are ongoing. The outcomes of this study aim to contribute to the development of effective, low-cost disinfection solutions to ensure safe drinking water for rural populations in Peru.

3.9. Early Hydrochemical Evolution of Groundwater Under Landfill Leachate Influence: Case of the Tangier Municipal Site

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This study evaluates short-term changes in groundwater quality around the new municipal landfill of Tangier, Morocco. In total, 10 sampling sites (8 wells and 2 surface waters) within 2 km were sampled in late summer 2023 (S-23) and late winter 2025 (F-25), alongside the flow gradient. Major ions (ICs), trace metals (ICP-OES) and field parameters were analyzed; data were converted to milliequivalents and quality-checked by ionic balance error (IBE).

S-23 samples were mostly fresh Ca–HCO₃/Cl waters (EC 1000 µS cm^{−1}; TDS 500 mg L^{−1}). By F-25, downgradient wells evolved from Ca–Cl to mixed Ca–Na–Cl–SO₄ facies, with Cl[−] accounting for >70% of anions and Ca²⁺ contributing to 20–50% of cations; the Piper diamond collapses toward the strong acid corner. A PCA on major ions (meq L^{−1}) shows PC1 (80.9%) as a salinity/leachate axis, clearly separating F-25 downgradient waters (notably P3–P4–P8) from upgradient S-23 points. PC2 (10.8%) represents hardness vs. alkalinity (SO₄/Mg/Ca vs. HCO₃). A simple two-endmember chloride mixing model estimates the leachate fraction f_L increasing from (0.0–0.1 upgradient) to (0.2–0.5 at P3–P4) and (0.9–1.0 at P8). Paired Wilcoxon tests ($n = 10$) on Cl[−]/SO₄^{2−} show non-significant p -values (0.19–0.38), reflecting limited power, yet large effect sizes are captured by PCA, medians and f_L . Heavy metal enrichments (e.g., Fe, Mn and Zn) co-locate with high f_L and strong acid fractions.

Together, these lines of evidence indicate rapid salinization and leachate intrusion in less than 2 years along the downgradient axis. We outline a monitoring framework (quarterly sampling, sentinel wells P3–P4–P8, trigger thresholds on EC/Cl/SO₄ and IBE), and propose MODFLOW transport modeling constrained by the local stratigraphy and measured heads to forecast plume migration and guide mitigation (drainage capture, liner integrity checks and wellhead protection).

3.10. Effects of Rayleigh Number on Thermal Siphons in Triangular Water Bodies

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Natural convection, driven by surface cooling, in water bodies (lake, reservoirs etc.) has been investigated in the past with emphasis on the development of thermal siphons (large-scale overturning circulation). The latter is the result of faster cooling of the shallow nearshore regions and the development of horizontal exchange between shallow and deep waters. Initially, the water body is characterized by local, quasi-isotropic convective cells, and, afterwards, a two-layer exchange flow, which characterizes the large-scale circulation, develops. Finally, a quasi-steady state is achieved during which the produced water discharge remains constant.

The numerical models used for simulating thermal siphons in water bodies, especially for high Rayleigh numbers (turbulent natural convection), are limited and belong to two categories: (a) Large Eddy Simulation (LES) models (two- or three-dimensional), which usually require significant computer resources, and (b) Reynolds-Averaged Navier Stokes (RANS) models in conjunction with a turbulence model accounting for turbulence effects.

In this study a Large Eddy Simulation (LES) approach is used for investigating thermal siphons, due to surface cooling, in water bodies for high Ra numbers. The Wall-Adapting Local Eddy Viscosity (WALE) model is selected to compute subgrid-scale turbulence effects, offering improved accuracy over classical models for domains with laminar zones. In addition, a Navier–Stokes approach, considered as “Two-Dimensional Direct Numerical Simulation”, has provided results for comparison purposes from a previous study. Temperature and stream-function fields, based on both approaches, are presented and show features of the developed thermal siphons and the interaction between downslope gravity currents and downflowing convective plumes. Comparison of the results from the two approaches indicates important differences in the development of thermal siphons and the interaction between bottom gravity currents and convective plumes.

3.11. Fuzzy Triangular Finite Elements Solution for Solving the Nonlinear Boussinesq Equation

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In this work, the fuzzy solution of the nonlinear Boussinesq equation is investigated for an unconfined aquifer bordering a lake, where the lake water level undergoes a sudden rise (recharge event) from 4 to 6 m, followed by stabilization. The aquifer conditions are considered crisp, while the hydraulic parameters (hydraulic conductivity and specific yield) are treated as fuzzy due to uncertainties arising from measurement imprecision, data limitations, etc. To represent these uncertainties, fuzzy estimators of maximal specificity are employed. This novel methodology incorporates parameter uncertainty directly into the nonlinear Boussinesq equation, thereby advancing the reliability of groundwater flow modelling under uncertain conditions. The proposed approach (a) enables the construction of fuzzy numbers directly from statistical samples rather than relying on subjective expert judgment, and (b) allows efficient fuzzy arithmetic operations through well-defined formulae involving only statistical parameters of the samples. To solve the problem, the theory of fuzzy differential equations is applied, reformulating the fuzzy system into a set of second-order crisp boundary value problems, referred to as the corresponding system. A triangular fuzzy finite element method (FEM) based on the Galerkin approach is then developed and solved using the α -level method. The objectives of this study are threefold: (1) to design and implement a fuzzy FEM numerical scheme based on triangular elements tailored to the nonlinear Boussinesq problem; (2) to determine the range in which the

semi-analytical solution approximates the new triangular fuzzy FEM solution, and to perform comparative analysis with both semi-analytical and previously developed orthogonal fuzzy FEM approaches; and (3) to provide engineers and water resource planners with improved tools for quantifying hydraulic properties under uncertainty. The findings show that the triangular fuzzy FEM solution is strongly consistent with the orthogonal fuzzy FEM method and demonstrates good agreement with the semi-analytical solution, validating its effectiveness for recharge volume estimation in practical hydraulic applications.

3.12. Groundwater Vulnerability Assessment Using the GOD Method in the Grombalia Coastal Aquifer, Tunisia: Focusing on the Soliman Lagoon Area

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This study, carried out in the framework of the MedProgramme Project, presents an evaluation of the intrinsic vulnerability of the Grombalia coastal aquifer in northeastern Tunisia using the GOD method, with particular attention to the Soliman Lagoon zone. The GOD method—based on Groundwater occurrence (G), Overall lithology of the unsaturated zone (O), and Depth to water table (D)—provides a qualitative framework for identifying zones most susceptible to contamination. The Grombalia aquifer system is under increasing pressure from intensive agriculture, urban expansion, and saline water intrusion, particularly near the Soliman Lagoon, a sensitive interface between groundwater and coastal ecosystems.

The resulting vulnerability map shows a spatial variation ranging from low to high vulnerability, with the highest risk zones concentrated along the Soliman Lagoon's southern perimeter. These areas are characterized by shallow phreatic levels, highly permeable lithologies (sands and silty sands), and limited natural protective layers. The GOD index values in these high-risk zones exceed 0.6, placing them in the moderate-to-high vulnerability category. In contrast, more inland zones with deeper water tables and less permeable overburden exhibit lower vulnerability scores.

The findings underscore the necessity for integrated groundwater protection measures, especially in the lagoon's vicinity, where both ecological and socioeconomic stakes are high. This study supports the implementation of land-use regulation, monitoring programs, and pollution mitigation strategies aimed at preserving water quality and ensuring the long-term sustainability of the aquifer system.

3.13. Hydrogeological Facies Evolution in a Mining Context: The Case of the Kankan Aquifer (Guinea)

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In the mining areas of the Kankan administrative region (Guinea), access to drinking water is problematic due to population explosion and gold mining, particularly various artisanal and industrial techniques that can cause lasting disruption to water systems. The aim of this study is to assess the physical and chemical quality of drinking water in these mining areas. Nineteen traditional wells and fourteen boreholes were sampled to identify any contamination of these groundwater sources. The analyses reveal the presence of certain trace metals (As, Pb) among the major ions. Of the thirty-three water points analysed, calcium ion concentrations exceed the WHO (World Health Organization) drinking water standard at more than half of the sites (seventeen out of thirty-three water points). With regard to trace metals, arsenic concentrations exceeded the WHO standard by more than seven times in three-quarters of the samples. The same is true for lead, but to a greater extent. Indeed, concentrations of this element are always above the drinking water standard. Furthermore, in three-quarters of the wells and boreholes analysed, the concentrations measured exceeded the standard by a factor of 7. The contamination of these water points by these various chemical elements appears to be linked both to local geological characteristics and to anthropogenic pressures associated with mining and industrial activities. The results of this study show a deterioration in the physical and chemical quality of all the water sources analysed in these mining areas in the Kankan region. Widespread contamination by arsenic and lead, far exceeding WHO drinking water standards, poses a major risk to public health, particularly for the populations that use these water sources.

3.14. Impact of Selected Parabens and Related Disinfection By-Products in Biofilms Formed by Bacteria Isolated from Drinking Water

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Water is a very valuable asset for human life, but quality drinking water is becoming scarce due to the presence of contaminants. Disinfection by-products (DBPs) such as chlorine are commonly formed in water treatment plants due to the processes involving disinfectants, which can result in the formation of parabens-related DBPs (p-DBPs), which have a higher impact on human health than the parent compounds. The presence of biofilms in drinking-water distribution systems is unavoidable, but scientific knowledge on the effects of parabens and their p-DBPs on microbial communities is scarce². Strains of *Stenotrophomonas maltophilia* isolated from drinking-water distribution systems in Portugal were used to assess their behaviour in planktonic and biofilm states (using polyvinyl chloride–PVC as an adhesion surface) after exposure to Methylparaben (MP), Ethylparaben (EP), and p-DBPs such as para-hydroxybenzoic acid (pHBA), 3,5-dichloroethylparaben (3,5diClEP), and 3,5-dichloromethylparaben (3,5diClMP) at 50 ng/L. The biofilms were analyzed for cultivability using CFU, cell density using DAPI, and EPS content using polysaccharides and protein quantification. Planktonic analysis was carried out in the presence of parabens and p-DBPs over 24 h at 610 nm. pHBA increases the number of polysaccharides (10.5 µg/cm²), followed by EP (10.37 µg/cm²) and MP (9.98 µg/cm²). PHBA also raises the amount of protein (6.5 µg/cm²), but it remains less than EP and MP (7.07 and 8.01 µg/cm², respectively). 3,5diClMP and 3,5diClEP show decreased polysaccharides but increased proteins, with 3,5diClEP having the highest protein content (16.6 µg/cm²) and a significant cell density reduction (−0.07 log cells/cm²), followed by pHBA. In planktonic

mode, parabens boost bacterial growth; biomass rises by ~30%, and growth rate by ~10%. 3.5diCIMP and 3.5diCLEP undergo more significant changes than their parent compounds. This is concerning, given that they are produced during chlorine water treatment. Paraben exposure affects biofilms of *S. maltophilia* isolated from drinking water, especially in planktonic form, which raises concerns about the potential threat to the quality and safety of drinking water.

3.15. Modulating Incipient Entrainment of Coarse Particles: The Impact of Flow Turbulence

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The incipient motion of coarse particles is a cornerstone of bed stability and sediment transport processes in turbulent flows, profoundly influencing riverbed morphodynamics and the resilience of hydraulic infrastructure. While traditional incipient motion criteria rely on steady-state shear stress thresholds, dynamic effects due to the inherent variability of flow turbulence remain poorly linked to the assessment of incipient particle entrainment in the lab or real-world field conditions.

This study aims to examine how alterations in flow conditions modulate the critical hydraulic thresholds for coarse particle entrainment under fully submerged, turbulent regimes. Leveraging instrumented particles integrated with inertial measurement units (IMUs) to capture real-time accelerations and angular velocities, we dissect particle responses at the brink of motion. Derived flow--particle interaction metrics illuminate the mechanistic pathways, including torque generation and hydrodynamic lift, that govern entrainment.

We hypothesize that flow turbulence can dramatically affect the energy imparted towards particle entrainment. These discoveries underscore the utility of IMU-derived metrics for predictive assessment of destabilization risks in dynamic river systems or scour-vulnerable channels.

3.16. Numerical Study of Turbulent Open-Channel Flow in the Presence of Emergent Vegetation Located at the Lee Side of a Single Groyne

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Groynes are widely recognized for their role in protecting river and coastal banks from erosion. Due to a reduction in velocity magnitude, the area downstream of the groynes becomes susceptible to sediment deposition, creating a favorable habitat for aquatic organisms and vegetation. In this study, a three-dimensional turbulent open-channel flow ($Fr = 0.19$) with a single groyne was numerically simulated using the ANSYS FLUENT code. The standard $k-\epsilon$ turbulence model was employed for turbulence closure, while the VOF method was used for free surface treatment. Furthermore, the case of a vegetated patch located at the lee side of the single groyne was also examined. Vegetation was modeled using vertical, rigid cylinders located near the downstream face of the emerged, impermeable groyne, within its recirculation zone. The emergent vegetated stems were arranged in a uniform, parallel array of eighteen (3×6). The computed velocities were found to be in good agreement with the experimental data as well as the numerical results. In the case of a single groyne without vegetation, the numerical results showed that a recirculation zone is created with a reattachment length that varies between $15b$ and $12b$ from the bed to the free surface, where b corresponds to the groyne length. Furthermore, a comparison of reattachment lengths as well as the flow structure between the vegetated case and the non-vegetated case was also conducted.

3.17. Surface Water Quality in a Rapidly Urbanizing Region of Southwest Nigeria: Hydrogeochemical Characterization, Trace Metal Pollution, Irrigation Suitability, and Ecohealth Risk Evaluation

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This study presents a comprehensive hydrogeochemical characterization and human-ecological risk assessment of trace metals in surface waters of Ondo Town, Nigeria. Surface water samples (n = 20) were analyzed for physicochemical parameters and trace metals (Fe, Pb, Cu, Cr, Mn, Zn, Ni, Co, Cd) using atomic absorption spectrophotometry (AAS). Hydrogeochemical analysis revealed Ca-Mg-HCO₃ as the dominant water type, indicating silicate weathering and ion exchange as key processes controlling water chemistry. However, anthropogenic influences were evident, with elevated concentrations of Fe (0.12–7.54 mg/L), Pb (0.01–0.99 mg/L), Cr (0.01–0.13 mg/L), and Cd (0.002–0.004 mg/L) exceeding WHO permissible limits in several samples. Multivariate statistical analyses (PCA, HCA) identified geogenic weathering, agricultural runoff, and industrial effluents as major contamination sources. Pollution indices (CF, CD, PLI, MI, NPI) indicated moderate to very high contamination, particularly for Fe, Pb, and Cd. The Water Quality Index (WQI) classified 25% of samples as “excellent,” 20% as “good,” 20% as “poor,” 20% as “very poor,” and 15% as “unsuitable” for drinking. Ecological risk assessment (PERI) highlighted considerable risks from Fe ($E_r = 36.82$), Pb ($E_r = 26.46$), and Cd ($E_r = 68.70$), posing threats to aquatic ecosystems. Health risk assessment revealed higher non-carcinogenic risks ($HQ > 1$) for children due to Pb and Co exposure, while carcinogenic risks from Cd and Cr were significant for adults. The study underscores the need for urgent remediation, stricter industrial regulations, and community awareness programs to mitigate contamination. Recommendations include water treatment interventions, sustainable agricultural practices, and long-term monitoring to safeguard public health and aquatic biodiversity in the region.

3.18. Sustainable Management of Springs in a Crystalline Basement Context Using a Coupled Hydrogeophysical and Hydrodynamic Modelling Approach (Daloa, Central-Western Côte D’Ivoire)

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Spring management in crystalline basement regions is essential in order to respond to the impacts of climate change and the challenges of supplying drinking water to large urban areas. This study therefore aims to understand the hydrogeological functioning of the aquifer system supplying springs in altered and fractured crystalline basement regions, in order to ensure effective and sustainable protection of springs in these regions. To achieve this objective, the methodological approach first consisted of describing the aquifer system supplying the springs based on drilling and field data in a representative crystalline aquifer (Daloa, Côte d’Ivoire). Next, electrical resistivity tomography was used, after validation of the appropriate inversion method, to develop the Hydrogeological Conceptual Model (HCM) of the springs. This HCM was then used as the basis for

developing a groundwater flow model using a finite element numerical code (FEFLOW). The results show that the most productive part of the fractured horizon is located within the first 40 metres below the saprolite, with an average transmissivity of $1.3 \times 10^{-4} \text{ m}^2/\text{s}$. The saprolite has an average hydraulic conductivity of $6.9 \times 10^{-6} \text{ m/s}$ and an average effective porosity of 5.6%. The estimated direct recharge is 35 mm/year (4% of rainfall, 2022). The cumulative average discharge of the springs is 9 L/s. The conceptual model developed reveals that the springs are mainly fed by isalterites, composed of sands and arenas. The underlying fractured layer, located a few dozen meters deep below the springs, does not contribute directly to their supply. The digital model made it possible to define springs capture zones (0.17 to 1 km²) and protection perimeters (30 m: immediate perimeter, 130 m: close perimeter, capture zone for the distant perimeter). These results provide essential information of sustainable management springs in crystalline basement environments and for guiding decision-makers in defining effective action programmes.

4. Water Resources Management, Policy and Governance

4.1. Assessment of Pollutant Bioaccumulation in Fish Communities from Human-Induced Water Pollution: A Machine Learning and Statistical Approach

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Aquatic animals, particularly fish communities, are highly susceptible to toxic chemicals and the buildup of heavy metals resulting from various anthropogenic activities. Despite several individual studies on human and aquatic life, there is a notable gap in integrating a machine learning (ML) approach to assess toxic accumulation differences in different fish sample types, sexes, and ages. Therefore, the objectives of this research are to incorporate ML to perform statistical analyses and determine if there is any dissimilarity in bioaccumulation between different fish sexes, ages, and among different fish sample types. For this purpose, a bid dataset containing 37 variables and 28,616 observations from the Michigan Department of Environment, Great Lakes, and Energy (EGLE, 2024) was used for ML analyses. The dataset included monitoring data on chemicals that bioaccumulate in fish from Michigan waters. Specifically, two-tailed hypothesis tests, neural network analysis, and principal component analysis were conducted to address the objective. The results suggested that older fish accumulated 25.51 times higher levels of DDT than younger fish, and the highest content of toxaphene (0.131 ppb) was observed in fish with a longer length (69.3 cm) and higher weight (3225 gm). Hypothesis test results indicated that female fish accumulated significantly higher amounts ($0.3 \pm 0.19 \text{ ppb}$) of toxic substances, especially mercury, compared to male fish. A neural network analysis with a three-layer network and four nodes produced the best results based on the error percentage. The biplot identified a reciprocal relationship between fish length, weight, and Perfluorooctane sulfonic acid (PFOS) content, while Polychlorinated Biphenyl Congeners (PCBCs) increased with fish length and weight. Overall, this study suggests that hypothesis testing might be accurate for a small subset of data; however, to include the entire dataset, principal component analysis might be a better option depending on the focus of the research.

4.2. Controllability and Observability of Microbial Purification Systems in Small–Micro Water Bodies: A Complex Network Theory Perspective

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As critical terminal units within watershed aquatic ecosystems, small–micro water bodies exhibit dynamic water quality responses to coupled environmental factors. Due to disparities in hydrological connectivity, limited self-purification capacity, and external pollution inputs, certain small-micro water bodies (e.g., stagnant systems with weak groundwater exchange and affected by non-point source pollution) are prone to pollution intensification and ecological degradation, presenting significant challenges in watershed management. This study proposes a novel analytical framework grounded in complex network theory to addresses the controllability and observability challenges of biological purification systems under pollutant overload conditions.

The research methodology involves three key phases: First, a hydro-bio-chemical coupled kinetic model of contaminant migration and transformation, as well as their state-space representations, are constructed. And then, they are mapped onto a directed network with heterogeneous node weights and adaptive edges. Subsequently, complex network metrics are employed to evaluate the full-state structural controllability and observability of photosynthetic bacteria-mediated purification systems, identifying critical input and monitoring nodes. Finally, case studies elucidate the performance enhancement mechanisms through network topology optimization.

Our results demonstrate that topology-guided regulation significantly enhances purification efficiency in low-connectivity, long hydraulic retention time systems, while optimized sensor placement improves system observability. This finding provides novel insights for the targeted remediation of environmentally stressed small–micro water bodies, with substantial practical implications for differentiated water governance and resilient water resource management. Field applications require adaptive adjustments based on site-specific hydrological characteristics to ensure operational efficacy.

4.3. Using the Shapley Value to Promote Water Consumption Reduction in Water Distribution Networks

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Introduction

Water consumption reduction often arises as a sustainable adaptation pathway under water scarcity conditions. Often, administrative units subsidize water users in order to promote water consumption reduction, either directly or indirectly through water pricing policies. However, horizontal measures might fail to address the complexity of the problem, promoting suboptimal or unfair strategies. We present a methodological framework that can be used to fairly subsidize water consumption reduction in water distribution networks.

Methodology

First, we use graph theory in order to represent water distribution networks. Typically, Nodes represent water consumption junctions and Edges represent water pipes. Then,

we model the networks in Python using the Water Network Tool for Resilience (WNTR), leveraging the EPANET hydraulic engine via WNTR'S EpanetSimulator. We consider the Nodes as Players (or groups of Players) under a game theoretical framework. We assume that every player reduces their consumption, resulting in an overall consumption reduction for the water distribution system. This reduction provides benefits to the system, such as head loss reduction, pressure increase and pump energy consumption reduction. Finally, we apply the Shapley Value, a cooperative game theoretical framework, to estimate each players' contribution to the water distribution system's overall improvement.

Results

We use the WNTR in Python to test various network topologies. The results indicate that the location of the players in the network is crucial to the players' subsidization. Specifically, the network topological characteristics, such as the distance between the Players and the water tank, need to be taken into consideration.

Conclusion

Overall, our work illustrates that the Shapley Value can be used in order to assign subsidization values in water distribution network users and we provide a methodological framework and numerical examples.

4.4. Assessment of Surface Water Quality Using Indices and Methods: A SWOT-Based Integrated Approach

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Degradation of surface water quality is a global problem, posing significant ecological, social, and economic risks with visible long-term effects. In this context, sustainable water resource management has become a strategic challenge that requires the development and use of appropriate tools for water quality assessment and aquatic ecosystem monitoring. In this study, a bibliometric analysis of the most important water quality indicators was conducted, such as the Water Quality Index (WQI), Canadian Council of Ministers' Water Quality Index (CCME-WQI), and Oregon Water Quality Index (OWQI), along with specialized indicators, such as the Trophic Status Index (TSI) and Heavy Metal Pollution Index (HPI). In addition, this study looks at complementary assessment methods, including multivariate statistical analysis, biological assessment, ecological risk assessment methods, remote sensing, geographic information systems (GIS), and mathematical modelling. These were critically evaluated through SWOT analysis, with particular attention paid to the relationship between the assessment indices and assessment models. The results highlight the limitations of some quality indices, such as the WQI, TSI, and HPI, particularly in terms of inflexibility, ambiguity, and lack of sensitivity to certain critical parameters, which can lead to inaccurate estimates of the state of the aquatic environment. In contrast to indices with rigid formulas, CCME-WQI offers a flexible approach that reduces the sensitivity of results to the fixed structure of parameters, an advantage highlighted in the SWOT analysis. The CCME-WQI demonstrates greater adaptability, providing a better response to parameter selection and weighting, an advantage highlighted in the SWOT analysis. It has also been found that objective mathematical approaches have the potential to reduce the uncertainty associated with these indices. The effective application of surface water quality indices and assessment methods depends on coherent and continuous monitoring programs, which are often affected by institutional fragmentation and economic constraints both locally and globally.

4.5. Assessment of Treated Rainwater Suitability for Filter Backwashing in Swimming Pool Systems

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The growing need for sustainable water management in recreational facilities has led to increased interest in alternative water sources, particularly in alignment with the European Green Deal and sustainable development goals. This study evaluates the effectiveness of using treated rainwater—processed through a sequential treatment system—for backwashing filters in public swimming pool installations. The research was conducted at a selected swimming pool facility immediately following summer season, allowing for performance evaluation during routine maintenance operations without disrupting active pool use.

The sequential rainwater treatment system implemented consisted of sedimentation, filtration, and disinfection stages, designed to produce water of sufficient quality for technical reuse. The treated rainwater was then employed exclusively for filter backwashing over an extended observation period.

Key performance indicators included the quality of swimming pool water post-backwashing and the operational efficiency of the filters. No deterioration in either was observed, suggesting that the treated rainwater did not negatively impact water quality or filtration performance. These findings support the technical feasibility and environmental benefit of substituting potable water with reclaimed rainwater for backwashing purposes.

This innovative approach not only significantly reduces freshwater consumption—a notable concern given the high water demand for filter cleaning—but also aligns with principles of integrated water resource management and circular economy. The use of rainwater in this context contributes to reducing the environmental footprint of pool facilities and offers a replicable model for sustainable operation in similar contexts.

The results confirm that the application of a sequentially treated rainwater system is an effective and environmentally sound alternative for technical uses in swimming pool operations. The study encourages broader implementation as part of sustainable facility management strategies.

4.6. Climate Change Impacts and Water Management in the Mediterranean Region

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The Mediterranean region is highly vulnerable to climate change, with impacts including rising temperatures, fluctuating precipitation, sea-level rise, and increasing water scarcity. These environmental changes intensify pressures on agriculture, food security, human health, and economic stability, while also amplifying geopolitical challenges linked to the management of shared and transboundary freshwater resources.

This study provides a multidimensional analysis of freshwater management in the Mediterranean, examining environmental, socio-economic, geopolitical, and technological dimensions. It evaluates how climate change undermines water availability and quality, and explores the consequences for agriculture, food systems, and regional stability. Technological opportunities, including improved smart irrigation systems, wastewater reuse, and desalination, are assessed alongside the limitations of existing water infrastructure.

In addition, the study identifies cross-cutting aspects of sustainability, highlighting the need to integrate ecological resilience, economic feasibility, and social equity into regional strategies. A SWOT analysis is employed to systematically assess the strengths, weaknesses, opportunities, and threats of different management approaches.

The findings show that effective solutions require a combination of technological innovation, sustainable land and water management practices, and strengthened regional cooperation. Frameworks such as the European Green Deal and the Union for the Mediterranean can support these efforts by fostering solidarity and reducing conflict potential.

Ultimately, this study underscores the importance of coordinated strategies that reconcile environmental science, economic policy, and societal engagement to secure a sustainable freshwater future for the Mediterranean.

4.7. Dual-Risk Management of Water–Energy–Environment Nexus Through Stochastic Programming: Regional Industrial Structure Adjustment

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The water–energy–environment nexus (WEEN) system constitutes a large-scale complex system plagued by multifaceted risks amid global challenges to sustain economic growth, resource security, and environmental resilience. Accelerated urbanization has triggered escalating water and energy demands, exposing over 60% of Chinese regions to severe resource shortage risks. Concurrently, policymakers face critical dilemmas in balancing systemic benefits against potential losses under tightening water and energy policies. To address this dual-risk challenge spanning resource scarcity and economic instability, this study develops a copula-based stochastic downside risk-aversion programming (CSDP) model for regional WEEN management. The CSDP framework synergistically integrates copula functions for dependency modeling and risk-aversion optimization techniques. It uniquely quantifies nonlinear interactions between water and energy risks under multivariate distributions—including scenarios with undefined prior correlations—while generating robust solutions through joint chance constraints. Crucially, the model establishes quantifiable tradeoffs between economic objectives (e.g., GDP targets) and system reliability through conditional value-at-risk metrics. Applied to Tianjin—a coastal metropolis grappling with chronic water deficits and coal-dependent energy systems—the CSDP examines 12 copula structures across five policy scenarios and three risk-tolerance tiers. The results demonstrate water scarcity's dominant influence (>68% impact) over energy constraints in industrial restructuring, directly affecting sectoral output allocations, wastewater discharge limits, and PM2.5 control strategies. Notably, tertiary industry expansion, while boosting GDP by 19.2% in optimal scenarios, intensifies the graywater footprint by 27% and requires integrated pollution mitigation frameworks. This research provides actionable pathways for sustainable resource co-management amid climate uncertainties.

4.8. Evaluating Phosphorus Fluxes in Portugal: Opportunities and Limitations for the Implementation of Regional Synergies Between the Wastewater and Agricultural Sectors

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Portugal is deficient in phosphate fertilizers. However, it also has a phosphorus (P) consumption chain with potential to promote sustainable management of P from waste. Creating a link between the waste and agricultural sectors supports a reduction in external dependence and promotes the circularity of secondary raw material.

Gathering information about productive quantities, pollutant discharge points (PDPs), and P concentration in industrial activities, it is possible to infer the following: the food industry is concentrated in coastal urban areas like Lisbon and Porto, but contributes minimally to P losses in the form of waste (383 t/year); wastes from slaughterhouses, while rich in protein and suitable for biogas production, only contribute minimally to P resources (82 t/year); urban solid waste management is more structured, although with efforts in recycling and biogas production, its role in P recovery remains modest (1.35 kt/year); urban wastewater, however, shows the greatest potential for P recovery due to its widespread geographic distribution, and nutrient-rich sludge (7.3 kt of P). This highlights opportunities for P management, enhancing biofertilizer production.

Using the concept of Regional Resilience (RR) and Territorial Metabolism (TM), this work estimated agricultural demand for P fertilizer in mainland Portugal and P content in sewage sludge, from urban wastewaters, to partially replace the use of inorganic P fertilizers, at the municipal level. So far, the Lisbon Metropolitan region appears to have the potential to reach 2631.87 t/year of P recovered from wastewater, surpassing local agricultural demand (126.83 t/year). In the northern region, sewage sludge contains enough P to meet 25% of the region's fertilizer needs. In the Centro Litoral region, it is possible to meet 48% of the corresponding P needs. Opportunities for implementing synergy require accurate information on infrastructures, technology assessments corresponding to local characteristics, economic and environmental contributions, and compliance with legislative targets.

4.9. Hydrogeochemical Modeling of Control Strategies for Acid Mine Drainage and Water Resource Protection

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Environmental hazards associated with mine waste dumps, particularly the formation of acid mine drainage (AMD) and the mobilization of toxic metals into surrounding water bodies and soils, represent some of the most critical challenges in metal mining operations.

This study presents an integrated approach, supported by numerical modeling, to control AMD generation and limit contamination of nearby water resources. Aligned with the principle of “prevention prior to remediation,” source control strategies were defined to minimize the interaction between water, atmospheric oxygen, and sulfide-bearing materials. Specifically, measures such as dry cover systems composed of compacted clay, geosynthetics, and recycled industrial materials, along with stratified encapsulation of acid-generating waste within neutralizing agents, were simulated using hydrogeochemical models. A laboratory-scale physical model was developed and implemented to validate the numerical predictions. The results showed that the combination of a 0.15 m thick dry cover and encapsulation process reduced oxygen ingress and AMD formation by up to 52%. Additionally, the pH of the leachate increased from 2.3 to 6.4, while iron and lead concentrations decreased by approximately 63% and 48%, respectively. These findings provide practical guidance for improving the environmental design and management of mine waste dumps and inform more effective strategies for protecting water resources and aquatic ecosystems in mining environments.

4.10. Impact of Rainfall Variability on Rainwater Harvesting Potential

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Depletion of water resources, triggered by population growth, climate change, and pollution, remains a serious threat to human well-being and ecosystems. Rainwater harvesting (RWH), known for its feasibility and sustainable environmental benefits, has emerged as a solution to this problem.

Standard traditional approaches to identify suitable RWH sites often rely on GIS-based Multi-Criteria Decision Analysis (MCDA) techniques, using proxy indicators such as slope, land use, drainage density, and runoff characteristics. While these approaches provide valuable pixel-based specific insights, they typically overlook the temporal variability of rainfall, which is a factor that plays a key role in determining the actual availability and reliability of the potential for harvesting water.

This study addresses this gap by focusing on the importance of rainfall variability in assessing RWH potential. By integrating long-term inter-annual spatial variability in temporal rainfall patterns into the evaluation framework, the method captures fluctuations in rainfall that affect both the quantity and time of water availability. The strategy is applied to the Upper Tiber River basin in central Italy, showing that addressing rainfall variability leads to more realistic and dynamic assessments of RWH potential.

Therefore, this study depicts how addressing year-to-year changes in rainfall significantly influences the performance and resilience of rainwater harvesting systems. This highlights the need for informed planning in water resource management, reinforcing the importance of adaptive and data-driven strategies.

4.11. Modern Hydrogeochemical Regime of Mesozoic Sediments Influenced by Oil and Gas Production in Western Siberia

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In Western Siberia, the modern hydrogeochemical conditions of Mesozoic sediments form under the influence of longstanding multidirectional processes associated with oil and gas production. On the one hand, this is the extraction of groundwater to maintain formation pressure in productive horizons, on the other hand, the injection of excess formation water into absorbing horizons. The accumulated volume of extracted groundwater for use in formation pressure maintenance systems exceeded 7.4 bln m³. The total volume of liquid injected into the absorbing horizon is 671 mln m³. The relevance of the study is justified by the need to understand the changes in the hydrogeochemical conditions of the Mesozoic hydrogeological basin due to significant man-made impact according to monitoring data.

The article discusses the results of long-term studies of the groundwater composition of the Apt-Albian-Cenomanian hydrogeological complex (AAC HC) of the West Siberian mega basin in oil fields (a total of 27 water intake sites and 19 injection sites). During the observation period (2011–2024), a significant amount of information was accumulated on the composition of formation waters of the Aptian-Albian-Cenomanian sediments at monitoring sites (more than 4700 samples).

Monitoring of AAC HC groundwater quality consists in sampling to determine the density of water, the content of the main macro- and micro components, and other parameters. Research methods include quality analysis of laboratory measurements of groundwater chemical composition; rejection of data that do not meet the criteria of reliability; characterization of the groundwater type according to existing genetic classifications.

The research found that the typical natural affiliation and chemical composition of the AAC HC waters remain close to the natural background, despite the significant man-made load.

4.12. Multi-Objective Optimization of Desalinated Water Allocation in Lake Kinneret: Ensuring Ecological and Economic Stability

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Introduction:

Lake Kinneret (Sea of Galilee) is Israel's main freshwater reservoir, providing critical resources for domestic, agricultural, and ecological needs. However, climate variability, increased demand, and recurrent droughts have reduced water levels, heightened salinity, and threatened ecosystem stability. To address these challenges, the Israeli government is integrating desalinated water into the national water supply system. However, such integration requires strategies that balance economic feasibility with ecological preservation.

Methods:

This study develops a multi-objective optimization model for managing desalinated water allocation into Lake Kinneret. The model minimizes operational costs while maintaining ecological health, represented through the stratification index (SI), a surrogate for thermal stability and nutrient cycling. The optimization was implemented in MATLAB R2024a using IPOPT and Ipsove solvers. Several management scenarios were tested, varying the timing and volume of desalinated water inputs in response to seasonal demand and hydrological conditions.

Results:

Model simulations demonstrate that desalinated water integration stabilizes lake levels and mitigates salinity impacts. Optimal strategies highlight trade-offs between economic and ecological goals. In particular, scenarios with desalinated water introduction during periods of weakened natural stratification (October–March) minimized ecological disruption while maintaining economic efficiency. Pareto-optimal solutions revealed strategies that maintain SI values without significantly increasing operational costs, providing a clear understanding of the balance between economic and ecological objectives.

Conclusions:

The results confirm that multi-objective optimization is a robust approach for managing desalinated water allocation in Lake Kinneret. By simultaneously addressing cost and ecological indicators, the model supports informed decision-making for policymakers. Strategic and dynamic integration of desalinated water ensures both economic viability and ecological sustainability, offering a transferable framework for other freshwater ecosystems under similar conditions.

4.13. Technogenic Impact on Groundwater of Deep Aquifers and Oil-Bearing Complexes of the West Siberian Megabasin

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Groundwater in the West Siberian mega basin (WSMB) has been exposed to long-term technogenic loads due to the exploitation of hydrocarbon deposits. The objective of the study was to systematize the types of technogenic impacts on deep horizons to the use of a reservoir pressure maintenance system (RPMS). Over the past 10 years alone, the volume of water selected from the Aptian-Albian-Cenomanian complex (AAC GC) for RPMS has amounted to 380 million m³.

Data on the key fields in the central part of the WSMB (17 fields) were systematized. The research methods included: collecting data on the start time of the use of the RPMS, analyzing water sources and sampling volumes for use in the RPMS and analyzing hydrogeochemical transformation.

We have identified 6 types of fields. The first type includes fields where only oil is produced without RPMS. The second type is associated with forced RPMS at fields where AAC GC waters are used as a flooding agent. The third type: fields where fresh water from the upper horizons is used in the RPMS. The environmental consequences here are associated with a drop in the level of the freshwater horizon and a slight increase in mineralization. The fourth type pertains to areas for the associated water in AAC GC. The fifth and sixth types are associated with the most loaded fields, where the RPMS operates with fresh or salt water from AAC GC, and associated and wastewater is utilized (Fedorovskoye, etc.). Long-term exploitation has led to the appearance of elevated petroleum products, bromides, chromium, lead, chlorides and boron in the freshwater horizons. But appearances are not widespread. Currently, monitoring is standard for all deposits. We propose the introduction of new hydrogeochemical criteria as indicators of transformation (for example, Cl/Br) considering the established type of techno genesis.

5. Extreme Hydro-Meteorological Events: Sources, Mitigation and Adaptation

5.1. Flood Discharge Optimization for Sutlej River Using CFD Simulations

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This study presents a flood-mitigation strategy for the Sutlej River basin, tested on a scaled-down channel model with dimensions validated through a field survey to obtain accurate channel and floodplain and a proportionally reduced inlet velocity. Staggered rows of passive triangular columns on the floodplain guide flow back into the main channel. A detailed 3D reach model was constructed in ANSYS Workbench and solved in Fluent under three scenarios—flow confined to the channel, overbank flow on the floodplain without structures, and flow on a floodplain fitted with triangular columns—using a fine tetrahedral mesh, a constant velocity inlet of 0.30 m/s, and a pressure-outlet condition. Quantitative results demonstrate that just two rows of columns reduce downstream peak velocity by 20% (from 0.30 m/s to 0.24 m/s) and lower specific energy by 36% (from 0.00459 m to 0.00294 m), confirming effective dissipation of flow energy. Streamline analysis indicates flow convergence toward the channel center as pressure builds upstream of the columns, thereby enhancing central alignment and preventing excessive lateral spread across the floodplain. Observed lateral inundation extent is substantially curtailed compared to the unmodified case, while upstream water levels remain stable with negligible backwater effects. These quantitative benchmarks confirm that passive triangular column arrays outperform conventional overbank measures by redirecting flow momentum into the main channel and preserving hydraulic stability.

5.2. A Spatiotemporal Analysis of Extreme Minimum Temperatures in Portugal (1980–2024) Using Severity Heatmaps

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Rising nighttime temperatures, particularly ‘tropical nights’ where minimum temperatures (Tmin) exceed 20 °C, pose increasing public health risks by limiting nocturnal cooling. A comprehensive assessment of extreme Tmin trends across mainland Portugal was conducted for the 44-year period from 1980 to 2024, with a focus on changes in both the frequency and intensity of nighttime heat. High-resolution ERA5-Land reanalysis data (1012 grid-points) were employed to compare two 22-year subperiods (1980–2002 and 2002–2024), with extreme Tmin events defined using the 99th (Q99 = 21.75 °C) and 99.9th (Q99.9 = 24.41 °C) percentiles. Two key metrics were calculated: the Frequency of Extreme Tmin (FET), representing event occurrence, and the Tmin Anomaly Percentage (TAP), representing event intensity. These metrics were integrated into severity heatmaps, which classify each grid-point into four categories based on whether the most recent period shows an increase relative to the early period: (i) concurrent increase in both FET and TAP, (ii) increase in FET only, (iii) increase in TAP only, and (iv) no significant increase in either metric. This classification facilitates the identification of areas experiencing the most pronounced intensification of nighttime heat. The results reveal a substantial increase in nighttime heat, particularly across southern Portugal, where exceedances of the

Q99 threshold have increased by up to 45%. Additionally, TAP values indicate that extreme Tmin events have become, on average, 1.8 °C hotter in the recent period (2002–2024). These findings provide relevant insights for public health and urban adaptation planning, while the severity heatmaps present a transferable tool for risk assessment applicable to other Southern European regions experiencing similar climate pressures.

5.3. Multi-Scale Hydro-Meteorological Assessment of Extreme Flooding Events: The Case of Bangladesh's Eastern Deltaic Region

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Flash flooding in Bangladesh's eastern and southeastern deltaic districts, including Feni, Cumilla, Brahmanbaria, Chattogram, Khagrachhari, Noakhali, Lakshmipur, Moulvibazar, Habiganj, Sylhet, and Cox's Bazar, during August 2024, left nearly 5.7 million people affected and at least 23 dead. Using the HEC-HMS hydrological model and discharge data from four stations (SW110, SW212, SW334, and SW84.1), the events were simulated with satisfactory accuracy, with Nash-Sutcliffe efficiency values of 0.65–0.75 and percent bias between +2% and –10%. Meteorological analysis indicates that the disaster was triggered by extreme cloud concentration and convective cloudbursts, driven by the interaction of cold air masses from the west, a Bay of Bengal low-pressure system, and an intensified monsoon trough. These conditions produced 180–610 mm of rainfall within 3–4 days, while Tripura's steep topography accelerated runoff into downstream Bangladesh. Simultaneously, the full moon on 19 August coincided with spring tides in the Bay of Bengal, causing exceptionally high sea levels that delayed the drainage of floodwaters into the ocean, confirmed by the Delft3D model. Historical patterns show that when floods occur around new or full moon phases, tidal surges slow river discharge, intensifying inundation and prolonging flood duration. Although water release from India's Dumbor Dam on the Gomti River occurred at the same time, the modeling results indicate that natural hydro-meteorological drivers were dominant, while the dam's contribution was negligible. However, the absence of early transboundary communication aggravated the crisis. The disaster devastated croplands, housing, and transport infrastructure, while government agencies, the armed forces, and volunteers mobilized coordinated relief operations. Neighboring Tripura also experienced parallel impacts, with 350–375 mm of rainfall recorded in South Tripura and Gomati. This study shows how cloud cover, geomorphology, and tides together intensify flash floods, highlighting the need for better early warnings, tidal-hydrology integration in forecasts, and stronger transboundary water governance.

5.4. Optimizing Pooling Regions for Rainfall Frequency Analysis Using Genetic Algorithms in Complex Networks

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Extreme precipitation events have significant environmental and societal impacts. Frequency analysis of such extremes is challenging due to the high spatial and temporal variability of rainfall and sparse gauge coverage. Conventional regionalization methods address this by grouping gauges into homogeneous regions and applying the index flood

method, which assumes stations in the same region share a common distribution scaled by local indices. Although widely used, this method faces challenges in clustering, as grouping by geographic proximity alone may overlook important statistical similarities in rainfall extremes. In this study, we introduce a network-based framework to define pooling regions for regional frequency analysis of daily annual maximum rainfall in the region of Thessaly, Greece. First, we build a weighted adjacency matrix representing the Euclidean distances between all pairs of gauges using four widely available physical covariates: latitude, longitude, elevation, and mean annual precipitation. The decision of whether two nodes should be connected is determined by a genetic algorithm, which optimizes a cost function designed to capture global network characteristics. The network communities are identified using the Walktrap algorithm, which analyzes short random walks that tend to remain within the same community. For comparison, we construct a second network in which connections are based on both spatial proximity (latitude, longitude) and statistical similarity expressed with L-moments. Our comparison shows that the physically based method produces larger regions that are more heterogeneous. On the contrary, the statistically informed method identifies smaller, more fragmented homogeneous regions. Notably, the physical clustering fails to achieve an optimal partition, meaning it does not group all stations into homogeneous regions. These differences emphasize the need to understand why rainfall extremes behave differently statistically than their physical locations suggest. This understanding will lead to more robust estimates of extreme rainfall.

5.5. Assessing the Impact of the 2024 Valencia Cut-Off Low on Urban Mobility: Patterns, Routes, and Reconstruction Challenges

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On 29 October 2024, the province of Valencia (Spain) experienced an exceptionally intense Depresión Aislada en Niveles Altos (DANA), during which up to 771 mm of rain fell in 24 h, including a national record of 184.6 mm in a single hour, triggering catastrophic flooding that claimed 227 lives and severely damaged critical infrastructure. This study analyses the impact of the event on urban and interurban mobility in the Valencia metropolitan area, focusing on disruptions caused by road network failures and collapsed bridges. We use anonymized mobile-phone-based travel data (2022–2025) from the Spanish Ministry of Transport to construct and compare origin–destination (OD) matrices before and after the event. Complementarily, we employ an Open Source Routing Machine (OSRM) to model typical travel routes under changing infrastructure conditions. Our results show a statistically significant decline in trips involving the southern municipalities, the most affected—during the week following the flood, with gradual recovery over the subsequent five months, reflecting the pace of reconstruction. Route modelling reveals increases of 39% in average travel distance and 55% in duration due to key bridge closures. Furthermore, the analysis of reconstruction timelines exposes marked differences in response efficiency among national, regional, and provincial infrastructure authorities. These findings underscore the vulnerability of mobility systems to climate-induced disruptions and point to critical areas for improvement. We recommend that metropolitan areas prioritize the design of resilient transport infrastructure, including redundant river crossings to prevent total network collapse during floods. Additionally, integrating real-time flood alerts into public navigation systems could improve commuter response, and the establishment of unified crisis coordination bodies may help reduce delays in post-disaster recovery. By documenting the cascading effects of extreme weather events on daily travel, this research offers practical guidance for more adaptive urban planning and governance in the face of accelerating climate risks.

5.6. Assessing the Impacts of Climate-Induced Droughts on Vegetation in Mirpurkhas Division, Sindh: A Spatio-Temporal Analysis

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Drought is one of the most acute environmental issues in the arid and semi-arid regions, especially under the impact of climate variability. This study aims to assess the impacts of climate-induced droughts on the health of the vegetation during the years 1991–2021 within the spatio-temporal Mirpurkhas Division of Sindh. The SPEI was conducted to determine the main drought years and the magnitude of drought occurrences, whereas satellite-based vegetation indices, Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Difference Vegetation Index (DVI) were used to describe the vegetation dynamics. The analysis has been carried out at four illustrative years that are chosen on a decadal basis, that being 1991, 2001, 2011, and 2021. The SPEI findings show the years 1991, 2001, and 2021 were established as severe drought years when the climatic water balance was negative. Although the year 2011 was not characterized as a severe year of drought according to SPEI, it was included so as to compare the post-drought vegetative responses as well as to obtain decadal compositions. In 1991 and 2001, there was significant stress, especially in the region of Tharparkar and southern Mirpurkhas, where most of the vegetation was sparse and degraded. Localized resilience manifested as moderate recovery in Umerkot and Sanghar in 2011. In 2021, there was a combination of recovery and ongoing stress, where moderate-vegetation-dense areas expanded in terms of moderate to dense vegetation, whereas Tharparkar continued being vulnerable. In general, the findings show a strong relationship between the severity of drought and vegetation degradation, and the process is determined by a combination of climatic factors and the given interventions by human beings towards the irrigation activities and the use of the land. Integrated applications of SPEI, NDVI, EVI, and DVI offers in-depth knowledge regarding the effects of drought and vegetation dynamics to enable sustainable management of resources and climate adaptation plans in the region.

5.7. Assessment of Future Precipitation Patterns in Greece Using ETCCDI Climate Indices

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Extreme hydroclimatic events are expected to increase in intensity, frequency, and duration, with droughts posing a major threat to Mediterranean countries. In regions such as Greece, the anticipated reduction in water availability may have significant impacts on critical economic sectors. This study investigates the effects of climate change on the hydrological regime of Greece over the period 1971–2100. To this end, high-resolution regional climate simulations were employed under two Representative Concentration Pathways (RCPs): the moderate-emissions scenario RCP4.5 and the high-emissions scenario RCP8.5. Twelve precipitation-related indices from the Expert Team on Climate Change Detection and Indices (ETCCDI) were calculated annually for 58 meteorological stations across the country. Long-term trends were assessed using Sen's Slope estimator, and projected percentage changes were computed for the end of the 21st century. Our results indicate a clear trend toward drier conditions across most of Greece. The most substantial reductions in total precipitation were observed in mountainous western areas, while

lowland regions showed notable increases in consecutive dry days. By 2100, mean annual precipitation (PrcpTOT) is projected to decline by approximately 12% under RCP4.5 and 29% under RCP8.5. Consecutive dry days (CDD) are expected to increase by 12% and 40%, respectively. Furthermore, indices representing the percentage of total precipitation from very wet (R95pTOT) and extremely wet days (R99pTOT) reveal a growing contribution of extreme rainfall events, particularly in the northern and western mainland, as well as the North Aegean islands. This study combines high-resolution projections with multiple precipitation indices, providing a comprehensive assessment of long-term hydroclimatic conditions in Greece. However, uncertainties remain due to limitations in climate models, especially in precipitation modelling, which may affect the precision of local-scale projections. Overall, these findings highlight the increasing variability and severity of future hydroclimatic extremes in Greece, emphasizing the urgent need for effective mitigation and adaptation strategies to address climate change.

5.8. Characterisation of Recent Climate Extremes in Mainland Portugal Using ETCCDI Indices and Validated ERA5-Land Data

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To address the need for updated climate analysis in Portugal, spatiotemporal trends in climate extremes from 1980 to 2023 were studied, overcoming the limitations of outdated observational datasets. The high-resolution ERA5-Land reanalysis dataset was used, having first been validated against gap-filled observational records from a Portuguese water resources data system. Eighteen core indices from the Expert Team on Climate Change Detection and Indices (ETCCDI)—nine related to temperature and nine to precipitation—were calculated using daily data for 1004 grid points. Monotonic trends in the annual indices were identified using the non-parametric Mann–Kendall test, with magnitudes quantified by Sen’s slope estimator. The trend analysis revealed significant and widespread warming. Statistically significant increasing trends were observed for indices related to warm extremes, such as tropical nights (TR) and warm days (TX90p), particularly in southern and interior regions, while a decrease in cold extremes was noted. Precipitation trends were found to be more spatially varied, although a notable increase in consecutive dry days (CDD) is evident across the country, especially in the south, alongside a general decreasing trend in consecutive wet days (CWD). A comprehensive, high-resolution assessment of recent changes in climate extremes across Portugal is thus provided, offering critical evidence to inform targeted regional adaptation strategies, improve water resource management, and support national climate resilience actions. Future research should include climate change scenarios to identify projected changes, using recent historical data—such as that employed in this study—as a robust baseline for comparison.

5.9. Drought Assessment in the Portaikos Mountainous Watershed (Thessaly, Greece) Using Ground-Based and Reanalysis Data

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Accurate drought assessment and monitoring in ecologically sensitive and data-scarce mountainous watersheds is crucial for sustainable water resource management under climate change. This study investigates drought variability in the Portaikos watershed (Thessaly, Central Greece) using the Standardized Precipitation Index (SPI), a widely applied drought index, at multiple timescales (12-month and 6-month wet and dry seasons). Calculations were performed from two long-term ground stations, Stournareika (1959–2017) and Elati (1949–2017), and compared with SPI values derived from ERA5-Land, a high-resolution global reanalysis dataset. In Stournareika, the 12-month SPI revealed extreme droughts in 1991–1992 (SPI = −3.29) and 2006–2007 (SPI = −2.48). ERA5-Land detected the 2006–2007 event and another in 2000–2001, while downgrading the 1991–1992 drought to severe. Agreement in drought class between ground and ERA5 data was 45% overall, with ERA5 showing wetter conditions in 25% of years and drier conditions in 30%. Agreement rose to 55% in the wet season (October–March) but dropped to 28% in the dry season (April–September), suggesting that ERA5 performs better under wetter conditions. In Elati, the 2006–2007 drought appeared only moderate based on 12-month SPI, while ground data highlighted multiple severe to extreme events between 1960 and 2004. ERA5 classifications matched 33% of years, while 31% appeared wetter and 36% drier. The 6-month SPI confirmed similar discrepancies, with reduced ERA5 performance likely influenced by its coarser resolution and local topographic effects in this high-relief watershed. These findings highlight the strong spatial variability of drought signals and the limitations of reanalysis data in complex terrains. Nonetheless, ERA5 remains a valuable resource where ground observations are lacking, provided its uncertainties are acknowledged. Importantly, the results align with broader evidence of intensifying and spatially heterogeneous droughts across the Mediterranean region.

5.10. Drought Vulnerability Assessment in the Sindh Province, Pakistan, Using Multicriteria Decision Analysis (MCDA) Technique

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Drought is a recurring environmental hazard that significantly impacts agricultural productivity and ecosystem stability. This study assesses drought vulnerability in Mirpurkhas Division, Sindh, Pakistan, in March 2021 using the Analytical Hierarchy Process (AHP) model. The analysis incorporates 11 parameters: rainfall, Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), Land Surface Temperature (LST), Moisture Stress (I), elevation, slope, soil type, Topographic Wetness Index (TWI), Land Use/Land Cover (LULC), and population density (PD). The Standardized Precipitation Evapotranspiration Index (SPEI) was applied to climate data from 2021, revealing that March was among the months that were affected by drought conditions. Subsequently, Landsat imagery from March 2021 was integrated into a Geographic Information System (GIS)-based AHP framework to generate a drought vulnerability map. This approach enabled the spatial evaluation of drought-prone areas by combining remote sensing data with multi-criteria decision analysis. The result reveals that about 2.9% of the study area experienced no drought, 19.1% was affected by low levels of drought, 40.2% by moderate drought, 21.1% by severe drought, and 16.6% by extreme drought. These findings highlight significant drought vulnerability within the Mirpurkhas Division. The resulting model showed a high performance level, with a Kappa coefficient of 0.921. This high correlation

of the predicted and observed drought vulnerability classes indicates the reliability of the model. The resulting vulnerability map can assist policymakers and administrators in the design and implementation of effective drought mitigation strategies, thus mitigating possible drought-related effects.

5.11. *Extreme Storm Surge Events and the Deposition of Plastic Pellets on Beaches of Todos Os Santos Bay, Bahia, Brazil*

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Extreme positive storm surge events, often followed by storms, are referred to as storm surges. In Brazil, the informal term *ressaca* is commonly used to describe these events. The occurrence of *ressacas* in coastal regions can lead to flooding, destruction of urban infrastructure, and beach erosion. Coastal erosion is a natural process resulting from a negative sediment balance, leading to beach narrowing, habitat degradation or loss, increased frequency and intensity of *ressacas*, destruction of man-made structures, and the decline of tourism potential. Between June and September of 2023, fieldwork was conducted to assess the presence of plastic pellets on beaches within the Todos os Santos Bay/Bahia. This assessment involved the observation of beach morpho dynamics, the presence of ordinary and recent storm surge strandlines, and the identification of preserved strandlines that had not been subjected to anthropogenic disturbances—such as beach cleaning via tractor or rake, recreational activities, or boat traffic. Following these observations, sand samples containing pellets were collected from two specific zones: the Current Strandline Zone (ZDD), typically associated with the swash zone, and the Post-Storm Strandline Zone (ZDPP), often linked to the most recent high-energy storm surge events. Across the eight beaches studied, 74 sampling points were marked, and a total of 203 pellets were found. Most of these pellets were located in the higher beach zones, i.e., within the ZDPP. These findings indicate that extreme storm surge events are the primary drivers of plastic pellet distribution on beaches.

5.12. *Numerical Study of the Effectiveness of Water-Filled Canals for Reducing Tsunami-Induced Forces on a Nearshore Structure*

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Catastrophic tsunami events, such as the 2004 Indian Ocean and 2011 Tohoku Tsunamis, have highlighted the vulnerability of coastal infrastructure and the urgent need for effective mitigation strategies. Among various countermeasures, water-filled canals have been proposed as an effective approach for reducing tsunami-induced forces on structures located near affected shorelines. Although a limited number of field observations, experimental studies, and numerical simulations have demonstrated the potential of canals to dissipate tsunami bore energy, further research is needed to understand better the detailed interactions between tsunami bores and water-filled canals. This study presents the results of a series of numerical simulations calibrated and validated with experimental results to evaluate the effectiveness of rectangular water-filled canals in mitigating the

horizontal force exerted by a tsunami-like bore on a vertical column located behind the canal. The simulations were conducted at a prototype scale using FLOW-3D, a well-known CFD tool known for its ability to model complex free-surface flows and fluid-structure interactions. A dam-break method was used to generate a tsunami-like bore that propagated along a dry horizontal bed, crossed over a water-filled canal, and impacted a square column. The analysis focused on bore hydrodynamics, the time history of the force, and bore interactions with the canal and column. Results show that canal geometry plays a critical role in reducing bore front velocity and the resulting impact force on the column. For a canal with a depth of 4.5 m and width of 40 m, the maximum horizontal force exerted onto the column was reduced by up to 40%. These findings demonstrate that well-designed water-filled canals have the potential to serve as effective tsunami mitigation countermeasures and that proper design of such a canal geometry is essential for optimizing its performance.

5.13. Probabilistic Modeling of Drought Effects on Maize Yield in Basilicata, Italy: Impacts of Shifting Planting Dates and Irrigation Regimes as Adaptation Strategies

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Climate change is amplifying drought frequency and severity across the Mediterranean, threatening agricultural water supply and food security. Low-cost, locally adaptable strategies, such as shifting planting dates and adjusting irrigation regimes, are essential for mitigating climate risks. This study evaluates maize yield loss risk under various drought conditions in the provinces of Matera and Potenza in the Basilicata region in southern Italy and assesses two adaptation strategies: planting date shifts (early, mid, late) and irrigation levels (full irrigation, 75%, 50%, 25% deficit irrigation, and rainfed).

Copula-based bivariate statistical models were developed to capture the dependence between drought severity and yield loss. Yield losses were estimated from simulated yields for different planting dates combined with irrigation levels using a calibrated CSM-CERES-Maize model, initialized with weather (1991–2023), soil, and management data. Marginal distributions for yield loss and drought indices were fitted, and copula functions were used to model their joint distribution, allowing estimation of conditional probabilities of yield loss across drought categories (moderate to exceptional).

Results indicate that under rainfed conditions, both provinces face a very high likelihood of yield losses ranging from 1.5 to 3.5 MT ha^{−1}. While irrigation reduced losses, Matera still showed a considerable probability of reductions (0.5–1 MT ha^{−1}), even under full irrigation. Potenza exhibited comparatively lower probabilities, particularly when late planting was combined with deficit irrigation (75–50%), with losses often remaining below 0.5 MT ha^{−1}. This suggests that late planting effectively enhances resilience in Potenza, whereas Matera may require additional adaptation measures beyond irrigation schemes.

Coupling crop simulation with copula-based probabilistic modeling provides a robust decision-support tool to assess drought-induced yield risks. The findings emphasize the need for location-specific adaptation planning to strengthen agricultural resilience under escalating drought pressures.

5.14. Spatio-Temporal Dynamics of Rapid Drought-to-Wet Transitions in Thessaly, Greece (1990–2024)

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This study fills a significant knowledge gap in hydroclimatic studies by exploring rapid transition from droughts to wet conditions—an influential yet incompletely known process. Instead of viewing wet events and droughts as separate extremes, it highlights the shift dynamics that characterize hydroclimatic variability in Thessaly, Greece, a significant cropland region. Using ERA5-Land soil moisture data at 0.1° (~9 km) spatial resolution and pentad (five-day) time resolution for the period of 1990–2024 this analysis focuses on developing the temporal and geographical pattern of shift from droughts to wet events. Four diagnostic indexes were used: duration (length of transition), change (magnitude of increase of soil moisture), intensity (rate of change per pentad), and peak (maximum soil moisture reached during transition). Spatially, the longest transitions, up to 17 pentads (~85 days), are located in central and east Thessaly, while the strongest moisture recoveries (change up to 72%) and greatest intensities remain mostly in the west and north. Seasonally, most of the transitions occur from late spring to mid-summer, and with May to July being the period of peak events, marking the usual end of drought events in the region. The statistical analysis also shows a strong significant negative correlation between duration and intensity ($r = -0.82$), implying that shorter-length transitions are more intense and abrupt. In contrast, the positive correlation between change and peak ($r = 0.53$) associates larger moisture recoveries correspond to greater wet extremes. These findings provide an integrated view of the temporal and spatial development of sudden hydroclimatic shifts and potential practical applications for optimizing irrigation scheduling, creating early warning systems, and improving adaptive water management strategies in Mediterranean farming conditions with respect to climate change.

6. Ecohydrological Approaches and Ecosystems Conservancy

6.1. Water Transparency Boundaries Assisting the Ecohydrological Management of Greek Natural Lakes

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It is widely known that water transparency is a simple but efficient indicator to monitor Mediterranean lakes, as it is strongly related to frequent disturbances/stressors occurring in this climatic region, namely, intense warm periods, eutrophication, hydrological modifications and extended draught related to climatic variability. Twenty years ago, the Water Framework Directive (WFD) demanded from European Member States the establishment of physico-chemical thresholds for natural waterbodies. Our aim is to define water transparency boundaries for Greek natural shallow and deep lakes to assist water management and support the WFD good water quality goal. For this attempt, the official lake monitoring timeseries (period: 2013–2020, lakes: 8 shallow and 7 deep) of Secchi Depth (SD) and ecological quality ratios (expressed by all biological quality elements) were used. These were processed according to the “Best Practice Guide” utilizing the Shiny application (JRC) coupled with mixed statistical modeling (e.g., different types of linear regressions, box-plots, binary logistic regression). The results reflect the lake functioning

and the multiplicity of pressures; thus, for shallow polymictic lakes, whose majority fails to achieve good ecological status, the proposed SD Good/Moderate boundary is stricter, while for the warm deep monomictic lakes with a better status, the boundary depicts the tolerance these waterbodies have. These findings are crucial tools for linking policy objectives to management actions, ultimately assisting restoration. The designation of data-driven boundaries for both shallow and deep Greek natural lakes offer multiple benefits. High-frequency SD measurements can assist in tracking water transparency and trophic status, perform as bloom warning systems, act as a proxy for hydrological parameters (i.e., residence time, flushing rate), monitor restoration projects' efficiency, capture the trend of climate change impact and guide lake management actions related to water uses (i.e., fisheries, tourism, recreation), while enabling local communities' stewardship (via citizen science campaigns).

6.2. *Assessing the Potential of Biomass Hydrothermal Liquefaction Hydrochar for Soil Amendment: Chemical/Physical Characterization and Water Holding Capacity and Retention*

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Extensive research has investigated biochar from pyrolysis and hydrothermal carbonization (HTC) for soil amendment, yet hydrochar produced via hydrothermal liquefaction (HTL) has received limited attention. This study addresses this gap by evaluating the potential of HTL hydrochar, derived from corn stover at 280 °C, as a soil amendment to enhance agricultural sustainability. The hydrochar was characterized by using advanced analytical techniques to examine its functional groups, morphology, and specific surface area. Results revealed a BET surface area of 27.6 m²/g, with particles forming micro-sized stacks of nanometer-thick foliates, indicating a unique structural composition suitable for soil applications. When applied to sandy loam soil, the HTL hydrochar significantly improved water holding capacity (WHC), achieving 50–55% compared to 48% in unamended soil. This enhancement was consistent, with improved water retention observed over a four-day period, suggesting its potential to support crops in water-scarce environments. Additionally, the hydrochar demonstrated remarkable resistance to biodegradation, showing no significant degradation over 106 days in moist soil at ambient temperature. This stability enhances its long-term efficacy as a soil amendment. These findings highlight HTL hydrochar's underexplored benefits, including improved soil water management and support for sustainable agricultural practices. By addressing the research gap on HTL hydrochar, this study underscores its potential to contribute to ecohydrology and agricultural water systems, offering a sustainable solution for enhancing soil health, water retention, and crop productivity in farming systems facing environmental challenges. Further research could expand its applications in diverse soil types and climates.

6.3. *Bio-Ilhas Project: Science, Education, and Awareness for River Conservation*

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Under the scope of the Bio-Ilhas project, a pilot floating island was installed in the urban section of the Fervença River (Bragança, NE Portugal—latitude: 41°47' N; longitude 6°46' W) for scientific and educational purposes. This river section was chosen for the implementation of this nature-based solution because it is highly regulated, eutrophicated, and has a concrete embankment on the left bank, preventing vegetation establishment. The installed island consists of two square floating matrices of 4 m² (each 2 × 2 m), one made of recycled expanded polystyrene and the other of cork agglomerate. The plants selected for this structure were *Lythrum salicaria*, *Juncus effusus*, and *Iris pseudacorus*, chosen because they are autochthonous in the river. The main objectives of this project are: (1) to assess the feasibility of this solution for future rehabilitation efforts and biodiversity enhancement, and (2) to promote public literacy and awareness about rivers and their ecological value. Therefore, the project includes scientific monitoring of water quality and vegetation development, alongside educational initiatives aimed at schools and the local community. These include workshops, guided visits, and informative materials to foster environmental awareness and encourage public involvement. This communication presents the key scientific and educational activities carried out to date, while also addressing the challenges of a project that integrates science, education, and environmental awareness as a model for future urban river management. The Bio-Ilhas project also aims to demonstrate the potential of nature-based solutions to improve urban aquatic ecosystems and strengthen the connection between society and rivers.

6.4. Evaluating Trophic State of Lakes in Cold and Arid Zones: An Integrated Approach Based on Neural Networks and Genetic Algorithms

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To investigate the nutritional status and spatiotemporal variations of Ulansuhai Lake—a typical lake in a cold and arid region—monitoring data from January and June 2019 were utilized to develop three evaluation models, a BP neural network model, a genetic algorithm-based Shepard similarity model, and a logistic curve model, for simulating and analyzing the eutrophication level of the lake. The results revealed that according to the BP neural network model, the lake was predominantly severely eutrophic during both ice-covered and ice-free periods, accounting for 80% and 55% of the nutritional state evaluations, respectively; the Shepard similarity model indicated that the lake was mainly moderately eutrophic during the ice-covered period and eutrophic during the ice-free period, representing 55% and 70% of the assessments, respectively; and the logistic curve model suggested that the lake was primarily moderately eutrophic in both periods, comprising 55% and 75% of the evaluations for the ice-covered and ice-free phases, respectively. Furthermore, during the ice-free period, all three models consistently demonstrated that eutrophication was more severe in the central–northern part of the lake and decreased gradiently from north to south, whereas no significant spatial trend in eutrophication was observed during the ice-covered period. These findings underscore the importance of adopting season-specific and spatially targeted eutrophication control strategies to improve water quality management and guide policy-making in cold and arid lacustrine environments.

6.5. Integrating Multidimensional Frameworks and Management Strategies for Sustainable Water Security: Insights from Assessment, Indicators, and Policy Approaches

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Water security faces escalating threats from both natural and anthropogenic pressures, including scarcity, pollution, climate change, disasters, and conflicts, with an increasing share of the global population—particularly in China—experiencing acute shortages. Rising population, economic development, and agricultural expansion intensify water demand, while untreated wastewater and agricultural pollutants exacerbate quality concerns, highlighting the intertwined challenges of water quantity and quality. To address these issues, this study provides a comprehensive review of current water security research. Our methodology involved a systematic synthesis of peer-reviewed literature, structured around four key themes: (1) assessment frameworks, (2) core indicators, (3) analytical methods, and (4) management strategies. This thematic analysis was designed to map the evolution of these tools, identify persistent research gaps, and inform pathways toward sustainable governance. The results, directly linked to our analytical framework, reveal a clear trend in assessment frameworks toward multidimensional, resilience-oriented approaches that integrate water quantity, quality, accessibility, ecological needs, and socioeconomic factors. Our review of analytical methods and indicators confirms the widespread application of tools such as DPSIR-based models, hierarchical systems like the Water Security Index, water footprint metrics, and hydrological models (e.g., SWAT, VIC) for evaluating water stress and supply–demand balances. However, our synthesis also highlights that these tools often struggle to capture complex causal dynamics, spatiotemporal variability, and critical water–society–ecology interconnections. Finally, the analysis of management strategies underscores the importance of combining technological, institutional, and governance measures—from traditional practices to adaptive urban management—to secure long-term water access under future pressures. Overall, by systematically mapping the applied tools and their limitations, this study underscores the need for holistic, context-sensitive, and forward-looking approaches to enhance water security at local, regional, and global scales.

6.6. Macrophyte Depth Distribution in Relation to Carbon and Nitrogen Isotope Signatures ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) of Bulk Organic Matter in Lakes of Northern Poland

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Submerged macrophytes play a key role in freshwater ecosystems by influencing carbon and nitrogen cycling. Stable isotope analyses ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$) of macrophyte bulk organic matter provide valuable insights into the biogeochemical processes shaping these cycles. We investigated the isotopic signatures of vascular macrophytes (elodeids) and macroscopic green algae (charophytes) across lakes differing in depth and mixing regimes. A general trend of ^{12}C enrichment in macrophyte organic matter with increasing depth was observed, consistent for both elodeids and charophytes. This pattern was less pronounced in lakes with limited depth gradients, where mixing likely homogenized the availability of inorganic carbon sources. Nitrogen isotopic signals were more variable: *Elodea canadensis* in Lake Czyste and *Stuckenia pectinata* in Lake Borzyszkowskie showed increasing $\delta^{15}\text{N}$ with depth, whereas *Nitella flexilis* in Lake Czyste exhibited the opposite trend. In Lake Dymno, *S. pectinata* displayed no clear depth-related pattern for $\delta^{15}\text{N}$, underscoring species-specific and lake-specific responses. To identify the environmental drivers of isotopic variability, we applied multivariate analyses. Principal Component Analysis indicated that depth played a crucial role for $\delta^{13}\text{C}$, while $\delta^{15}\text{N}$ was most strongly correlated with Ca^{2+} , pH, and conductivity, parameters typically associated with hardwater lakes. Variation partitioning analysis further showed that water chemistry variables (pH, Ca^{2+} concentration) explained 30% of the total variation, environmental variables (depth, photosynthetically active radiation) explained 9%, whereas nutrient-related parameters

(total nitrogen and total phosphorus) explained only 3% of measurable variation. Our findings demonstrate that physical processes predominantly influence $\delta^{13}\text{C}$, whereas $\delta^{15}\text{N}$ variability reflects chemical conditions related to lake hardness and redox processes, thus enhancing nitrification or denitrification processes. These results highlight the complexity of isotopic responses in submerged macrophytes and the need for further research into the environmental mechanisms controlling isotopic signatures in freshwater ecosystems.

6.7. Metallicity-Sorted Single-Walled Carbon Nanotubes for Water Treatment

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Single-walled carbon nanotubes (SWCNTs) include metallic and semiconducting conductivity types, which depend on their chirality. Metallicity-sorted SWCNTs are promising for water treatment. The aim of this work was the preparation of metallicity-sorted SWCNTs and the investigation of their electronic properties. The preparation procedure of the metallicity-sorted SWCNTs included density gradient ultracentrifugation of the arc-discharge SWCNTs, with a diameter of 1.4 nm. We analyzed the sorted samples by optical absorption spectroscopy and revealed that the sorted fractions of the metallic and semiconducting SWCNTs had high purity. In the metallic fraction, no absorption bands of the semiconducting SWCNTs were observed. In the semiconducting fraction, no traces of the metallic SWCNTs were revealed. The sorted SWCNT fractions were characterized by Raman spectroscopy with laser wavelengths of 458–568 nm (for the semiconducting SWCNTs) and 633 and 647 nm (for the metallic SWCNTs). The high purity of the sorted SWCNTs was proven. The sorted SWCNTs were studied by X-ray photoelectron spectroscopy and ultraviolet photoelectron spectroscopy. The C 1s peaks of the metallic and semiconducting SWCNTs had different positions and exhibited asymmetry. The peaks of van Hove singularities were revealed in the valence band spectra of the sorted SWCNTs. The obtained data on the electronic properties of the metallicity-sorted SWCNTs are required for water treatment applications.

6.8. Single-Walled Carbon Nanotubes Filled with Iron Chloride

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Single-walled carbon nanotubes (SWCNTs) possess outstanding properties for water treatment applications. The properties of SWCNTs are improved through functionalization. Filling of the SWCNTs allows them to be functionalized with different substances. The substances have various properties to achieve modified SWCNTs with the required characteristics. The properties of the encapsulated substances, such as the melting temperature and their work function, are varied. The properties of the SWCNTs are chosen, too. Among them are the diameter, metallicity type (metallic and semiconducting SWCNTs), and ionization potential of the SWCNTs. In this work, we filled 1.4 nm diameter metallicity-mixed SWCNTs with iron chloride (FeCl_2). The novelty of this work is the chemical nature of the filled substance. Iron chloride is a 3D metal chloride with unique properties. The aim of this work was to investigate the electronic characteristics of iron chloride-filled SWCNTs, such as doping and the Fermi-level variation, which are important for the improvement of water treatment applications of SWCNTs. We showed that iron chloride was a strong p-doping substance, which caused a Fermi-level variation of -0.43 eV. The data obtained on the electronic characteristics of the iron chloride-filled SWCNTs are important for water treatment applications.

7. Remote Sensing, Artificial Intelligence and New Technologies in Water Sciences

7.1. Two-Dimensional Convolutional Neural Networks for Watershed Modeling: Parameter Estimation and Transfer Learning Across Watersheds

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Accurate parameter estimation is critical to the reliability of process-based hydrologic and water quality models such as the Soil and Water Assessment Tool (SWAT). These models are extensively used to simulate watershed responses to changes in land use, management practices, and climate conditions. This study presents a deep learning-based workflow that leverages two-dimensional Convolutional Neural Networks (2D CNNs) for inverse modeling and parameter estimation within the SWAT framework. The approach was applied to the East Fork Shoal Creek (EFS) watershed, a subbasin of the Kaskaskia River watershed in Illinois, USA. CNN models were trained on large datasets of SWAT-simulated watershed outputs—including streamflow, sediment, total nitrogen, and total phosphorus—generated through Sobol sampling of parameter combinations. A comprehensive hyperparameter tuning process was conducted, examining variations in filter size, kernel size, pool strategy, learning rate, dropout rate, number of epochs, and batch size. The resulting CNN architectures were optimized to simulate all key watershed responses effectively, capturing complex spatial and temporal dynamics. The CNN-based approach achieved predictive accuracy comparable to or better than conventional tools like SWAT-CUP, with the EFS-CNN showing strong KGE (0.52–0.80) and PBIAS (5.09–26.72) across flow, sediment, nitrogen, and phosphorus. Transfer learning was effective, as EFS-trained CNNs performed equally well on the neighboring Lost Creek watershed within the Kaskaskia River basin. These findings underscore the potential of deep learning techniques to improve parameter estimation, facilitate efficient model transferability in watershed modeling, and help mitigate equifinality. The proposed approach significantly reduces computational demands and improves scalability, offering a robust pathway for advancing process-based hydrologic modeling in data-rich and regional-scale applications.

7.2. A Scalable Automated Framework for Multi-Year Landsat Surface Reflectance Mosaicking and Spectral Index Derivation Using Google Earth Engine for Environmental Monitoring

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This study presents an automated and robust framework for multi-year processing of Landsat satellite imagery to generate seamless mosaics and derive key spectral indices for environmental monitoring. The approach dynamically selects applicable Landsat sensors and image collections based on acquisition year, differentiating between Landsat TM (pre-2012) and Landsat OLI (post-2012) datasets. The methodology prioritizes image selection near a target date in the dry season (15 February), applying a cloud cover threshold of 10% to minimize atmospheric interference and temporal inconsistency among path/row tiles. Using Google Earth Engine, the framework filters and scales surface reflectance bands, then identifies unique Landsat path/row tiles within a designated study area. For each tile, the optimal image with the lowest cloud cover nearest to the target date is selected to ensure high-quality mosaics. The mosaicked reflectance images are clipped to the study area boundary, and a corresponding cloud quality assurance mosaic is generated for validation. Subsequently, several spectral indices, including NDVI, SAVI, MSAVI, NDWI, and MNDWI, are calculated from the mosaics using band-specific expressions suitable for

each sensor type. The system exports these indices alongside all surface reflectance and quality assurance bands with metadata-rich filenames that include satellite type, path/row identifiers, acquisition date, and cloud cover, enhancing traceability and reproducibility. Demonstrated on selected years (1988, 2009, and 2025), this automated workflow provides a scalable, efficient means for environmental change detection, vegetation health monitoring, and surface water mapping over multi-decadal timescales. The approach facilitates consistent, high-quality Landsat data utilization for long-term ecological studies and supports decision-making in climate impact assessment and land management strategies.

7.3. Enhancing Basin-Scale Hydrological Insights in Greece by Integrating Machine Learning and Satellite Gravimetry

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This study examines the potential of satellite gravimetry for monitoring basin-scale hydrological variability across Greece by downscaling coarse-resolution terrestrial water storage anomalies derived from the Gravity Recovery and Climate Experiment (GRACE) and its successor mission, GRACE Follow-On. Monthly Liquid Water Equivalent (LWE) anomalies from the Jet Propulsion Laboratory's mascon solutions ($\sim 1^\circ$ resolution) are refined to 0.1° (~ 10 km) using a supervised machine learning approach. A random forest regression model is trained on a suite of physically relevant environmental predictors, including precipitation, evapotranspiration, runoff, near-surface and land surface temperatures, relative humidity, and vegetation indices, aggregated to monthly scales and spatially aligned with the GRACE grid.

The resulting high-resolution product represents a data-driven reconstruction of GRACE-based water storage anomalies, whose hydrological validity is assessed through cross-comparisons with independent satellite datasets. First, correlations with surface soil moisture time series evaluate the coherence of near-surface and total water storage variability. Second, multi-mission radar altimetry data over Lake Kremasta and Lake Polyfyto are analyzed to determine consistency between lake level fluctuations and GRACE-derived patterns. These comparisons serve as an indirect validation of the downscaled product's hydrological relevance.

By integrating satellite gravimetry, environmental indicators, and machine learning techniques, this research offers a scalable framework for enhancing the spatial resolution of terrestrial water monitoring in data-scarce regions. It contributes to understanding the strengths and limitations of data-driven GRACE downscaling for hydrological applications.

7.4. Next-Generation Water Management: Integrating Generative and Agentic AI for Enhanced Efficiency and Resilience

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The management of water distribution and wastewater treatment facilities is confronting unprecedented challenges, including aging infrastructure, climate-induced stressors, and increasing operational complexities. While traditional automation has improved efficiency, it often lacks the foresight and adaptability required for dynamic system management. This abstract introduces a transformative paradigm integrating two advanced

artificial intelligence frameworks, Generative AI and Agentic AI, to create self-adapting, resilient water systems.

Generative AI is leveraged for its powerful predictive and simulation capabilities. By training on vast datasets of historical and real-time operational data, it can generate highly realistic digital twin simulations to forecast system behavior, predict component failures, and model the impact of various environmental or demand scenarios. Furthermore, generative models can design optimized operational schedules and novel infrastructure configurations that enhance efficiency and minimize energy consumption.

Complementing this foresight, Agentic AI provides the capacity for autonomous action and real-time decision-making. Deployed as a network of intelligent agents, this framework can independently control physical assets such as pumps, valves, and chemical dosing systems. These agents interpret the predictive insights from generative models to proactively adjust operations, autonomously manage maintenance tasks, and coordinate rapid, localized responses to disruptions like pipe bursts or contaminant ingress.

The synergy between generative foresight and agentic action creates a robust, closed-loop management system that not only optimizes day-to-day operations but also fundamentally enhances the long-term resilience and sustainability of water infrastructure. This integrated approach promises significant reductions in operational costs, minimization of water loss, and a higher standard of water quality and security for communities.

7.5. A Citizen Science and Crowdsourcing Framework for Community-Led Water Security Monitoring Ekolle Eya ¹, Ben Jarihani ²

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The significant absence of localized, real-time data on water resources hinders water security for agricultural and WASH (Water, Sanitation, and Hygiene) purposes in the context of climate change. This research seeks to address this gap through the design and validation of a citizen science framework designed to enable local communities to monitor their own water resources. In this research, we propose a novel citizen science approach that fuses crowdsourced data from a co-designed mobile platform with satellite remote sensing and in situ sensors. Our research utilizes a Participatory Action Research approach to co-develop a mobile platform with community participants. The platform crowdsources high-resolution information on important indicators, such as surface water level, water point functionality, water quality, rainfall, temperature, and Water, Sanitation, and Hygiene-related health events. This grassroots data is integrated with in situ sensor measurements and satellite remote sensing products (e.g., MODIS, Sentinel) to improve the spatiotemporal accuracy of hydrological risk models that will help produce high-resolution hydro-climate information for the community and develop an integrated WASH Risk Index at the village scale. This research aims to validate the reliability of community-generated data and establish a scalable and sustainable model for community-led water monitoring. The expected outcome is a proven, open-source platform and a co-developed framework that provides policymakers with precise, actionable insights. This contribution will enable more informed water resource management, helping to enhance community resilience against water scarcity, safeguard agricultural productivity, and mitigate water-related health crises in a changing climate.

7.6. A Machine Learning Algorithm for Urban Water Classification Based on Radar and Multispectral Imagery from Sentinel Satellite Data

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The study of water is a crucial factor in the ecosystem. This study investigates an improved classification method for urban water by integrating data from Sentinel-1 (Synthetic Aperture Radar) and Sentinel-2 (Multispectral) from the European Space Agency's Sentinel constellation. The analysis leverages the power of the Random Forest Algorithm and Python's Sklearn library to create a classification map. Usually, water mapping extraction relies on a single data source, resulting in limitations in accuracy and the ability to differentiate water types. In this work, first, we performed independent classification of water using the Normalized Difference Water Index (NDVI) and Radar Water Index (RWI). Secondly, to enhance classification accuracy, we incorporated a combination of each index, NDWI and RWI, with the Modified Normalized Difference Water Index (MNDWI) and Automated Water Extraction Index, and we identified the water classes exhibiting the highest prevalence. Thirdly, by using the proposed fusion method, we combined the Modified Normalized Difference Water Index and Automated Water Extraction Index with the fusion of Normalized Difference Water Index and Radar Water Index, and we compared the density variations among water types. The results showed that the effectiveness of the fusion approach significantly improved the classification accuracy, achieving a perfect 100% of overall accuracy and a perfect 100% of Kappa index in all the prediction elements. It also showed a classification result by class for the Random Forest Algorithm, where each water type was "present", and it showed the agreement level by class for the Random Forest Algorithm. Some water types were classified as perfect, moderate, fair, slight, poor, very poor, or inexistent. These results provide valuable information for ecological efforts and future land management strategies.

7.7. A Rapid Method for Generating Long-Term Wetland Inundation Time Series Using the Landsat Archive on Google Earth Engine

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A long-term time series of wetland inundation maps is essential for eco-hydrological analysis and modelling of these vital ecosystems. Although the Landsat archive offers extensive optical/infrared global datasets, mapping wetland inundation using surface water algorithms remains challenging due to the complex spectral responses from soil, algae, and vegetation cover. In this study, we developed a method to rapidly generate binary inundation maps using Google Earth Engine by transforming Landsat imagery into a "mirror image" collection composed of bands related to water and vegetation indices. The entire time series over the Macquarie Marshes, a Ramsar-listed wetland in New South Wales, Australia, was classified using a random forest algorithm trained on representative samples covering diverse inundation scenarios.

This method allows for the rapid generation of a continuous long-term inundation time series, in contrast to event-based approaches, such as change detection using pre- and post-flood imagery or thresholding of single-date images during flood events, which are limited to isolated events and require specific temporal conditions. The resulting maps showed strong agreement with existing inundation datasets and demonstrated

improved performance in capturing inundation patterns compared to traditional surface water mapping techniques. Additionally, we produced inundation probability maps and compared them with vegetation-type maps, revealing a high level of consistency. The proposed method offers a robust, scalable solution for generating wetland inundation maps when tailored to local conditions in other wetland regions.

7.8. A Romanian-Language Local AI Voice Alert System for Flood Preparedness and Mitigation

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AI allows technological systems to perceive the environment in which they operate, process those perceptions and resolve issues, acting in order to reach a preset objective.

This research aims to show that a non-cloud AI voice assistant in a non-major language can fulfill more customizable functions than typical Big Tech AI solutions, such as enabling a context-sensitive voice alert system in case of a disaster, such as a flood.

The system receives data (already prepared or collected through its own sensor network), processes them and reacts.

A case study was conducted, in which a local instance of a Home Assistant server was connected to flood sensors, presence sensors, cameras and two-way voice systems with a local AI backend, which could work together to identify whether people were present in a certain area, deliver a warning to them in Romanian and notify relevant authorities of their presence.

The system of presence sensors and cameras correctly identified that movement in an area was due to the presence of people, counted them, warned them of an impending flood and sent its findings to a notification system that could be accessed by authorities.

Using affordable, off-the-shelf hardware and open-source software, it is now possible to create a customized disaster alerting system for essentially any language, which can automatically function both as a warning for potentially affected people and a notification for authorities of the scale of the problem.

7.9. Application of SWOT Satellite for Monitoring the 2025 Extreme Floods in Australia's Channel Country River System

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Australia's Channel Country rivers experienced their highest recorded flood in 2025, caused by extreme rainfall from a monsoonal low-pressure trough. This extreme flood event surpassed the previous record from 1974, as confirmed by the measurements from the few gauging stations operated by the Queensland and South Australian water departments. In addition to the sparse gauging records, satellite imagery indicates that the 2025 flood resulted in the largest satellite-derived inundation extent ever observed, surpassing the previous maximum inundation recorded by the Landsat satellites (1987–2025).

In this study, we present a novel method for assessing the magnitude of the 2025 extreme flooding event in the Cooper Basin, one of the most severely affected rivers in Australia's Channel Country. SWOT pixel cloud data, optical satellite imagery, and a

Lidar-derived digital elevation model (DEM) were used to assess flood depth and volume. Flood depth hydrographs were validated against water level data at four gauging stations, showing excellent agreement with the best results of ± 11 cm (RMSE) and ± 8.1 cm (MAE). The results were compared with the 100-year recurrence JRC global flood map for the same event in the Cooper Basin, highlighting that our proposed approach improves estimations for large-scale inundation predictions. Our results demonstrate the capability of SWOT observations to monitor flood dynamics through transect profiling and volume estimation. Furthermore, the derived peak floodwater depths provide valuable inputs for calibrating hydrodynamic models, improving predictive accuracy and local flood assessments. Overall, this study represents the largest remotely sensed arid zone flood in Australia and highlights the potential for incorporating SWOT observations into the correction and validation of flood models, particularly in data-scarce regions.

7.10. Artificial Intelligence for Modeling Multi-Phase $BOD_{(20)}$ Kinetics in Urban Lakes Under Anthropogenic and Climatic Pressure

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Accurate modeling of biochemical oxygen demand over 20 days ($BOD_{(20)}$) remains essential for understanding the biodegradation dynamics of organic matter in urban aquatic systems. In this study, we apply artificial intelligence (AI) techniques to estimate kinetic parameters of the $BOD_{(20)}$ process in lakes of Szczecin, Poland—ecosystems subjected to high human pressure and climatic variability. Based on daily incubation tests performed in dark conditions at 20 °C, we reconstructed multi-phase $BOD_{(20)}$ curves and extracted key kinetic descriptors: the delay phase (t_0), exponential growth (t_1), monomolecular reaction (t_2), oxygen consumption markers (y_1 , y_2), ultimate and residual BOD (L_0 , L_1), growth and degradation rate constants (K_v , K_1), and endogenous respiration slope (Re). The classical Fujimoto method and continuity conditions were used to derive K_1 and K_v analytically. The dataset integrates daily-resolved $BOD_{(20)}$ kinetic indicators (t_0 , t_1 , t_2 , L_0 , L_1 , y_1 , y_2 , K_1 , K_v , Re) with a broad spectrum of environmental variables, including over 50 physicochemical water quality metrics (e.g., DO, pH, COD, nutrient loads, metal concentrations), meteorological conditions (temperature, wind, solar radiation, precipitation), and seasonal or site-specific human pressure indicators. Various AI models—ranging from ensemble learning to neural networks and hybrid approaches—have been explored to capture complex relationships governing oxygen demand dynamics. Preliminary results confirm the high potential of AI-based methods to enhance predictive accuracy, reveal latent patterns, and support robust water quality assessment under rapidly changing environmental conditions.

7.11. Comparative CFD Study of Vegetation Scenarios on an Embankment Between Two Irrigation Channels in Khanpur

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The performance and efficiency of irrigation canal systems are critical for sustainable water resource management in agricultural regions. This study investigates overtopping flow in a dual-channel irrigation canal separated by an earthen embankment, under four vegetation configurations: bare, tall vegetation, short/submersible vegetation, and alter-

nating vegetation strips. CFD simulations were conducted in ANSYS Fluent to model the hydraulic behavior for each scenario. A novel image-based method was developed to extract overtopping discharge, head loss, and percentage reduction directly from CFD velocity contours when numerical export files are unavailable. The method was validated against analytical weir-based calculations.

Results show that the tall vegetation reduced overtopping discharge by approximately 61%, short vegetation by 33%, and alternating vegetation by 22% compared with the bare case, demonstrating the significant influence of vegetation arrangement on inter-channel flow control.

This work introduces a practical, image-based quantification method for overtopping discharge and hydraulic losses in CFD-modeled irrigation canals. Unlike prior studies dependent on field measurements, raw data exports, or purely analytical models, the proposed method enables reliable parameter extraction from simulation images alone. The study further provides a comparative evaluation of three vegetation layouts under identical hydraulic and geometric conditions, offering new insights into their relative effectiveness for overtopping mitigation.

7.12. Comprehensive Evaluation of Imputation Methods for Reconstructing GRACE/GRACE-FO Terrestrial Water Storage Data

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The Gravity Recovery and Climate Experiment (GRACE) and its Follow-On Mission (GRACE-FO) have transformed our understanding of global terrestrial water storage (TWS) dynamics by revealing previously unknown mass changes. However, persistent data gaps induced by sensor breakdowns, orbital constraints, and processing aberrations significantly limit their utility in crucial hydrological applications that necessitate a continuous, uninterrupted time series. This study examines four different imputation methods: two traditional statistical approaches (linear interpolation and mean substitution) and two sophisticated machine learning techniques (Random Forest regression and K-nearest neighbors). We use 18 years of GRACE/GRACE-FO measurements spanning 2002–2020 from 15 globally distributed river basins covering varied hydroclimatic regimes (including tropical, temperate, and dry systems) to execute a rigorous evaluation framework. The methodology uses three controlled gap situations (10%, 15%, and 20% missing data) to model realistic data interruption patterns, as well as two complementing performance metrics (Root Mean Square Error and R-squared) to evaluate both accuracy and variance explanation. Our thorough investigation shows that, while traditional methods perform well for short gaps, machine learning approaches outperform them when dealing with bigger data discontinuities. Specifically, the Random Forest approach outperforms all investigated cases by effectively retaining both long-term trend components and seasonal amplitudes in the rebuilt time series. These findings provide hydrologists and water resource managers with an evidence-based framework for selecting effective gap-filling strategies that are suited to individual application requirements. The improved data continuity improves the reliability of GRACE/GRACE-FO datasets for critical applications such as groundwater monitoring, drought early warning systems, and climate change impact assessments, especially in data-scarce regions with few alternative observations.

7.13. Enhancing Flash Flood Prediction Accuracy with Bi-LSTM and Satellite Rainfall Estimates

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Flash floods pose a serious threat in hilly catchments, where steep slopes and intense rainfall often trigger rapid water level rises that endanger lives and infrastructure. In this study, a deep learning-driven flash flood early warning system is proposed and evaluated for the BWDB (Bangladesh Water Development Board) station at Muslimpur on the Jhalukhali River, Sunamganj, Bangladesh. A supervised bidirectional Long Short-Term Memory (Bi-LSTM) neural network was used to forecast river water levels 25 time steps ahead, or with a 5-day lead (each day is divided into five time steps: 6:00, 9:00, 12:00, 15:00, and 18:00). The model incorporates a wide range of input features, including precipitation data using half-hourly IMERG satellite rainfall estimates for five geographical locations, temporal indicators (hour, day of year, month, and monsoon flags), lagged values, rolling statistics, and cumulative precipitation. Its architecture leverages two input streams: one processing 25 past time steps for each feature using Bi-LSTM layers, and the other projecting 25 future time steps, with outputs concatenated to predict the final output. For increased sensitivity to outlier events, a peak-weighted loss function was specifically employed. The model demonstrated robust predictive capability, with coefficients of determination (R^2) between 0.88 and 0.93, mean absolute errors between 32.5 and 41 cm, and root mean square errors between 36.5 and 54.5 cm for flood events in April 2017, May 2019, and May 2020. Visualization of predicted and measured water levels confirmed that the system effectively replicated both gradual changes and abrupt flood maxima, accurately simulating the rapid increases in water level characteristic of flash floods. These results highlight the ability of deep learning models utilizing satellite data to provide more reliable and enhanced preemptive alerts than traditional early warning systems.

7.14. Erosion Severity Mapping in the Portaikos Mountainous Watershed (Thessaly, Greece) Using Earth Observation Data

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Accurate identification of erosion-prone areas in steep and geologically fragile mountainous watersheds is essential for effective management. This study applies the Erosion Potential Method (EPM, Gavrilović model) to assess and map erosion severity in the Portaikos mountainous watershed (Thessaly, Central Greece) using multi-source Earth Observation data. The ϕ coefficient, which in the EPM represents the type and extent of erosion processes and is traditionally derived from field observations, was herein estimated in an innovative way from the Bare Soil Index (BSI) calculated from Sentinel-2 imagery. This step was implemented entirely in the Google Earth Engine (GEE) cloud environment, while the remaining model inputs—CORINE Land Cover (CLC), a high-resolution bare-earth DEM (FABDEM), and the national Soil Map of Greece (MEEN)—were processed in a GIS framework for the final computation of the erosion coefficient (Z). The resulting

Z values were classified into five severity categories (from excessive to very slight) to depict the spatial variability of erosion risk within the watershed. Excessive and severe severity classes together occupy approximately 7% of the watershed area, mainly on steep slopes with sparse vegetation cover. Moderate-severity zones cover about 40%, while slight and very slight classes account for the remaining 53%. Areas mapped as excessive or severe severity closely match locations of documented debris flows and landslides from historical records, supporting the model's reliability. These results confirm that integrating open-access EO datasets with targeted cloud-based processing can enhance erosion risk assessment in mountainous watersheds, enabling more frequent updates and supporting targeted conservation and hazard mitigation measures.

7.15. Evaluating Sentinel-1 DEMs for Geospatial Applications: A Benchmark Study with Copernicus DEM, SRTM, and LiDAR

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Digital Elevation Models (DEMs) underpin watershed delineation, landform classification, hydrologic/hydrodynamic modelling, and environmental monitoring. While SRTM (~30 m) is a common global baseline, advances in SAR processing (e.g., SNAP) enable locally tailored DEMs from Sentinel-1 interferometry. This study generates a Sentinel-1 InSAR DEM and evaluates it against Copernicus DEM (GLO-30, ~30 m DSM), SRTM (1-arcsec, ~30 m DEM), and very-high-resolution LiDAR patches over the study area. We assess accuracy using RMSE, MAE, and correlation (stratified by land cover, slope, and coherence), and qualitatively via elevation profiles, slope/aspect, and planform inspection. We diagnose error sources—temporal decorrelation, atmospheric delay, and baseline geometry—and examine long-wavelength ramps to gauge the benefit of stacking multiple interferograms. Results: The Sentinel-1 DEM provides enhanced local detail (~10–30 m posting) and sharper terrain expression than global products on open to moderately vegetated slopes, but its performance degrades in dense vegetation/low-coherence zones. Published comparisons indicate that Copernicus GLO-30 typically outperforms SRTM by ~1–2 m RMSE, with global assessments showing most GLO-30 tiles ~1.2 m RMSE against space-borne lidar references. In contrast, single-pair Sentinel-1 InSAR DEMs in humid, vegetated tropics can show RMSE in the tens of meters (e.g., ~22.5 m), though stacking multiple interferograms improves accuracy relative to single-pair results. SRTM offers a smoother, more conservative surface but misses fine relief; Copernicus generally improves vertical consistency and landform depiction. LiDAR patches show the upper bound on accuracy and reveal local biases across coarse DEMs. We propose a practical selection framework—favoring Sentinel-1 for local detail/recent acquisitions, Copernicus for global consistency, SRTM for baseline coverage, and fusion with LiDAR where available—and outline integration steps for hydrologic/hydrodynamic and geomorphic change applications.

7.16. Laccase-Functionalized Nanoparticles for Endocrine Disruptors Oxidation: From Synthesis to Characterization

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The increasing prevalence of emerging pollutants in aquatic environments poses serious risks to both public health and ecosystem sustainability. Among these contaminants, endocrine-disrupting compounds, such as bisphenol A, are of particular concern due to their ability to interfere with hormonal systems even at trace concentrations. Conventional wastewater treatment plants are unable to completely remove these pollutants, highlighting the need for innovative and sustainable remediation strategies. In this context, enzymes such as laccase have attracted attention due to their ability to oxidize and eliminate endocrine disruptors, including bisphenol A. However, the direct application of free enzymes in large-scale systems is limited by challenges related to stability, recovery, and reuse. To overcome these limitations, this work explored the covalent immobilization of laccase onto superparamagnetic iron oxide nanoparticles (SPIONs) functionalized with epoxy groups.

For that purpose, different immobilization incubation times and acetate buffer concentrations were evaluated to optimize enzyme loading and catalytic activity, which was monitored by UV–Vis spectroscopy. Dynamic light scattering measurements showed an increase in particle size upon enzyme addition, suggesting successful attachment of laccase to the nanoparticle surface. Immobilization was achieved with increasing enzyme concentrations, though with modest yields (~20%) as quantified using the BCA assay. Alternative buffers (Tris-HCl, phosphate, borate) were tested, although the acetate buffer proved to be more suitable.

Future work will be focused on assessing the nanoparticles performance in removing endocrine disruptors. These findings contribute to advancing sustainable water treatment technologies by integrating enzymatic efficiency with nanomaterial-based recovery strategies.

7.17. Land Use and Land Cover Analysis and Prediction Using Machine Learning Approach: A Case Study of Gaibandha District, Bangladesh

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Land use and land cover (LULC) change analysis is crucial for sustainable environmental management and policy formulation in Bangladesh's rapidly changing landscape. This study employs Google Earth Engine and machine learning techniques to analyze LULC dynamics and predict future changes in Gaibandha district, Bangladesh, using ESRI Global Land Cover data from 2019 and 2022, with predictions extending to 2025. A Random Forest classifier was developed using multi-temporal satellite imagery, incorporating elevation data from SRTM and temporal variables to model land cover transitions. Nine LULC classes were identified: water, trees, flooded vegetation, crops, built area, bare ground, snow/ice, clouds, and rangeland. The model achieved high accuracy (>90%) and kappa coefficient (>0.9), validated through hyperparameter tuning and cross-validation across different random seeds. Results reveal significant landscape transformations between 2019 and 2022, with notable transitions from agricultural to built-up areas and changes in vegetation cover. The Shannon diversity index analysis indicates fluctuating landscape heterogeneity over the study period. Transition matrix analysis identified crop-to-built area conversion as a dominant change pattern, reflecting rapid urbanization pressures. The 2025 predictions suggest continued urban expansion and agricultural land conversion, highlighting potential environmental challenges. Model stability over seeds and overfitting analysis indicate the robustness and reliability of the machine learning framework. Analysis of importance analysis revealed that historical land cover patterns and elevation are primary drivers of change. The methodology demonstrates the effectiveness of cloud-based remote sensing

platforms for large-scale LULC monitoring and prediction, supporting evidence-based decision-making for regional development and climate adaptation planning.

7.18. *Leveraging Lightweight Large Language Models for Hydrological Interpretation of Precipitation Time Series in Greece*

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As hydrological systems grow increasingly complex and data-rich, new tools are needed to support rapid interpretation and communication of climate and water cycle trends. This study evaluates the applicability of instruction-tuned large language models (LLMs) to interpret long-term precipitation records in the context of hydrological variability. Using a 23-year (2002–2024) ERA5 monthly precipitation time series from a location in Greece, the study tests whether lightweight, open-source models—including TinyLlama (1.1B) and Phi-2 (2.7B)—can generate semantically coherent summaries of seasonal dynamics, detect hydrological anomalies, and answer natural language questions relevant to water resource monitoring.

The time series is preprocessed into prompt-compatible text blocks, enabling models to produce narrative outputs describing dry and wet seasons, interannual shifts, and extreme events. Responses are evaluated against visual and statistical baselines to assess their hydrological fidelity. Phi-2 demonstrates a stronger correlation with observed patterns, while TinyLlama provides fluent but less consistent outputs. All models show limitations in numerical reasoning and require tight prompt structuring to avoid hallucinated values.

Our findings suggest that even low-resource LLMs can serve as effective interpretive aids in hydrology, particularly for rapid diagnostics, stakeholder reporting, and data contextualization. When paired with physical constraints and structured input formats, LLMs could enhance exploratory analysis and decision-support capabilities in water management, climate services, and early warning systems. A reproducible Google Colab notebook and annotated model comparisons are included to support further hydrological application and refinement.

7.19. *LiDAR-Based Gully Detection and Bare-Earth Modelling in Australian Rangelands*

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Rangeland gullies are key drivers of sediment export and landscape change, yet their detection is often constrained by vegetation cover and coarse topography. We acquired high-density airborne LiDAR over ~50 ha of Australian rangelands and produced a bare-earth Digital Terrain Model (DTM) and Digital Surface Model (DSM) and derived DEM products to characterize the gully morphology and near-surface hydrology. Point clouds were quality-checked, georeferenced, and classified into ground/non-ground classes using a terrain-adaptive workflow; terrain grids were generated at a sub-meter resolution and coupled with co-registered optical imagery processed via photogrammetry to derive complementary surface models and orthomosaics. Gully features were mapped from terrain derivatives (slope, curvature, openness, topographic wetness) and drainage enforcement,

with targeted manual validation against ortho-imagery and field observations. The results show that LiDAR reliably resolves gully heads, thalwegs, banks, and interfluves beneath dense grass and scattered woody cover, where image-based photogrammetry alone is limited by canopy occlusion; in open patches, photogrammetry improves planform delineation and texture cues. The LiDAR-derived DTM provides a robust foundation for repeat-survey geomorphic change detection (cut/fill and volumetrics) and for hydrological and hydrodynamic modelling of runoff generation, flow concentration, and sediment pathways at the paddock to hillslope scales. We outline a practical decision framework for selecting the model resolution, filtering parameters, and derivative metrics to balance noise suppression against feature preservation. Although developed and validated at our case-study site, the decision framework is intended to be generalizable to rangeland systems more broadly, requiring only modest parameterization to local terrain, vegetation, and data-availability conditions. The workflow supports monitoring and evaluation of gully remediation, erosion-risk screening, and the design of nature-based interventions in data-limited rangelands and is readily extensible to larger areas using tiled processing and cloud-hosted data services.

7.20. Low-Cost IoT Sensor for Real-Time Streamflow Measurements

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Accurate measurement of streamflow is fundamental for water resources management, ecological conservation, flash flood early warning, and climate change impact studies. Traditional gauging stations, while effective, are costly and difficult to deploy in mountainous streams. Although Parshall flumes can be equipped with ultrasonic water level sensors and telemetry systems for real-time monitoring, their installation requires fixed hydraulic geometry, calibration, and maintenance, which may be impractical in small, remote, or temporary stream contexts. This study presents a proof of concept on the usage of IoT for automatic streamflow measurements using commercial off-the-shelf (COTS) hardware. The system is designed, implemented, and field-tested as a low-cost, solar-powered IoT device tailored to small-order streams and headwater tributaries. At its core is the hall-effect YF-S201 flow sensor. Although primarily designed for closed-conduit applications, the sensor was tested in a controlled setup where stream water was diverted into a short pipe section, enabling continuous monitoring and calibration against known discharge. The sensor can be easily incorporated with a variety of boards (Arduino, Raspberry, OrangePi, etc.) with or without wireless capabilities, based on the usage scenario and user requirements (demand for cloud storage, virtual dashboards, etc). This paper provides analytical details on the design and validation of a low-cost, solar-powered streamflow measurement system based on a water flow sensor, using wireless communications, and cloud storage based on an ESP32 board, PostgreSQL, and a web interface. The device was tested in a simulated environment. Results indicate the proposed device reliably tracks flow variability, while offering portability, energy autonomy, and cost efficiency, and may serve as a feasible alternative for low-infrastructure, temporary deployments.

7.21. Multiparameter Optical Probes and IoT Networks for Real-Time Water Quality Monitoring

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Access to safe water is increasingly challenged by agricultural runoff, wastewater discharges, and diffuse pollution. Current country-wide monitoring relies heavily on manual

sampling and accredited laboratory methods, which are costly, logistically demanding, and limited to a few measurements per year. These constraints leave regulators and water managers without sufficient temporal resolution to identify pollution trends or respond rapidly to emerging threats.

We present a work in progress of a novel multiparametric optical probe capable of simultaneously measuring key water quality parameters, including nitrates, turbidity, Abs@254, water quality index, and temperature. The device requires minimal maintenance, is cost-effective, and has been validated against accredited laboratory methods to a practical extent. While inherent differences exist between in-situ optical sensing and gold-standard analytical techniques, the advantage lies in frequency and affordability: our system can record measurements every 15 min, powered by batteries or solar panels, and is suitable for long-term field deployment.

When constant trends are observed, laboratory validation may be unnecessary, but deviations trigger an early warning and targeted manual sampling. Over time, such probes complement rather than replace accredited methods, significantly increasing data availability while reducing the cost per measurement to cents. This high-frequency data stream enables tracking both stable and shifting water quality trends, supported by first-principle modeling or AI-based applications for aquatic environments.

The concept is already being tested in partnership with the National Water Testing Laboratory at the Water Research Institute Slovakia, within the framework of the EU Nitrates Directive. Their national network of approximately 1200 groundwater wells, of which around 200 exceed the nitrate health standard, provides an ideal platform to evaluate the system. By combining in-situ sensing with IoT connectivity, this approach enables scalable, data-driven environmental protection and supports compliance with European water quality policies.

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7.22. Non-Invasive Heart Rate Sensing in Fish Using Video Imaging: A Novel Approach for Water Quality Monitoring

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Environmental stressors such as water pollution, temperature fluctuations, and dissolved oxygen depletion significantly impact the physiology and behavior of aquatic organisms. Among physiological indicators, heart rate is one of the most immediate and sensitive biomarkers of stress and can serve as a reliable proxy for environmental health. In this study, we present a novel, non-invasive method for monitoring the heart rate of small transparent fish using video imaging and motion analysis techniques, without the need for electrodes, anesthesia, or restraint.

We conducted experiments using *Danionella translucida*, a genetically unmodified, naturally transparent teleost fish with a clearly visible cardiovascular system. High-frame-rate video recordings were analyzed using frame-differencing and luminance-based motion detection to extract cardiac pulsations from the heart region. The estimated heart rate was validated against manual annotations, showing consistent agreement with less than 5% error across multiple trials. The system demonstrated a robust performance in detecting subtle changes in heart rate under varying environmental conditions, including temperature changes and exposure to low levels of chemical contaminants.

Our technique is cost-effective, accessible, and well suited to long-term in vivo monitoring, making it applicable not only in laboratory experiments but also in aquaculture and environmental surveillance. Furthermore, we discuss the potential of integrating this

system with AI-based anomaly detection and remote sensing platforms to create a scalable, real-time water quality monitoring solution. These findings highlight the utility of fish cardiac physiology as a biological sensor and offer a new pathway for linking individual-level stress responses to broader ecological and environmental health indicators.

7.23. *Optimized UAV-LiDAR Workflows for Fine-Scale Stream Network Mapping in Low-Gradient Wetlands: A Kushiro Wetland, Japan Case Study*

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Accurate stream network delineation in low-gradient wetlands is essential for hydrological modeling, flood risk assessment, and ecological restoration. However, the subtle terrain features and dense vegetation in these environments present significant challenges. This study systematically evaluated 48 UAV-LiDAR processing workflows to identify the optimal approach for mapping fine-scale stream channels in the Kushiro Wetland, Japan, a Ramsar-protected site known for its ecological importance. Workflows combined three ground filtering methods (PMF, CSF, MCC), four interpolation techniques (IDW, TIN, KRG, MBA), two sink-filling algorithms (Wang & Liu, Planchon & Darboux), and two flow direction models (D8, D-infinity). Performance was assessed using the Intersection over Union (IoU) metric to quantify the accuracy of channel network delineation.

The results showed that workflow configuration significantly impacts detection precision, with the optimal workflow—CSF, MBA, Planchon, and D8—achieving a high IoU of 0.85. CSF excelled at preserving complex terrain structures crucial for wetland hydrology. While KRG provided robust interpolation for general terrain representation, MBA was more effective for channel delineation within the optimal workflow. Planchon's sink-filling algorithm substantially improved hydrological connectivity representation, outperforming Wang & Liu. Minimal differences were observed between D8 and D-infinity flow direction models, suggesting D8's computational efficiency makes it preferable for similar environments.

These findings provide actionable recommendations for high-resolution wetland mapping and hydrological analysis. The methodological framework developed in this study supports the ongoing Kushiro Wetland Restoration Project and can be applied to other degraded wetland systems globally, contributing to conservation, restoration planning, and ecosystem management efforts.

7.24. *Predictive Model of Hydraulic Valve Failures Using Artificial Neural Networks (ANNs)*

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Recent advances in artificial intelligence (AI) and machine learning (ML) have enabled significant progress in pipeline failure prediction. However, research focusing on critical hydraulic components -as particularly valves are- remains surprisingly limited despite their operational importance.

Based on the foregoing, this study proposes a predictive model for hydraulic valve failures using artificial neural networks (ANNs) to mitigate operational risks and costs associated with malfunctions. Considering that hydraulic valves are critical components in water supply and distribution systems, implementing an AI-based failure prediction

system will enable early fault detection, optimize maintenance planning, and reduce costs linked to emergency repairs.

The methodological framework includes collecting operational data—such as pressure, flow rate, temperature, and vibration measurements—from a set of valves. These data will be pre-processed to train ANNs capable of identifying patterns associated with potential failures. Different ANNs architectures will be evaluated, including multilayer perceptrons (MLPs) and recurrent neural networks (RNNs), to determine the most accurate approach for early anomaly detection. The model will be validated using real-world operational data, with performance comparisons against statistical models and other techniques documented in the literature.

The expected outcomes include precise fault identification and, where feasible, estimation of the valves' remaining useful life (RUL). These results will support a transition toward predictive and proactive maintenance strategies. Furthermore, this approach could be extended to other hydraulic components, thereby improving the efficiency of water supply and distribution systems.

7.25. Remote Sensing-Based Water Balance Assessment of the Syr Darya and Amu Darya Basins Sandunika Rathnayake ¹, Ben Jarihani ²

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The Syr Darya and Amu Darya rivers in Central Asia are critical water sources for the region. However, hydrological monitoring remains challenging due to limited ground-based observations. In this study, we applied a fully remote sensing-based approach to quantify the water balance dynamics of these two large catchments from 2003 to 2024.

We utilized total water storage anomalies (TWSA) from GRACE and GRACE-FO, satellite-based precipitation (P) from CHIRPS, and actual evapotranspiration (AET) from MODIS. Monthly water balance components were assessed, with precipitation representing input, evapotranspiration representing loss, and GRACE-derived TWSA reflecting residual storage changes.

The results reveal a strong correlation between P–AET and GRACE-derived storage changes, confirming that satellite observations can effectively track basin-scale water balance in data-scarce regions. Nonetheless, divergences are observed in certain months, particularly during winter and spring, likely due to contributions from snow accumulation and subsequent melt. Runoff data from ERA5-Land further show a sharp increase from April to June, highlighting the influence of spring snowmelt. Seasonal analysis illustrates storage gains during winter due to precipitation and snow accumulation, followed by depletion in spring–summer driven by evapotranspiration and water withdrawals.

This study demonstrates the potential of integrating multiple satellite datasets to monitor hydrological variability in the Syr Darya and Amu Darya basins. This approach provides a solid framework for supporting water resource management and offers new insights into how climate variability affects water availability in Central Asia.

7.26. Soil Moisture Time Series Gap-Filling Using Random Forest Machine Learning Models: A Case Study in the Arta Plain

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Soil moisture content (SMC) is a key environmental variable which influences numerous hydrological and ecological processes. However, the complex and dynamic nature of SMC makes it difficult to estimate. Moreover, invalid SMC measurements and data gaps in sensor-based SMC monitoring are common occurrences due to various reasons. This study investigates the effectiveness of the Random Forest (RF) machine learning algorithm in reconstructing missing SMC time series at depths of 10 cm, 30 cm, and 50 cm at two agricultural sites in the Arta plain, Greece. Input data included existing SMC time series at alternative depths and the NDVI vegetation index derived from Sentinel-2 satellite data. RF models were trained using daily SMC data from 2020 to 2021 and validated with 2022 observations. Model performance was evaluated using the Nash–Sutcliffe efficiency (NSE) and Root Mean Square Error (RMSE). The results demonstrated high predictive accuracy, with NSE values up to 0.98 and RMSE as low as $0.33 \text{ m}^3/\text{m}^3$. The best results were achieved when two SMC series were used as inputs. NDVI contributed less to model improvement, possibly because the NDVI daily time series is derived through temporal interpolation, as the NDVI values are not originally available on a daily basis. In addition, some NDVI values are discarded when the satellite image has more than 10% cloud cover. Overall, the study confirms that RF models are effective for imputing missing SMC data and can support irrigation management by reconstructing reliable soil moisture records even with limited sensor information.

7.27. Spatio-Temporal Drought Assessment in the Pinios River Basin Using Ground Observations and Satellite Data

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The aim of this paper is to analyze the spatial and temporal characteristics of drought in the Pinios River Basin, a water-limited Mediterranean basin in Thessaly, Greece, by comparing drought indices calculated by ground-based meteorological observations and satellite-derived data. Drought analysis was carried out for the period of October 1981–September 2002 using the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) at multiple time scales, in comparison with the Surface Runoff Index (SRI) representing hydrological drought. Ground precipitation and temperature data were spatially interpolated using a Multiple Linear Regression method to create a 487-pixel grid ($5 \times 5 \text{ km}$). The CHIRPS precipitation data and the ERA5 reanalysis temperature data had the same resolution as the ground-observed data to allow comparisons. The potential evapotranspiration was estimated by the Thornthwaite method. Correlation analyses confirmed the satisfactory agreement between ground-based and remote sensing data. The results identified the severe and persistent droughts during the late 1980s, early 1990s, and early 2000s, with their spatial extent and intensity effectively captured by the indices calculated by the remote sensing data. Furthermore, the drought indices of various time scales were compared for an unregulated sub-basin of the Pinios River with the SRI index, and the results indicated that a meteorological drought index (SPI and/or SPEI) at a 6-month time scale correlates well with the SRI. Overall, the results demonstrate that satellite data from international databases can serve as a cost-effective and

reliable alternative in regions with sparse observational networks, offering significant value for drought monitoring and water resources management in Mediterranean environments.

8. Wastewater Treatment and Reuse

8.1. Cost-Effective Hybrid System for Wastewater Treatment: The State of the Art

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Access to potable water remains a significant global challenge due to the elevated levels of pollutants present in water bodies. As a result, there is an increasing demand for freshwater resources and/or a critical necessity to utilize treated effluents as a new and innovative source of water supply. It is estimated that about 3% of the world's electricity generation is used in the treatment and supply of water. Therefore, reducing energy costs in water and wastewater treatment plants (WWTPs) is critical. To achieve these objectives, innovative concepts must be developed to cope with the drawbacks of conventional treatment technologies. A hybrid system (HS) is an integration of two or more treatment methods employed synergistically for effective pollutant removal. Nowadays, hybrid wastewater treatment systems are gaining attention due to their potential to reduce the cost, footprint, process time, chemical and energy usage, and production of secondary pollutants. They can effectively enhance the overall treatment efficacy and sustain energy as a renewable resource. This study provides an up-to-date overview of different HSs involving biological, physical, and chemical processes for wastewater treatment. A brief background on hybrid wastewater treatment technologies with different case studies is given. In addition, the research gaps are addressed with conclusions and recommendations. Consequently, integrating hybrid models presents significant promise for advancing wastewater treatment technologies and achieving the dual goals of contaminant removal and energy production. They can start perceptively to displace the conventional technologies which already consume around 30% of the cost in wastewater treatment, without any hindrance. Hybrid wastewater treatment systems can overcome the limitations of conventional systems. They can minimize the cost of energy, minimize the wastewater treatment cost, and increase the quality of the effluents, to comply with strict discharge regulations and establish a renewable source of fresh water.

8.2. Microplastic–Microalgae Interactions: Effects on Nutrient Uptake and Growth of *Chlorella Vulgaris*

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Microplastics (MPs) are persistent emerging contaminants in wastewater (WW) that conventional treatment systems fail to remove effectively, posing environmental and human health risks. Microalgae-based systems have emerged as sustainable alternatives for WW treatment, offering efficient nutrient removal and biomass production. However,

the impact of MPs on microalgal performance under different WW conditions remains poorly explored.

This study evaluated the physiological responses and bioremediation efficiency of *Chlorella vulgaris* exposed to 100 mg/L of five of the most common MPs, namely polypropylene (PP), polystyrene (PS), polyamide (PA), low-density polyethylene (LDPE), and high-density polyethylene (HDPE). For that, different experimental conditions were studied, including variations in nitrogen (N) and organic carbon levels and photoperiod regimes (12/12 h light/dark vs. continuous light).

Results revealed heterogeneous metabolic responses depending on MP type and environmental conditions. PE derivatives (HDPE and LDPE) consistently reduced esterase activity, while PS under N-limited conditions increased it. LDPE triggered intracellular oxidative stress only under N limitation. Despite these metabolic effects, *C. vulgaris* maintained its growth and biomass generation in most scenarios, except under nutrient-starved and 12/12 h light/dark conditions, where growth was inhibited by 13–27%. Heterotrophic metabolism partially compensated for reduced photosynthetic activity during dark periods. Under N-limited conditions, *C. vulgaris* demonstrated high bioremediation efficiency, with up to 94% N and >97.5% glucose removal, even in the presence of MPs. In contrast, limited organic carbon (as glucose) severely impaired nutrient removal due to energy deficits. A 12/12 h photoperiod also reduced N uptake by constraining light-dependent energy production, although glucose consumption remained high (>98%).

Overall, the study highlights that different WW experimental conditions modulate MP-induced stress. Nutrient limitation and light/dark cycles can intensify metabolic disruption, while N-limited environments promote adaptive responses. *C. vulgaris* demonstrated high resilience, maintaining its bioremediation capacity and supporting its potential as a robust, eco-friendly tool for MP-contaminated WW polishing.

8.3. Shifting Sands: The pH-Dependent Removal of Emerging Contaminants Using Sustainable Materials

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Concerns over contaminants of emerging concern (CECs) in wastewater effluent have renewed interest in low-energy sustainable treatment solutions. The authors evaluated the removal of two widely co-detected antibiotics, sulfamethoxazole (SMX) and trimethoprim (TMP), in two bench-scale columns—one packed with sand alone and one supplemented with modified sawdust adsorbent. Nine influent conditions were tested, single CECs at 1 mg·L⁻¹, both CECs in a mixture (0.5 mg·L⁻¹ each), and single CECs at 0.5 mg·L⁻¹, across three different pH levels. Samples were collected (n = 3) and concentrations were quantified by high-performance liquid chromatography. The sand-only columns exhibited high TMP removal at both influent dosages (−81.4%) when alone but decreased markedly to −42.2% ± 3.3 in the presence of SMX, indicating competitive or antagonistic effects. However, the addition of treated sawdust doubled this TMP removal from antibiotic mixtures to −85.3%. SMX-alone demonstrated leaching in sand (+19.3% ± 31.3), and sawdust amendment did not improve its removal, increasing concentrations 70.3% ± 106.4 in the TMP+SMX mixture. When the pH was modulated, TMP removal decreased with increasing influent acidity, with statistically significant differences observed (Welch's *t*-test, *p* < 0.05), confirming pH-dependent interactions. In contrast, SMX removal improved under acidic conditions, though removal at pH 3 did not differ significantly from that at

pH 4 in either single- or dual-media filters. Fourier-transform infrared (FTIR) analysis of adsorbent materials demonstrated functional groups, and it subsequently explained the interactions controlling adsorption; hydrophobic, electrostatic, and hydrogen bonding interactions were possible due to non-polar, carboxyl, and carboxylic acid groups present, respectively, in the silica (sand) and lignocellulosic (sawdust) materials. Our initial results indicate that lignocellulosic amendments can enhance slow-sand filter removal of resistant compounds such as SMX. Ongoing pilot-scale experiments assessing biofilm development and long-term performance will probe mechanisms and scale-up feasibility.

8.4. Aqueous Two-Phase Extraction Using Choline Salts: A Green Strategy for Tackling Pharmaceutical Pollution in Water

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Aqueous Two-Phase Systems (ATPSs) based on choline salts represent a promising, environmentally friendly alternative to conventional liquid–liquid extraction methods due to their high water content, biocompatibility, and non-toxic nature. These characteristics make them particularly suitable for the recovery of active pharmaceutical ingredients (APIs), such as antibiotics and antipyretics, from contaminated water streams. The presence of pharmaceutical residues in aquatic environments has become a growing global concern, as these compounds are persistent and capable of inducing adverse effects on aquatic organisms, microbial ecosystems, and even human health. In this study, the liquid–liquid equilibria (LLE) of ATPSs composed of propan-1-ol, choline dihydrogen citrate ([Ch][H₂Cit]) or choline bicarbonate, and water were determined at 298.15 K and 0.1 MPa. The cloud-point method was used to estimate solubility curves, while tie-line compositions were established using third-degree polynomial correlations of electrical conductivity and liquid density data. The experimental tie-line compositions were accurately correlated using empirical models and successfully described using the electrolyte-Non-Random Two-Liquid (eNRTL) thermodynamic model. During thermodynamic modelling, non-randomness factors (α) for the solvents were derived from Density Functional Theory (DFT) calculations, with values of 0.1970 for propan-1-ol and 0.3333 for water. This approach reduced the number of adjustable parameters and enhanced the physical interpretability of the model. The studied systems demonstrated efficient extraction of salicylic acid, with partition coefficients (K) ranging from 2.1 ± 0.3 to 5.6 ± 0.9 , confirming that ATPSs based on choline salts not only align with green chemistry principles but also provide a viable and sustainable strategy for the selective removal of pharmaceutical contaminants from polluted water streams. As water quality challenges intensify globally, the development of such eco-compatible separation systems is critical to promoting safer and more resilient aquatic environments.

8.5. Assessment of Trombididae (Acari) as Biondicators for Wasterwater Treatment in a Constructed Wetland

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The family Trombidiidae (subclass Acari), commonly known as red velvet mites, exhibits dietary habit shifts throughout their development. Larvae are parasitic, while nymphs and adults transition to a free-living, soil-dwelling predator stage. Predation by these mites is usually done in rocks, tree stumps, plants, leaf litter, and moss, with other arthropods and their eggs being their prey. These hunting environments fit the habitat created by constructed wetlands (CWs) biological wastewater treatment systems, mimicking the processes and conditions that occur in natural wetlands. Trombidiidae are recognized for their potential as bioindicators due to their sensitivity to a range of environmental factors. The presence of Trombidiidae was confirmed in all seasons in a 15-year-old CW located at a rural tourism house, implying that this CW maintains favorable environmental conditions year round. The simultaneous occurrence of spiders within the same system indicates that their life cycle is likely sustained within this system. As both parasites and predators of the biodiversity presented in the CW, Trombidiidae may contribute to a deeper understanding of the food web within these systems, and provide proof as bioindicators of the ecological and habitat benefits CWs can provide.

This work involved seasonal sampling of macrofauna at multiple collection spots within and around the CW, complemented by substrate core sampling to assess below-ground communities. The collected specimens were sorted, identified, and quantified, with statistical analysis currently underway. Preliminary results indicate a robust and well-structured ecosystem, with the consistent presence of Trombidiidae across all seasons, suggesting a stable population.

8.6. Catalytic Performance of Carbon Nanotubes on Glass Frits for Oxalic Acid Degradation by Ozonation

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Emerging contaminants are increasingly detected in aquatic environments due to the limited removal efficiency of conventional treatment processes, highlighting the need for more advanced tertiary treatments. Among these, catalytic ozonation has shown relevance, as it enables the degradation of even highly recalcitrant byproducts. Within this framework, catalysts immobilized on inert, macro structured supports have attracted attention since they eliminate the need for post-treatment separation steps, thereby enhancing the applicability of heterogeneous catalytic reactions in full-scale water treatment. In this study, carbon nanotubes (CNTs) supported on glass frits were investigated as catalysts for the degradation of oxalic acid (OXL), a typical ozone-resistant byproduct generated during the ozonation of various organic pollutants. Carbon nanotubes (CNTs) were immobilized on glass frits through successive impregnation in a solution with the CNTs dispersed in ultrapure water containing Triton X-100, followed by ultrasonication and thermal treatment at 550 °C under N₂. The glass frits were impregnated five times (CNTs@5x). Catalytic ozonation experiments were conducted in a recirculating batch reactor, where ozone (O₃) was continuously bubbled. The CNTs@5x resulted in a CNTs loading of 1.9 mg and enabled 93% OXL degradation within 3 h of catalytic ozonation. This same material was reused for five cycles to evaluate its activity after consecutive reactions. A decline in efficiency was observed in the fourth cycle (20% OXL removal), followed by recovery in the fifth cycle (80% OXL removal). No significant CNTs loss was detected across the cycles, except in the fifth cycle, where CNTs@5x lost 21% of its mass. Overall, CNTs supported on glass frits demonstrated promising catalytic activity for OXL degradation, combining high efficiency,

environmental compatibility, and stable activity over several cycles without the need for any type of reactivation.

8.7. Constructed Wetland: Multi-Functional Benefits of an Ecological Engineered System

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Introduction: Constructed wetlands (CWs) are engineered systems that are inspired by natural wetlands. They are often applied for decentralized wastewater treatment, but while their performance in pollutant removal is well established, other potential ecosystem services are often underappreciated. This study aims to bring attention to the broader multifunctional benefits of CWs—beyond treatment—by exploring a real-scale horizontal subsurface flow CW (HSSF-CW) located at a tourism facility in northern Portugal. **Method:** The CW, in operation since 2010, serves a rural guesthouse in Calheiros and consistently treats domestic wastewater generated from the guesthouse's occupancy of between 6 and 40 people. The system covers an area of 40.5 m² and is vegetated with a polyculture of ornamental species, which is primarily for wastewater treatment at the facility but has also served aesthetic purposes. The CW operates under Mediterranean climatic conditions and discharges into a small polishing pond. Previous studies at this site have focused on pathogen removal and microbial communities. The current investigation builds on this foundation by identifying and evaluating other potential ecosystem functions. **Results:** The system's stable operation provides a unique opportunity to assess additional services such as carbon sequestration (using biomass and substrate), energy recovery (from microbial fuel cell), soil amendments (biomass composting), safe water reuse for irrigation, and the possibility of enhanced wastewater treatment (using photocatalytic modules and nanostructured filters). These aspects are now being explored to better understand the full value of CWs in multifunctional, real-world contexts. **Conclusions:** Recognizing the broader ecosystem functions of CWs is essential to reposition them as more than just wastewater treatment technologies. This study uses a successful, long-running HSSF-CW as a platform to investigate underexplored multifunctional benefits to show CWs's role as valuable ecosystem infrastructure—especially in decentralized settings like tourism where aesthetics, sustainability, and recovery of resources are essential.

8.8. Correlation of the Catalytic Behavior with the TOF and TON Indices of Three Bimetallic Alloy Nanoparticles Assisted by a NaBH₄/Visible Irradiation System for Phenolic Compounds in Their Aqueous Solutions

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The invention of fabricating new metal catalysts has remained a viable solution for eradicating aquatic diseases caused by oil pollutants with specific treatments. The objective's work was divided into two parts: First, to fabricate three alloy nanoparticles (AuAg NPs, PtAu NPs and PtAg NPs) with different structural properties using the probe sonication method. The second part of the aim is to evaluate their different structural performances through a correlation study (catalytic behavior & catalytic indices). The three pure fabricated alloy nanoparticles were crystallized according to the FCC system with well-defined crystalline indices, as determined by the XRD pattern study and EDX spectra for each of them. The surface morphology of the as-fabricated nanospheres was varied based on FESEM images. The catalytic behavior of two petroleum derivatives that polluted the aquatic environment (4-nitrophenol and 2,4-nitrophenol) was studied in the presence/absence of NaBH₄ under visible light irradiation. By calculating the conversion rate of the two contaminants, the *AuAg NPs* and *PtAg NPs* were higher than that of the *PtAu NPs*. Furthermore, the conversion of 2,4-nitrophenol was significantly better than that of 4-nitrophenol. In addition, the conversion to 2,4-nitrophenol was significantly better than to 4-nitrophenol. The results showed a good correlation between the conversion ratio and the TON and TOF indices, where the significant change of both supported the outstanding catalytic performance of this group of alloys.

8.9. Design of an Electrocoalescer Cell for Oil–Water Separation: Comparison of Droplet Distribution

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The oil industry faces significant challenges in the treatment and disposal of oily effluents, as large volumes are generated during refining. Oil–water separation methods have received increasing attention, particularly electro coalescence, which uses external electric fields to induce the coalescence of water droplets in oil–water emulsions, favoring separation. This work presents an experimental and simulation study focused on the design of an electrostatic oil–water separation cell, evaluating the influence of the electric field on the droplet size distribution.

The experimental setup conditions are as follows:

Simulation tool: FEMM 4.2 to define the electrode shape; emulsion composed of 60% mineral oil + 40% distilled water with dye. Applied electric field: 1 kV, 1 kHz, for 1 min; droplet size analysis using ImageJ software.

The experimental comparison is as follows:

Control (C1–C4): Without direct action of the electrodes. Electrodes (EDGE1–EDGE4): Regions under the influence of the electric field.

According to the results, the distribution in the control is the predominance of droplets 1.5 µm, characterizing low spontaneous coalescence; reduction in the frequency of microdroplets (1 µm); greater presence of droplets between 1.6 and 3 µm; increase in the average diameter to 1.6–2.6 µm; occurrence of larger droplets (>6 µm), absent in the control; increased separation efficiency due to the reduction of critical microdroplets; and greater

heterogeneity in the distribution near the electrodes, possibly due to irregularities in the electric field and local turbulence.

The electro coalescence process proved to be efficient in oil–water separation, promoting increases in the average droplet diameter and reduction in the microdroplet fraction, favoring decantation. Improvement in overall process efficiency compared to the control. However, the observed heterogeneity suggests the need for optimizations in electrode positioning and electric field intensity to standardize the coalescent action.

8.10. Eco-Friendly Chitosan (CTS) Films for Indigo Carmine Removal and Wastewater Treatment

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The discharge of synthetic dyes such as indigo carmine (IC) into industrial effluents poses serious environmental risks due to their persistence, toxicity, and resistance to conventional treatment. This study developed chitosan (CTS)-based films as biodegradable, eco-friendly adsorbents for IC removal and wastewater reuse. CTS was dissolved in acetic acid (AA) solutions (0.05%, 1.5%, and 3%), and homogenized hydrogels were prepared by stirring in sealed vials at ambient temperature for 3 h. In our trials, casting on glass and watch glass at 73 °C for 35 min caused irreversible adhesion, whereas polyethylene (PE) at ambient temperature produced homogeneous, transparent, and detachable films. The optimized formulation (1% CTS in 1.5% AA) on PE plates yielded stable, transparent films used for further experiments. Fourier-transform infrared (FTIR) spectroscopy of CTS, AA, the homogenized hydrogel, and dried CTS–1.5%AA/PE films confirmed structural interactions. Adsorption tests were carried out with IC solutions (16 mg/mL) prepared in ultrapure water and secondary treated wastewater supplied by Aquasoil Company (Italy). Full decolorization of the solutions occurred within the first hour, accompanied by a visible change as the initially transparent CTS films turned blue, confirming rapid dye uptake. Subsequent irradiation with a UV lamp (365 nm, UV-A range) promoted photodegradation; after 2 h, the films lost their blue coloration and exhibited a light yellow tone. The films remained structurally stable and could be readily removed. These findings confirm a dual adsorption–photodegradation mechanism, demonstrating the promise of CTS–1.5%AA/PE films as low-cost, biodegradable, and scalable materials for sustainable wastewater treatment. Further studies on biodegradation, reusability, and large-scale application are recommended to validate their industrial potential. Acknowledgments: This project was supported by S.D. through a Doctoral Fellowship funded by the National Operational Programme Research and Innovation 2014–2020 (grant CCI2014IT16M2OP005).

8.11. Efficiency Assessment of Wastewater and Sludge Treatment Using Dielectric Constant and Loss Factor Measurements

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In wastewater and sludge treatment processes, it is important to develop rapid and green measurement methods (i.e., with minimal chemical usage) that can be applied under industrial conditions, in addition to detailed analytical methods. Such methods could, for example, be used in the future for real-time efficiency monitoring. These requirements—non-destructive measurement, no chemical reagents required, and rapid determination—

may be fulfilled by dielectric measurements. However, practical applications in the field of wastewater and sludge treatment remain limited.

In our research, an open-ended coaxial dielectric sensor (DAK3.5, SPEAG, connected to a Rohde & Schwarz ZVL3 VNA) was used to investigate the dielectric constant and loss factor within the 200–2400 MHz frequency range during various wastewater purification and sludge pre-treatment processes. Quantitative changes in organic pollutants in the wastewater were monitored by determining COD and BOD. During sludge treatments, changes in the solubility of organic matter (COD fractionation method) as well as aerobic and anaerobic biodegradability indicators (BOD and mesophilic biogas production) were also assessed.

The research results indicated that the decrease in organic matter concentration has a strong correlation with dielectric parameters in the 200–800 MHz frequency range. Moreover, it was found that, by jointly analyzing the frequency- and temperature-dependent dielectric behavior of wastewater of different origin and composition, characteristic differences in dielectric parameters could be observed—even for the same organic matter content. During sludge biodegradation, the critical frequencies corresponding to the maximum values of the dielectric constant and loss factor (within the 200–2400 MHz range) shifted towards higher frequencies, in accordance with the change in the organic matter removal efficiency and biogas production.

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8.12. Energy-Positive Wastewater Treatment and Nutrient Recovery in a Combined Hydroponics and Microbial Electrochemical System

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As the global population grows at a rapid rate, the need for effective wastewater management coupled with resource recovery to preserve natural resources is increasingly critical. Conventional wastewater treatment processes are energy- and chemical-intensive, increasing the demand for fossil fuels that produce greenhouse gases (GHGs). Microbial Electrochemical Systems (MECs) offer promising advantages by simultaneously treating wastewater and producing renewable electricity. In this study, a combined MEC–hydroponic system facilitates lettuce (*Lactuca sativa*) growth, supported by nutrients recovered from energy-positive wastewater treatment in the MEC anode chamber. The aim is to identify pertinent transmembrane nutrient transport pathways and their potential benefits for lettuce growth and wastewater treatment. This combined setup is a cost-effective 3D-printed reactor wherein the lettuce plants grow in the cathode chamber, immersed in hydroponic wastewater (nutrient solution). This is compared to a standard air cathode cell. Local municipal wastewater was used as the anolyte. Performance was measured through the COD and total nitrogen removal in the anolyte, as well as power generation potential. The combined system had an average COD removal efficiency of 48.98%, an average N removal efficiency of 52.27%, and a peak power density of 4.27 mW/m². The rate of plant growth (measured as wet weight) was found to be 24.88%. In comparison, the standard system had an average COD removal efficiency of 61.59%, an average N removal efficiency of 48.58%, and a peak power density of 0.29 mW/m². These findings demonstrate the

potential application of combined MEC–hydroponic systems for both wastewater treatment plants and agricultural systems in a circular economy framework.

8.13. Enhanced Removal of Micropollutants from Secondary Effluents Using UV/Sulfite and Biochar-Coupled Advanced Oxidation Processes

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Emerging micropollutants (MPs) in environmental matrices have received growing attention due to their detrimental effects on aquatic ecosystems. As a result, there is an urgent need to develop efficient removal strategies. Ultraviolet-based advanced oxidation processes (UV-AOPs) have emerged as a promising approach for degrading MPs in secondary wastewater effluents (SWEs). This study investigated the occurrence and advanced treatment of 50 MPs—including 8 perfluorinated compounds (PFCs), 23 pharmaceuticals, 2 pesticides, 4 endocrine-disrupting chemicals, 7 nitrosamines, 2 corrosion inhibitors, and 4 preservatives—across five wastewater treatment plants (WWTPs) in Korea. Detected concentrations ranged from 4.7 to 7851 ng/L, with metformin, cimetidine, caffeine, naproxen, atorvastatin, iopromide, estrone, and ibuprofen being the most prevalent. Most targeted PFCs and nitrosamines were detected at trace levels, typically between 1.4 and 28 ng/L. Under UV photolysis, the removal efficiency for most MPs was below 30% at UV fluence 750 mJ/cm². However, the UV/sulfite process significantly enhanced the removal of UV-resistant MPs (e.g., metformin, DEET, carbamazepine), achieving removal efficiencies greater than 80%. In contrast, PFCs exhibited notable degradation only when treated with UV/sulfite-coupled biochar systems. This study presents a comprehensive dataset on the occurrence, removal efficiency, and potential risks of MPs in Korean WWTPs. Furthermore, it highlights the effectiveness of UV/sulfite-coupled biochar systems as a promising strategy to enhance quaternary treatment and improve overall wastewater management.

8.14. Evaluating Sand-Based Clay for Adsorption of Caffeine, Methylparaben, and Trichlorocarbanilide Across Aqueous Media

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Water pollution faces significant challenges, particularly in urban and industrial settings, necessitating cost-effective and sustainable treatment methods. Adsorption using natural materials like clay has gained attention for its simplicity and efficacy in removing such pollutants. This study evaluates the adsorption efficiency of sand-based clay for removing caffeine, methylparaben, and trichlorocarbanilide (TCC) from wastewater (WW), river water (RW) (from Klodnica river, Gliwice), and distilled water (DW) over 96 h using UV-Vis spectrophotometry. Absorbance measurements revealed DW's superior removal efficiencies (caffeine: 81.92–84.21%, methylparaben: 80.19–85.94%, TCC: 79.46–87.63% at 96 h), followed by RW (caffeine: 57.67–75.19%, methylparaben: 73.27–76.34%, TCC: 64.92–84.43%) and WW (caffeine: 49.40–63.46%, methylparaben: 65.05–67.88%, TCC: 73.38–75.95%). Caffeine removal peaked at pH 7.12 in RW and DW, but pH 5.0 in WW; methylparaben showed optimal removal at pH 5.0 in DW and RW, and pH 9.0 in WW; TCC adsorption was highest at pH 9.0 across all media. A critical adsorption phase occurred between 48 and 72 h. These findings highlight sand-based clay's potential and its limitations as a cost-effective, sustainable adsorbent with performance varying by media and pH, informing advanced water treatment strategies. The results inform the development of clay-based filtration sys-

tems for municipal and industrial water treatment, offering scalable solutions for emerging contaminant removal. Further research is needed to optimize clay modifications and assess long-term performance in complex water matrices.

8.15. Heavy Metal Removal from Acid Mine Drainage Using Continuous-Flow Constructed Wetlands with Clamshell Substrate

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This study aimed to examine lab-scale constructed wetlands (CWs) for removing heavy metals from acid mine drainage (AMD). Two horizontal-subsurface-flow CWs filled with clamshells were prepared in parallel. One was planted with common reeds, while the other remained unplanted. Synthetic AMD containing 67.3 mg/L of Mn, 10.6 mg/L of Zn, and other minerals, with a pH of 5.3, was continuously fed to the CWs under hydraulic retention times (HRTs) of 12, 24, and 48 h. Throughout the experimental period, clamshells with high CaCO₃ contents exhibited great neutralization potential for AMD, with the effluent pH reaching 7.4–8.4. All clamshell-based CWs demonstrated high efficacy in removing Mn (83.6–92.3%), Zn (99.4–100%), and Cd, Cu, Fe, and Pb (97.8–100%) from AMD across all HRTs. However, slight Mn re-elution was noted at 48 h. Higher removal efficiency was observed in the planted CWs, with all heavy metals meeting the effluent standards. Oxygen and organic matter exuded from the roots of common reeds can promote the growth of Mn-oxidizing microbes, leading to the precipitation of Mn oxides. The Mn and Zn concentrations correlated negatively with pH values, implying that Zn was removed as Zn hydroxide and adsorbed onto Mn oxide. The findings highlighted the potential of clamshells, an aquaculture byproduct, as a filter medium in CWs for AMD treatment. This study offers an ecological approach to reducing the environmental burden of seashell waste while lowering the cost of wastewater treatment.

8.16. Hybrid Ultrasonic–Oxidative Treatment of PFASs in Firefighting Foams and Enriched Foam Waste

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Per- and polyfluoroalkyl substances (PFASs) are highly persistent and toxic contaminants, frequently associated with aqueous film-forming foams (AFFFs), a major source of soil and groundwater pollution. Foam fractionation (FF) is often used to concentrate PFASs from AFFFs, producing PFAS-rich foams that pose disposal challenges. Ultrasonic degradation has emerged as a promising remediation strategy, generating extreme cavitation conditions that induce both radical-mediated and pyrolytic breakdown of PFASs. This study evaluates the effect of oxidants—ferric chloride (FeCl₃), sodium persulfate (Na₂S₂O₈), and hydrogen peroxide (H₂O₂)—on the ultrasonic degradation of two model PFASs (PFOA and PFOS), AFFF, and FF. Ultrasound alone achieved notable defluorination in real-world matrices, with 40% and 46% efficiencies for AFFF and FF, respectively. Addition of Na₂S₂O₈ slightly increased AFFF defluorination to 46% but decreased FF defluorination to 44%, while H₂O₂ maintained 40% for AFFF and enhanced FF to 47%. These results indicate that oxidant effects depend on the matrix: components in AFFF can scavenge reactive species, limiting the benefit of added oxidants, whereas FF allows modest enhancement

with H₂O₂. In contrast, pure PFAS solutions consistently exhibited improved defluorination with oxidants. This work underscores both the potential of combining ultrasonication with oxidation chemistry and the critical role of matrix effects in designing effective hybrid PFAS remediation strategies.

8.17. Innovative Synergies: How SFDMBR, Electrochemical Processes, and Algae Transform Wastewater into a Resource

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The increasing water scarcity and the urgent need to mitigate climate change demand innovative approaches to wastewater treatment. This abstract explores a promising and novel technological approach that combines Self-Forming Dynamic Membrane Bioreactors (SFDMBRs) with electrochemical processes and algae integration, aiming to reuse wastewater and reduce CO₂.

SFDMBRs represent an evolution of conventional Membrane Bioreactors (MBRs), where a dynamic membrane forms in situ on a support structure. The application of an electric field enhances reactor performance by reducing membrane fouling, improving pollutant removal, and potentially disinfecting the effluent. This technology offers several advantages, including high effluent quality, a reduced footprint, and lower operational costs compared to traditional processes. The integration of electrochemical processes, such as electrocoagulation or electrolysis, can further enhance wastewater treatment. These processes effectively remove suspended solids, heavy metals, and other contaminants that are difficult to eliminate through biological treatments alone. Additionally, electrochemical processes facilitate the recovery of valuable resources from wastewater, such as phosphorus or metals.

The incorporation of algae into the system provides an additional treatment layer and an opportunity for CO₂ removal. Algae can absorb residual nutrients in wastewater, such as nitrogen and phosphorus, promoting their growth. During photosynthesis, algae consume CO₂, contributing to greenhouse gas emission reduction. The resulting algal biomass can be further utilized for bioenergy production or other valuable products.

This combination of technologies offers a sustainable and efficient approach to wastewater treatment. The results demonstrate that the high-quality water obtained enables reuse in various applications, reducing the demand for freshwater resources. Algae-driven CO₂ removal helps mitigate climate change. The synergy of SFDMBR, electrochemical processes, and algae has the potential to transform wastewater treatment into a resource-oriented process, contributing to a circular economy. Further research and development are needed to optimize the system and assess its economic feasibility on a large scale.

8.18. Integrating Hybrid Nature-Based Solutions for Pollutant Reduction and Biodiversity Promotion

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Aquatic ecosystems face increasing pressure from anthropogenic drivers, particularly emerging contaminants such as pesticides, pharmaceuticals, and PFAS. These pollutants are persistent, harmful to non-target species, and compromise ecosystem structure and function. Conventional wastewater treatment plants are often ineffective at removing such compounds, creating urgency for new, efficient, and sustainable solutions.

This project addresses this by integrating hybrid Nature-Based Solutions (NBSs)—constructed wetlands, artificial floating islands, and microalgae ponds—under real environmental conditions and at an intercontinental scale. This approach improves pollutant and nutrient removal, aligning with key policies, such as the EU Urban Wastewater Treatment Directive, the Water Framework Directive, and SDG 6. The project also explores interactions between sewage treatment and biodiversity support, contributing to enrichment and conservation in line with the EU Green Deal, EU Biodiversity Strategy for 2030, and SDG 15. Further, this project emphasizes the valorisation of wetland biomass for biogas and biochar production, fostering circular economy practices while enhancing NBS performance. The expected results are as follows: (1) the promotion of biodiversity and associated ecosystem services; (2) better removal efficiencies of emerging contaminants; (3) treated effluent post-intensified solution will show fewer toxic effects on model species compared to those treated with current solutions; (4) production of clean energy through the optimization of biogas production; and (5) promotion of environmental sustainability, climate mitigation, and human well-being through improved water quality, economic benefits, and enhanced recreational and resource recovery opportunities.

8.19. Investigation of Urea Behavior in Water Treatment and Wastewater Reuse Plants as Potential Sources for Ultrapure Water

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With the increasing demand for ultrapure water (UPW) in the semiconductor industry, alternative water sources such as wastewater reuse are being considered. However, the presence of low-molecular-weight organic matters like urea in wastewater treatment effluent can impair UPW quality, particularly by increasing total organic carbon (TOC) levels. Standard regulation limits for TOC are 1 ppb. This study examined urea behavior across different treatment processes, focusing on the source water and treatment stage. Three water treatment plants (WTPs) using various raw water sources and one wastewater reuse treatment plant (WRTP) were selected. Urea concentration, TOC, and other properties were analyzed at each stage to assess removal efficiency. In the WTPs, influent urea concentrations varied significantly depending on the water source, ranging from 20 to 250 ppb. Oxidative processes such as ozonation and UV treatment showed urea removal efficiencies of 0 to 30%. Notably, urea concentrations consistently decreased after the filtration–adsorption process (removing 5 to 60%) and in the clearwell. This reduction is likely due to microbial degradation within the filter media and potential reactions between urea and residual chlorine. In the WRTP, the RO process following biological treatment achieved urea removal efficiencies of 80 to 88%. This study reveals that urea behavior is

influenced by both source water quality and specific treatment processes. These findings are intended to help in designing and optimizing UPW system operations with alternative water sources.

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8.20. Liquid Biphasic Systems: Principles and Potential for Wastewater Treatment

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Water is one of the most vital natural resources, essential to all forms of life. As demand increases and pollution from domestic, industrial, and agricultural sources continues to grow, wastewater treatment has become an urgent challenge that must be addressed. Therefore, investment in novel techniques useful for the treatment and purification of this resource is of utmost importance. Liquid Biphasic Systems (LBSs) are a simple, biocompatible, and easily scalable liquid–liquid extraction technique which has shown significant potential for the recovery of target compounds, such as antipyretics and antibiotics, from water, enabling its purification. In this study, two new LBSs composed of three biodegradable, low-toxicity solvents were investigated: {ethyl acetate (1) + propan-1-ol or ethyl lactate (2) + water (3)}, at 298.15 K and 0.1 MPa. The second component in each system is miscible with ethyl acetate while being largely immiscible with water, allowing for the formation of two distinct liquid phases. The systems were characterised by determining the solubility curves using the cloud-point method and calculating the composition of 6 tie-lines through third-degree polynomial correlations of liquid density and refractive index. The tie-line lengths ranged from 41 to 77% in mass for the propan-1-ol system and from 47 to 103% in mass for the ethyl lactate system. Moreover, the experimental tie-line data were successfully correlated using the Othmer–Tobias and Bancroft–Hubard models, with both systems yielding coefficients of determination (R^2) greater than 0.985 for both models. The experimental liquid–liquid equilibria (LLE) data were then effectively described using the UNiVersal QUAsi-Chemical (UNIQUAC) model, with standard deviations (σ) lower than 10^{-3} being obtained for both systems. This work offers valuable insights into the phase separation behavior of two new LBSs, contributing to the advancement of greener and more efficient extraction techniques for sustainable wastewater purification.

8.21. Microplastic as a Pollutant That Poses Challenges in the Treatment of Stormwater

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Stormwater is increasingly being utilized for purposes beyond simply watering green spaces, cleaning public squares and parking lots, or flushing toilets. There is growing interest in developing technologies that allow for the use of stormwater across various industries, including recreational applications. One promising innovation in this field is the SwimmInRain technology, a method for utilizing rainwater in swimming pool installations that aligns with the principles of a circular economy. However, to assess the effectiveness of newly developed solutions, it is essential to understand the potential contaminants present in stormwater and their origin. To evaluate the effectiveness of new collection and treatment solutions, it is necessary to understand the potential contaminants present in stormwater, with particular emphasis on organic micropollutants and microplastics,

which can enter rainwater not only from the atmosphere itself but also from rainwater collection elements. This study aimed to identify those micropollutants in rainwater treated using SwimmInRain technology, an innovative method of using rainwater in swimming pool installations. Rainwater was collected from the roofs of industrial buildings in Spring 2025, straight from tanks made of HDPE with a capacity of 1000 L. The presence of microplastics and organic micropollutants was detected in each of the samples taken. The primary source of microplastic contamination is the high-density HDPE water storage tanks. Approximately 70% of the identified microplastic particles were blue fibers, corresponding to the typical color of HDPE tanks. Additionally, other types of microplastics, such as white and transparent fibers, were also found, indicating possible additional sources of contamination or degradation processes. The research conducted confirmed the hypothesis that microplastics are a source of other micropollutants and their gradual decomposition leads to their release into rainwater.

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8.22. Oxidative Aging of Polyvinyl Chloride (PVC) Microplastics: Implications for Vector Potential Toward Methylene Blue

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Polyvinyl chloride (PVC) microplastics (MPs) and methylene blue (MB) frequently co-exist in sewage effluents, raising concerns regarding their interactions and combined impacts during wastewater treatment. To explore the vector potential of PVC, MPs were subjected to controlled aging using potassium permanganate (KMnO₄) for two and five days under different operating conditions (pH, oxidant dosage, and reaction time) to simulate environmental oxidation. Surface characterization revealed the formation of manganese oxides (MnO₂) on aged PVC, which significantly modified its physicochemical properties. Scanning electron microscopy coupled with EDS (SEM-EDS) confirmed surface roughening and Mn deposition, while FTIR analysis identified the introduction of oxygen-containing functional groups, highlighting chemical transformation during aging. XRD provided evidence of MnO₂ crystallite deposition, and BET surface analysis demonstrated changes in surface area and porosity, both of which contributed to modified adsorption behavior.

Adsorption experiments showed that pristine PVC displayed minimal uptake of MB, whereas KMnO₄-aged PVC, particularly after oxidation, exhibited enhanced MB affinity due to MnO₂ nanoparticle coating. Furthermore, the desorption studies indicated reduced release of MB, suggesting strong MnO₂-dye interactions and greater persistence of pollutant-polymer complexes. Therefore, these results highlight the aging role of KMnO₄ in PVC, which facilitated its affinity for MB, increasing its vector role potential and revealing corresponding associated environmental risks.

Overall, these findings offer mechanistic insights into how oxidative aging alters MPs' structure and reactivity. Therefore, the findings not only contribute to understanding the fate and transport behavior of MPs with contaminants in aqueous systems but also inform sustainable remediation strategies for mitigating microplastic-pollutant risks in aquatic environments.

8.23. Polyurethane–Biochar Composite from Bauhinia Purpurea Pods for Efficient Dye Removal from Industrial Wastewater

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Discharge of dye-containing industrial effluents into water bodies poses a threat to the environment and public health due to the recalcitrant and toxic nature of synthetic dyes such as methylene blue (MB). In this study, a low-cost and environmentally friendly approach towards the removal of MB from water systems was investigated using a new composite adsorbent. The adsorbent was synthesized by incorporating activated carbon—prepared from Bauhinia purpurea seedpods—into a polyurethane matrix. Batch adsorption experiments were conducted to examine the influence of the most significant operating parameters, such as pH, contact time, initial dye concentration, and activated carbon loading, on the efficacy of the removal of dye. Material characterization techniques such as Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), and X-ray Diffraction (XRD) were used to quantify morphology and functional groups, whereas X-ray Fluorescence (XRF) was used to quantify the elemental composition of the raw biomass. The results verified that optimum removal of dye (97% efficiency) was achieved using a 30% loading of activated carbon, initial dye concentration of 100 mg/L, unchanged pH, 25 °C temperature, and 240-min contact time. Data for adsorption isotherms were best described using the Langmuir isotherm model, which points towards monolayer adsorption, whereas kinetic data fitted well with both pseudo-first-order and pseudo-second-order models. This research recognizes the potential of agro-waste composites as efficient and green adsorbents for wastewater treatment and dye decolorization in enhancing circular and sustainable water management.

8.24. Removal of Heavy Metals from Drinking Water Through Agri-Food Bioadsorbents

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This research experiment explores the feasibility of employing agro-industrial residues, specifically pig hair and rice husk, as bio adsorbents for the removal of heavy metals from contaminated water. Controlled laboratory experiments, supported by spectroscopic analyses, were conducted to evaluate their effectiveness as a sustainable, low-cost, and environmentally responsible alternative to conventional treatment technologies. The research objectives are threefold: (i) to determine the bio adsorptive capacity of both materials against selected metal species; (ii) to identify optimal experimental conditions, including variations in pH, initial concentration, and contact time, and to characterize the mechanisms governing the adsorption processes; and (iii) to propose an approach based on low-cost, widely available resources with potential application in decentralized small-scale water treatment systems. The preliminary results obtained indicate that both agro-industrial residues exhibit a significant capacity to remove Cr⁶⁺ and Al³⁺ from aqueous solutions. In this regard, pig hair has demonstrated higher efficiency (85% compared to 65% in the case of rice husk). On the other hand, the main limitation lies in the exclusive use of synthetic water, which necessitates validation under real water matrices. Future applicability could

materialize in modular, adaptable treatment solutions, particularly relevant for industries discharging metallic effluents and for rural communities with technological constraints.

8.25. Removal of Organic Contaminants via Electro-Activated Biochar Suspensions

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Conventional water and wastewater treatment methods are often inadequate for the complete elimination of persistent contaminants of emerging concern (CECs), which can cause risks to human health and ecosystems. Given that clean water is fundamental, the development of new sustainable technologies to ensure both access to clean water and its safe discharge has become an urgent priority.

Electrochemical-advanced oxidation processes (EAOPs) have emerged as a promising alternative. EAOPs operate under mild conditions to produce reactive oxidants (e.g., $\bullet\text{OH}$) that oxidize and mineralize pollutants into less harmful species. In addition, to improve reaction efficiency, carbon-based catalysts were added into EAOPs. For the synthesis of these materials, grape pomace was used as biomass for the biochar (BC), thiourea and dicyandiamide were used as functionalizers (BC-T and BC-D) and potassium hydroxide was used for activation (BC-TK and BC-DK).

This study focused on the degradation of venlafaxine (VFX), a common CEC found in wastewater by assessing different cathodes (i.e., Nickel, Stainless Steel, Titanium and Carbon Foam) paired with boron-doped diamond (BDD) as an anode for the EAOPs. Also, for electrolytes, sodium-based salts were assessed. Adsorption tests showed that after 2 h BC-DK and BC-TK removed 35% and 87% of VFX, respectively, improving efficiency when compared to non-activated ones. However, when BDD was paired with a nickel cathode in a solution of 6 mM of NaCl; as a result, VFX removal increased significantly, with BC-T reaching 80% and BC-DK 95% within 5 min, whereas electrolysis without catalysts removed less than 20% within the same period of treatment. These findings highlight the potential of combining EAOPs with carbon-based catalysts as a sustainable and highly efficient approach for water and wastewater treatment, while valorising solid waste that would otherwise be discarded.

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8.26. Removal of Pharmaceutical Compounds onto Activated Carbon: Insights into the Adsorption Mechanism

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Water pollution has intensified in recent years, with pharmaceutical residues emerging as critical contaminants of global concern. Commonly detected in rivers, lakes, and even drinking water, these compounds pose serious ecological and health risks, including embryotoxicity, oxidative stress, antimicrobial resistance, and cardiovascular dysfunction. Conventional wastewater treatments are often ineffective in eliminating such micropollutants, which has motivated the exploration of advanced and sustainable remediation methods. Among these, adsorption is considered one of the most reliable and efficient approaches, with activated carbon widely recognized as the benchmark adsorbent in water treatment applications.

In this study, we evaluate the adsorption efficiency of three widely used pharmaceuticals, ofloxacin, ceftriaxone, and metformin, which are mainly excreted in unmetabolized form and frequently reported in aquatic environments. Batch adsorption experiments were performed at an initial pollutant concentration of 50 mg/L, in the presence of activated carbon, while investigating the effects of adsorbent dosage, initial concentration, and pH conditions. Results demonstrated that the antibiotics achieved removal efficiencies exceeding 90% at neutral pH values. In contrast, metformin adsorption was negligible under the same conditions but increased significantly in acidic media, consistent with its structural and ionization characteristics.

Adsorption data for ceftriaxone and ofloxacin fitted the Langmuir isotherm model with high correlation coefficients ($R^2 = 0.983$ and 0.986 , respectively), confirming a monolayer adsorption process. These findings clarify the contrasting adsorption behaviors of antibiotics and antidiabetic drugs, emphasize the importance of optimizing operational parameters, and provide valuable insights into the mechanisms governing pharmaceutical adsorption on activated carbon.

8.27. Sustainable and Digitalized Water Management in Rural Areas of the SUDOE Region: The GestEAUr Project

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Rural areas in the SUDOE region (Portugal, Spain, Andorra, and the south of France) face multiple common challenges in relation to the integral water cycle: water scarcity (exacerbated by climate change); the impact of agricultural activity on water quality (and the resulting difficulty of reconciling compliance with European directives, the continuity of economic activity, and the availability of drinking water); and inefficient and unprofitable management (with obsolete facilities and limited human resources). In this context, it is essential to strengthen the networks of collaboration between the many actors involved in water resource management to implement efficient, sustainable, and cost-effective techniques for water purification, reuse, and treatment. To this end, it is necessary to create a new system of governance based on territorial cooperation. Through the development of a strategy to improve water efficiency and quality in these rural areas and in the context of climate change, the aim is to improve water supply and treatment services by experimenting with pilot plants for cost-effective and sustainable solutions for water purification, treatment, and reuse. This communication is focused on presenting the innovative approaches applied in the pilot tests within the framework of the GestEAUr project, addressing the entire water cycle holistically. Specifically, the focus will be on (i) membrane and electro-assisted technologies with “in situ” electrochemical synthesis of oxidants for drinking water treatment, (ii) nature-based solutions (NbSs) for wastewater treatment and water reuse, and (iii) advanced oxidation processes-based technologies for wastewater disinfection and detoxification.

8.28. *The Role of Cation and Anion Exchange Membranes on Power Generation and Nutrient Removal in a Microalgae-Assisted Microbial Fuel Cell*

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Microalgae have a wide array of bio electrochemical wastewater treatment applications, including their role as an in-situ oxygen supplier in the cathode chamber of a double-chamber microbial fuel cell (MFC). In this application, oxygen produced from the microalgae serves as a terminal electron acceptor to readily supplement the cathodic reduction reaction, which is the key to the sustenance of electron generation in MFCs. Furthermore, increased rates of nutrient removal (nitrogen and/or phosphorus) in the MFC can be observed. In this study, the growth and performance of cathodic microalgae, based on the above parameters, are examined in MFCs containing a cation exchange membrane (CEM) and an anion exchange membrane (AEM). Influent of a municipal wastewater treatment plant after the primary treatment is utilized as a substrate in the anode chambers, and pre-cultivated microalgae (*Chlorella vulgaris*) are introduced into the cathode chambers of both MFCs. The performance of the MFCs is constantly analyzed using various analytical methods. Phosphate buffers are utilized to manage pH spikes that could occur in the reactors. This study provides a unique understanding of how compositional differences in the cathodic substrate, imposed by the type of membrane, affect the algae's influence on the cathodic reduction reaction. The study's findings can supplement the establishment of more efficient MFC configurations to address certain limitations, such as low power density, and facilitate progression in the utilization of MFCs in large-scale wastewater treatment plants.

8.29. *Treatment of Reactive Blue Dye Textile Wastewater Using Copper-Based Metal–Organic Framework*

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Synthetic dyes in industrial effluents are known to persist in the environment due to their stability and resistance to conventional biological and chemical treatments. As a result, there is a growing interest in alternative approaches such as photocatalysis, which is regarded as an efficient and environmentally friendly advanced oxidation process. Metal–organic frameworks (MOFs), particularly those incorporating copper, have recently shown great potential as photocatalysts due to their unique structural features, light-responsive behavior, and catalytic capabilities. This study focuses on the development and evaluation of a copper-based MOF, [Cu(4,4'-bipy)Cl]_n, synthesized using a hydrothermal method with 4,4'-bipyridine as a linker, for the degradation of reactive blue dye under natural sunlight.

Comprehensive characterization of the synthesized MOF was performed using Fourier Transform Infrared Spectroscopy (FTIR) to identify functional groups, Scanning Electron Microscopy (SEM) to analyze surface morphology, X-ray Diffraction (XRD) for phase identification, and UV–Visible Diffuse Reflectance Spectroscopy (DRS) to investigate optical properties. The impact of various operational parameters such as initial dye concentration, photocatalyst loading, and solution pH was examined to establish optimal degradation conditions. Under the best experimental conditions (0.4 mg/L dye concentration, 0.45 g catalyst, and pH 10), the Cu-MOF achieved a high degradation rate of 93.7%. Control tests confirmed that dye removal by photolysis was negligible and that dark adsorption accounted for approximately 30% removal. The catalyst's stability was assessed over five reuse cycles, with degradation efficiency consistently exceeding 85%, indicating a modest reduction of approximately 8.7% in performance. The findings demonstrate that the Cu-based MOF is a robust and efficient material for the photocatalytic treatment of dye-contaminated water, presenting a viable solution for sustainable wastewater remediation.

8.30. Turning Vegetable Residues into Coagulants: Sustainable Solutions for Agri-Food Wastewater

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The increasing global population poses major challenges for food production. With the increasingly fast pace of people's lives and the growing demand for healthy and ready-to-eat foods, the frozen vegetable and ready-to-eat salad sector in supermarkets is expanding, driving growth in the agri-food industry. These industries generate large amounts of vegetable residues and wastewater. Coagulation/flocculation is a common treatment method, but its reliance on metallic salts poses environmental and economic drawbacks. This study explored sustainable alternatives using tannin-based coagulants from vegetable residues. Kale residues were first investigated as a potential tannin source. A Box–Behnken design evaluated extraction time, temperature, and liquid-to-solid ratio, with distilled water as solvent. Optimum conditions (50 min, 40 mL·g^{−1}, 75 °C) yielded 49.3 ± 0.1% extraction and 23.4 ± 0.8 mg GAE/g of extract. However, kale proved unsuitable due to its low tannin content. Given Portugal's role as a leading chestnut producer, along with the high tannin content of chestnut shells (CSs) and their proven capability as coagulant sources, this residue was selected as an alternative. CS tannins were chemically modified to enhance their cationic properties and for application as coagulants for agri-food industry wastewater treatment. The efficiency of the CS-based coagulant was compared with that of Tanfloc, a commercial tannin-based coagulant. The CS coagulant was able to reduce the initial color by 74% at pH 6, with a dose of 125 mg·L^{−1} and 30 min of sedimentation. In comparison, Tanfloc achieved a similar color removal (68%) under the same pH but required a higher coagulant dose of 450 mg·L^{−1} and longer sedimentation time (135 min). Regarding organic matter, Tanfloc reduced around 34% of the initial dissolved organic carbon, whereas the CS-based coagulant achieved only 3%. It is possible to conclude that

the CS-based coagulant is a good and sustainable treatment solution for color removal from agri-food industry wastewater.

8.31. Water Treatment by Adsorption on Sage-Based Adsorbents: Removal of Pollutants and Phytotoxicity

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Water pollution is a critical global issue that endangers ecosystems and human health. The development of eco-friendly and sustainable adsorbent materials is essential for removing various contaminants, including synthetic dyes, nitrates, phosphates, and pathogenic microorganisms from water sources. In this study, we explored the adsorption efficiency and phytotoxicity of three bioadsorbents derived from *Salvia officinalis* (sage): (1) untreated sage powder (S), (2) sage-derived biochar produced by pyrolysis at 300 °C (C), and (3) activated charcoal (AC) prepared by chemical activation with phosphoric acid followed by pyrolysis at 450 °C. The materials were tested for their capacity to remove methylene blue dye, nitrates, phosphates, and bacterial contaminants (*Escherichia coli*, total coliforms, and *Streptococcus D*) under controlled laboratory conditions. Results showed that activated charcoal (AC) had the highest removal efficiency for phosphates (0.122 mg/g, 49%) and nitrates (1.72 mg/g), along with the most significant reduction in bacterial concentrations. Interestingly, the untreated sage powder (S) displayed the greatest capacity for methylene blue adsorption (4.34 mg/g), suggesting its potential for dye-contaminated water treatment. Phytotoxicity assays using *Eruca vesicaria* (arugula) indicated that AC exhibited low toxicity in aqueous conditions, and both S and AC supported plant growth in solid (soil-like) media. These findings suggest that sage-derived bioadsorbents, particularly activated charcoal, offer a promising, low-cost, and sustainable solution for integrated water treatment. Their dual capacity to remove chemical and biological pollutants while maintaining low phytotoxicity makes them attractive candidates for eco-friendly environmental remediation strategies.

9. Agricultural Water Systems

9.1. Impact of Deficit Irrigation on Major Irrigated Crop Yield and Water Productivity: A Meta Analysis

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To meet global food demand, strategies promoting efficient water use are essential for sustainable agricultural practice. Deficit irrigation (DI) is currently promoted as a water-saving strategy, though reports on its effect on yield and water productivity (WP) remain inconsistent. To address this inconsistency, we conducted a meta-analysis on eight crops in Ethiopia: maize, wheat, sesame, bean, onion, potato, tomato, and pepper. We used climate, soil type, soil type, soil pH, irrigation method, crop type, and irrigation water amount as explanatory variables. As expected, the amount of irrigation water was found to be the primary factor influencing yield loss. Sesame, tomato, and wheat showed the greatest resilience to water stress even at low DI levels (50% crop water requirement (ET_c)). Applying DI at 50–70% of ET_c in wheat increased WP by 48% with only a 16% yield loss. Similarly, in tomato, WP improved by 51% with a 21% yield reduction. Across all moderators, applying DI at 80% ET_c was found to be statistically ($p > 0.05$) the same as full irrigation in terms of crop yield. Practicing DI with drip irrigation under DI levels below 80% ET_c was not found to be promising, as it resulted in high yield loss (up to 45%) with minimal WP gain. In contrast, alternate and fixed furrow irrigation methods performed well at 70–80% ET_c, maintaining low yield loss with significant WP improvement. These irrigation methods performed best at 100% ET_c with 50% WP improvement and 18% yield reduction. These findings provide valuable insights for optimizing irrigation strategies and support informed decision-making for sustainable agricultural water management.

9.2. Performance Evaluation and Energy Optimization of Centrifugal Pumps for Agricultural Water Systems in Pakistan Under a Changing Energy and Water Landscape

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Efficient water pumping is critical to sustaining agricultural productivity in water-stressed and energy-deficient regions. This study evaluates the hydraulic performance and energy efficiency of locally manufactured centrifugal pumps commonly used for groundwater extraction in Pakistan's agriculture sector. Field and laboratory-based testing were conducted on eight centrifugal pumps with varying impeller and casing sizes to develop performance curves under different operating conditions. Key metrics, including flow rate, head, energy input, and associated hydraulic losses, were measured to compute actual pump efficiency. The results indicate that oversized pumps and mismatched motor-impeller combinations lead to substantial energy wastage—up to 37% over design in some cases. Impeller trimming, a conventional technique used to align pump output with demand, was experimentally tested and found to reduce pump efficiency from 78.5% to 67.1% across trimmed stages. Larger pumps (e.g., 5''–6'' casings) exhibited higher efficiency (up to 76.5%) than smaller counterparts (e.g., 2.5''–3'' casing at 63.2%). The study also highlights significant head losses due to fittings like bends, reducers, and check valves, emphasizing the need for optimal pump system design. These findings underscore the

importance of optimized pump selection, performance monitoring, and energy efficiency retrofits in agricultural water systems, particularly under rising energy costs and declining groundwater tables. In the face of climate variability and water scarcity, such optimizations present scalable solutions for resilient and sustainable irrigation infrastructure in South Asia and beyond.

9.3. Subsurface Drain Spacing Estimation at the Watershed Level by Using the SWAT Model and the Donnan–Hooghoudt Equation

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The estimation of subsurface drain spacing at large scales remains a challenging task due to the combined influence of heterogeneous land uses, complex topography, diverse soil types, and variable soil hydraulic properties. In this study, a combined approach is developed based on the SWAT (Soil and Water Assessment Tool) hydrological model and the well-established Donnan–Hooghoudt equation to assess subsurface drain spacing at the watershed level. The SWAT model was first employed for watershed delineation and subdivision into hydrologically meaningful sub-basins, accounting for spatial variability in land use, topography, soil characteristics, and climatic conditions. Open access datasets were used for the SWAT input geospatial layers and also to derive soil hydraulic parameters (e.g., saturated hydraulic conductivity) as well as crop distribution at the parcel level. For each sub-basin, key variables were determined, including dominant crop type, representative root depth, depth to the impermeable layer, and target groundwater table depth. Subsequently, the Donnan–Hooghoudt equation was applied within each sub-basin to estimate the appropriate drain spacing, tailored to its specific soil, crop, and hydrological requirements. The methodology was tested in the Zazari–Chimaditida sub-basin in Western Macedonia, Greece. The results demonstrate substantial spatial variability in drain spacing across the sub-basins, ranging from 26 m to 73 m. This variability highlights the critical role of SWAT-based watershed discretization and the spatial resolution of input datasets in drainage design.

9.4. A Modified PhenoRice for Regional Mapping of Planting Date in Dry-Seeded Rice Systems in Northeast Thailand

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In Northeast Thailand, approximately 90% of paddies are rainfed, and planting activities depend on the onset of the rainy season. As a result, planting dates exhibit considerable spatial and temporal variability. However, previous studies estimating rice production in this region have rarely accounted for such variability, mainly due to the lack of observational data with sufficient spatiotemporal distribution. To address this limitation, we used PhenoRice, a satellite-based model that estimates rice planting dates by analyzing MODIS time series. PhenoRice identifies phenological stages using the Enhanced Vegetation Index (EVI), which reflects canopy greenness, and the Normalized Difference Water Index (NDWI), which indicates surface water. Nevertheless, in Northeast Thailand, most paddies

are established using dry direct seeding (DDS), where no standing water is present before planting. This contrasts with the assumptions of the original PhenoRice model, which relies on detecting pre-planting flooding. Furthermore, PhenoRice uses 250-m MODIS data, which makes large-scale analysis over the entire 170,000 km² region of Northeast Thailand impractical. Therefore, we developed a modified version of PhenoRice that is calibrated with local observations, adapted for DDS systems, and capable of using 1-km MODIS data for wide-area application. The model was validated using province-level monthly planted area statistics provided by the Office of Agricultural Economics, Thailand. The results showed a correlation coefficient of 0.59 and a root mean square error (RMSE) of 631 km², equivalent to about 10% of the regional rice area. However, model performance declined in 2002 and 2019, likely due to drought and typhoon-induced flooding. This indicates that while the model is effective under normal conditions, its accuracy is limited under extreme weather events during the growing season. The estimated planting dates from this model could be integrated into crop simulation models such as ORYZA2000 to improve rice yield estimation based on realistic planting conditions.

9.5. Assessing the Trade-Offs Between Nitrate Water Pollution and Water Conservation for Cost-Efficient River Basin Management

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The intensification of agricultural activities, which are crucial for sustaining crop productivity in rural areas, can also lead to the depletion of water supplies and the degradation of water quality. The challenge of simultaneously addressing nitrate water pollution and water scarcity at a river basin scale requires the consideration of trade-offs between economic and environmental targets. The adoption of Best Management Practices (BMPs) in agriculture to address this issue is becoming increasingly widespread. This study implemented the Soil Water Assessment Tool (SWAT), a process-based river basin model that simulates hydrology, nutrient cycles, and crop growth, to evaluate nitrate discharges from agriculture to surface water and conserve irrigation water in response to alternative agricultural management practices that were accurately costed. The model was embedded within a decision support tool, enhanced by a multi-objective optimization algorithm to analyze possible alternative management schemes, suggesting the most efficient allocation of BMPs to address the above-mentioned water objectives at the river basin scale. Various BMPs, such as individual and combined changes in livestock and farming practices (including reduced fertilization, deficit irrigation, precision irrigation, cover crops, livestock stocking rate reduction, and a shortened grazing season), were explored in the Pinios river basin, demonstrating the methodology's effectiveness. The results showed that a well-balanced combination of alternative agricultural practices is very effective in reducing nitrate nitrogen by up to 13% and irrigation water consumption by up to 22% without significantly affecting profits. Among the BMPs applied, fertilization control and deficit irrigation, along with cover crops used as green manure, appeared as particularly effective. The present methodological approach can assist in the prioritization of suitable management strategies by combining a process-based hydrological model with cost estimations and an optimization algorithm and is considered valuable in supporting decision-making aimed at the enhancement of water quality and quantity in extensively managed agricultural catchments.

9.6. Comparative Evaluation of the Yield Characteristics of *Sideritis Raeseri* Under Different Irrigation Levels

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Background-Objective

Sideritis raeseri (Greek mountain tea) grows naturally at high altitudes (over 1000 m). The plant is native and endemic, as it grows exclusively in Greece. Native plants are declining due to wildfires, uncontrolled grazing, harvesting, and climate change, while increased market demands lead to the need for cultivation, which in turn leads to sustainable utilization and protection of the plant. Usually, studies focus on genetics, nutrients, and essential oils; thus, there is a significant gap in water use. The present study aims to investigate the effect of irrigation levels on growth characteristics, yield, and water use efficiency (WUE) when cultivating *tea* in plains, where environmental conditions differ from its natural habitat.

Methods

An experimental design consisting of four treatments (0%ET-50%ET-75%ET-100%ET), three replications, 60 plants/plot, was configured at the University of Thessaly farm (70 m altitude). Water needs were based on Penman-Monteith. Considering factors as emitters/plant, distance between plants and rows, irrigation timing, dose, and duration were determined.

Results

The statistical analysis showed significant differences between the 0%ET and all other treatments regarding plant height, fresh and dry biomass, indicating that irrigation is essential at low altitudes. The 75%ET treatment showed the highest WUE; particularly, 75%ET and 100%ET treatments showed the best growth and yield characteristics with no statistically significant differences between them. However, the correlation of dry biomass with the total water applied indicated that the 75%ET treatment was superior in terms of WUE.

Conclusions

Given its demand, Greek mountain tea can be an alternative crop for farmers at low altitudes, under the condition of irrigation. High yield can be achieved by applying 75%ET, as the plant's water stress is tolerable, and significant water savings (25%) can be achieved simultaneously. The approach enhances the direction of sustainable water use and contributes to the long-term protection of the plant.

9.7. Effects of Hydraulic Retention Time on Performance, Mechanisms, and Microbial Communities in a Multi-Stage Constructed Wetland for Treating Aquaculture Tailwater

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In China, aquaculture accounts for over 80% of aquatic product supply, playing a vital role in safeguarding national nutrition and driving economic growth. However, the substan-

tial annual discharge of aquaculture wastewater has raised serious environmental-related concerns. As a result, the removal of nitrogen and phosphorus from such wastewater has become essential for promoting the sustainable development of the aquaculture. Although many multi-stage treatment systems, often referred to as “three ponds and two dams”, have been constructed to treat aquaculture tailwater, key operational parameters, such as hydraulic retention time (HRT) still lack scientific justification. Therefore, our study established a multi-stage constructed wetland system (MCWS) consisting of a sedimentation pond (SP), filtration dam A (FDA), an aerobic pond (AP), filtration dam B (FDB), and an ecological purification pond (EP). We investigated the effect of HRT on nitrogen and phosphorus removal and explored the associated microbial mechanisms. The system was operated continuously for 142 days under four HRT conditions (24 h, 48 h, 96 h, and 192 h), during which we monitored pollutant removal efficiencies and microbial community dynamics. The results showed that with the extension of HRT, the removal efficiency of TN and TP gradually increased. When the HTR was 192 h, TN decreased from 25.74 mg/L to 2.59 mg/L, TP decreased from 5.78 mg/L to 0.92 mg/L, and the removal rates were 89.77% and 80.91%, respectively. Functional units exhibited clear synergistic effects: denitrifying bacteria in SP facilitated heterotrophic nitrate reduction; photosynthetic nitrogen-fixing bacteria and polyphosphate-accumulating organisms thrived in the high-dissolved-oxygen environment of AP; and cyanobacteria in EP contributed to photosynthetic nitrogen fixation coupled with nitrate assimilation, enabling advanced nitrogen removal. This study clarifies the microbial metabolic pathways and pollutant removal mechanisms within each unit of the MCWS, providing a theoretical basis for the engineering design and operational optimization of multi-stage treatment systems for aquaculture wastewater.

9.8. Evaluating the Environmental and Economic Trade-Offs of Introducing Perennial Bioenergy Crops in the Low-Productivity Land of a Greek Agricultural Basin

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The Pinios River Basin in Thessaly, Greece, is the country's most important agricultural producer. Still, it faces increasing environmental pressures, particularly in relation to the decline in water quality, due to intensive farming practices. Cultivating perennial bioenergy crops can be a promising strategy since it supports both environmental and renewable energy production goals. However, to avoid competition with food and fiber crops, the highly productive agricultural land should remain prioritized for them and the installation of perennial bioenergy crops, such as switchgrass, miscanthus and cardoon, should be targeted in lower-productivity areas, characterized by poor soil texture, shallow rooting depth and steeper slopes. This study utilizes the river basin Soil and Water Assessment Tool (SWAT) to develop a representative model of the Pinios River Basin and evaluate its status with respect to nitrate (N-NO₃) water pollution. Based on a comprehensive representation of agricultural management, the model simulates crop growth and water N-NO₃ loads arising from the cropland of the basin. A multi-objective Genetic Algorithm embedded in MATLAB is linked to SWAT and after a large number of simulations, it identifies optimum spatial allocations of the bioenergy crops in the agricultural land with respect to the farmers' net income, biomass production and surface water quality. The analysis of the resulting

trade-off curves among the objectives reveals interesting spatial distributions of the crops, with selected optimal solutions indicating that each bioenergy crop responds differently to local conditions, showing higher effectiveness in certain areas of lower productivity in the basin. The results support the inclusion of perennial bioenergy crops in future sustainable cropping systems as a strategy towards the improvement in water quality and the generation of substantial biomass for renewable energy production.

9.9. Evaluating the Influence of Dripline Spacing on Corn Grain Yield in the Sandy Soil of Southeast Coastal Plains

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As drought stress increasingly threatens corn production, subsurface drip irrigation (SDI) has emerged as a critical component of adaptive corn management. However, the cost-effectiveness and agronomic performance of varying dripline spacings remain uncertain, especially in sandy soils. This three-year field study (2022–2024) in the Eastern Coastal Plains of Virginia evaluated the agronomic and economic impacts of two SDI dripline spacings, narrow (0.91 m) and wide (1.82 m), on corn grain yield. This study was conducted on a long-term SDI system established in 2017 using a split-split plot design with irrigation as the whole plot, seeding rates as sub-plots, and nitrogen (N) rates as sub-sub-plots. Irrigation scheduling followed the checkbook method. The analysis of three years of data revealed significant yield advantages for narrow spacing (11,466 kg ha⁻¹) over wider spacing (10,688 kg ha⁻¹) and the non-irrigated control (7359 kg ha⁻¹) ($p < 0.001$). Nitrogen application rates also significantly influenced yield, with 200, 267, and 333 kg N ha⁻¹ outperforming the 133 kg N ha⁻¹ treatment ($p = 0.008$). Seeding rates of 74,100 and 88,920 seeds ha⁻¹ achieved the highest yields (9984 and 10,132 kg ha⁻¹, respectively; $p < 0.001$). Notable interactions occurred between dripline spacing and N rates ($p = 0.002$), where narrow spacing with 333 kg N ha⁻¹ produced the highest yield (12,401 kg ha⁻¹). Overall, narrow dripline spacing proved more agronomically productive and potentially more cost-effective, despite the initial higher system cost (USD 6175). These findings suggest that tighter dripline spacing in SDI systems may offer better yield stability and return on investment in sandy, drought-prone regions.

9.10. Optimizing Irrigation in Lemon Trees: Balancing Water Savings and Yield Under Climate Change

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Mediterranean regions play a central role in lemon (*Citrus x limon* (L.) Osbeck) production but increasing water scarcity and temperature extremes under climate change have made orchards highly vulnerable. Deficit irrigation (DI) has been proposed as a strategy to improve water use efficiency without compromising productivity.

In this experiment, three irrigation regimes were compared: a Control at 4.0 L/h, DI1 at 3.5 L/h ($\approx 12\%$ reduction), and DI2 at 2.7 L/h ($\approx 32\%$ reduction). Each treatment consisted of ten trees, irrigated twice weekly with two drippers for 90–120 min over an eight-month period. All trees were mulched with black plastic. Growth dynamics, photosynthetic efficiency, and fruit organoleptic attributes were monitored.

Results showed that DI1 maintained yields at levels comparable to the Control, with only minor decreases ($\approx 5\text{--}7\%$) in photosynthetic rates, vegetative growth, and fruit quality traits. In contrast, DI2 produced substantial declines, with photosynthetic activity reduced by up to 25%, vegetative growth by 30%, and fruit sensory properties (flavor and juiciness) significantly affected. Nevertheless, DI2 ensured tree survival under severe water restriction.

The study demonstrates that a moderate water reduction (DI1) can be applied to young orchards (0–7 years old) during seasons with average or above-average rainfall, optimizing water use without compromising production. Severe restriction (DI2) is not suitable for commercial yield but may serve as an emergency strategy under extreme drought conditions.

These findings emphasize the potential of carefully adjusted DI strategies as an adaptation measure for Mediterranean lemon orchards, contributing to sustainable management in water-limited environments.

9.11. Photosynthesis-Driven Capillary Rise and Daily Salinity Dynamics in an Agricultural System of the Po River Lowland

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Introduction

In many places, soils and water resources are subject to growing salinity levels. Soil salinization processes are extremely complex and often related to various factors: climate, sea salt spray deposition, capillary rise of paleosaline groundwater, irrigation with poor-quality water and salt evapoconcentration triggered by plant activity. The latter is often overlooked, yet it is a significant additional source of salinity, particularly in agricultural soils. This study investigates the role of plant activity in the daily fluctuation of pore water salinity and soil volumetric water content (VWC) in an agricultural system.

Methods

The study site is located in the Po River lowland (Northern Italy) approximately 24 km from the Adriatic Sea. Soil bulk electrical conductivity (EC_b) and VWC were detected every 30 min using 5TE[®] probes from Meter. Concurrently, a fixed video camera monitored water level fluctuations in an adjacent irrigation canal.

Results

EC_b in the first 15 cm ranged between 0.76 and 5.75 mS/cm, while the VWC ranged between 0.26 and 0.44 m³/m³. In comparison, groundwater EC at -2.7 m below ground level ranged between 11.16 and 17.01 mS/cm. EC_b in the first 15 cm exhibited the lowest daily peaks in the early afternoon hours. In contrast, the VWC experienced its highest daily peaks during this time interval. At this time of day, plants' photosynthetic activity was at

its highest, absorbing more water and triggering an upward capillary flow. The monitoring of the canal water level revealed an exact opposite pattern to that of the soil VWC.

Conclusions

Photosynthesis-driven water uptake in crop systems can trigger significant capillary rise from irrigation canals, modulating soil moisture and salinity before irrigation. Integrating EC, VWC, and canal level monitoring can refine irrigation timing to match plant demand and natural capillary supply.

9.12. Productive Potential of Floating Wetland Islands for Sustainable Agriculture

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Floating wetland islands (FWIs) are artificial platforms designed to float on water bodies while supporting plant growth, representing a promising integration of ecological engineering and crop production. Originally developed for water quality improvement, FWIs have evolved into multifunctional systems capable of cultivating edible crops, such as lettuce, spinach, and rice, within nutrient-rich aquatic environments. Their dual role in environmental remediation and food production positions FWIs as innovative nature-based solutions (NbSs) aligned with sustainable development goals. This study identifies and discusses the key components, challenges and future opportunities for the application of FWIs in agricultural contexts. Design parameters, such as crop selection, substrate type and platform buoyancy, play a crucial role in system stability and productivity. Operational aspects, such as maintenance, cost-effectiveness and social acceptance, determine the feasibility of large-scale application. From an agronomic point of view, FWIs enable biomass production, nutrient uptake and safe food cultivation, although potential toxicity must be considered. Beyond agriculture, FWIs contribute to water treatment through nutrient removal, pollutant reduction and water reuse, reinforcing their role as low-impact, decentralized systems for polluted water bodies. They also offer important environmental benefits, such as carbon sequestration, nutrient cycling and improved landscape aesthetics. Looking ahead, FWIs present great potential for integration into the circular economy, technological innovation and climate adaptation strategies, especially in regions facing water scarcity, land degradation or urban sprawl. Their multifunctionality and adaptability highlight that FWIs are resilient systems that link food production with environmental sustainability. This study contributes to the growing knowledge gap on FWIs and supports their application as sustainable alternatives for integrated agriculture and water management.

9.13. The Effect of Water Quality on Lettuce Growth in Deep-Culture Hydroponic Systems

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Hydroponic systems are identified as efficient soilless alternatives to mainstream agriculture. Ensuring proper physical and chemical composition of the nutrient solution is the key to fostering the plant's growth in hydroponic systems. In this study, the effect of overall water quality parameters including electrical conductivity, nutrient levels, and the

effects of pH and aeration on the growth of lettuce in a controlled hydroponic environment was investigated. This research aims to identify an effective strategy to enhance resource efficiency, crop yield, and water quality management in hydroponic systems.

Seventy-two lettuce plants were grown hydroponically over a 42-day period in a recirculating deep water culture hydroponic system. The growth rates of each plant were closely observed for changes in leaf count, root lengths, and leaf size. Daily measurements included electrical conductivity, water temperature, total dissolved solids, and pH. Nutrient levels were analyzed for nitrate–nitrogen, ammonia–nitrogen, phosphorus, and chemical oxygen demand in the nutrient solution.

The system averaged a pH of 7.16, with electrical conductivity values ranging from 1680–2010 $\mu\text{S}/\text{cm}$. The peak of the highest dissolved solids was 1010 mg/L, showing a strong positive correlation with leaf count, which surpassed past 900. Nutrient analysis showed $\text{NO}_3\text{-N}$ levels as high as 226 mg/L and COD values varying between 53.7 and 88.3 mg/L. A drop in pH below 6.8 was closely related with slowdown in root growth and increased browning around plant edges. Plants that were exposed to optimal water chemistry showed faster leaf development and more complex roots, with root lengths exceeding 13 cm. These findings emphasized the importance of the water pH, nutrient balance, and oxygenation in hydroponic systems. This research adds strong evidence for the importance of close management of water quality and its necessary role in hydroponic systems.

9.14. Water Treatment by Adsorption Using Sage-Based Adsorbents: Removal of Pollutants and Phytotoxicity

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Water pollution remains one of the most pressing environmental challenges, threatening ecosystems, food security, and human health. Industrial effluents, agricultural runoff, and domestic wastewater often introduce dyes, nitrates, phosphates, and pathogenic microorganisms into aquatic systems. Conventional water treatment approaches can be costly or energy-intensive or produce secondary waste, emphasizing the urgent need for sustainable, eco-friendly alternatives. In this context, plant-based adsorbents have gained increasing attention due to their low cost, availability, and biodegradability.

This study explores the adsorption potential of sage-derived bioadsorbents in removing various classes of pollutants. Three materials were prepared and evaluated: untreated sage powder (S), pyrolyzed sage charcoal at 300 °C (C), and activated charcoal (AC), obtained through phosphoric acid activation followed by pyrolysis at 450 °C. The materials were tested against methylene blue dye, nitrate, and phosphate solutions, as well as bacterial suspensions containing *Escherichia coli*, total coliforms, and *Streptococcus D*. The results demonstrated that AC exhibited the highest efficiency in phosphate (0.122 mg/g, 49%) and nitrate removal (1.72 mg/g), as well as superior bacterial reduction, highlighting its multifunctional performance. Interestingly, untreated sage powder showed the greatest affinity for dye removal, achieving a methylene blue adsorption capacity of 4.34 mg/g, which suggests that different pollutants may interact preferentially with specific bioadsorbents. Phytotoxicity tests using *Eruca vesicaria* revealed low toxicity for AC in liquid

conditions, and both S and AC supported plant growth when incorporated into soil-like media, indicating safe agricultural reuse. Overall, these findings underscore the potential of sage-derived materials, particularly activated charcoal, as versatile, low-toxicity bio adsorbents for sustainable and integrated water purification systems.

10. Glacier Hydrology and Climate Change

10.1. Monitoring Glacier Elevation Change in Central Asia Using TanDEM-X DEMs

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Mountain glaciers are sentinels of climate change and play a critical role in water security across Central Asia's semi-arid landscapes, underpinning irrigation, drinking water, and hydropower. Recent warming, shifting precipitation, and accelerated glacier retreat threaten these cryospheric reserves, creating cascading implications for downstream hazards and water-resource reliability. We quantify high-resolution glacier elevation change using multi-source digital elevation model (DEM) differencing, with a particular focus on TanDEM-X products. Multi-temporal DEMs were rigorously co-registered and differenced and then intersected with glacier inventories to isolate ice-covered terrain. A distribution-based filter was applied to suppress extreme outliers and minimize noise, improving the fidelity of elevation-change estimates over complex mountain topography. The results reveal widespread glacier thinning across Central Asia, while adjacent non-glacierized terrain shows minimal elevation change. This supports the robustness of the workflow. The spatial patterns are heterogeneous, identifying hotspots of accelerated mass loss and zones of relative persistence that likely reflect contrasts in aspect, elevation, debris cover, and local climate forcing. These findings provide actionable evidence for water-resource planning and climate adaptation, including prioritization of basins at risk from diminished dry-season flows and glacier-related hazards. More broadly, the study demonstrates the utility of TanDEM-X-based DEM differencing for operational glacier monitoring in data-limited mountain regions and establishes a framework that can be extended with mass-balance conversion, uncertainty budgeting, and coupling to hydrological models.

10.2. Morphological Characteristics and Influencing Factors of Mercury Occurrence and in Typical Lakes in Cold and Arid Areas

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Lakes are an important part of the earth's ecosystem, and heavy metal pollution has always been a key problem in environmental research. Among heavy metals, mercury has unique physical and chemical properties, and its organic derivative, methylmercury, is a highly toxic and bio-rich pollutant. Therefore, it is particularly important to study the transformation mechanism of lakes in cold and arid regions between different seasons and different forms of Hg due to the existence of ice sheets. The content of Hg in the water of typical lakes in Inner Mongolia ranged from 0.02 to 1.82 µg/L, and belonged to water quality Class IV. The MeHg content in the water ranged from 0.1 to 10 ng/L, and some sites exceeded the baseline value of methylmercury concentration in the water. There were significant differences in the contents of Hg, MeHg, and MeHg% in the water during the glacial and non-glacial periods, and the contents of Hg and MeHg in the non-glacial

period were significantly higher than those in the glacial period. The Hg content in the sediments of typical lakes in Inner Mongolia was 0.02–1.74 mg/kg. There was a significant enrichment of Hg in the surface sediments of typical lakes in Inner Mongolia that was higher than the average levels of lakes in some areas in China. The Hg concentration of lake surface sediments showed large spatial variability under different land use types in different basins, which included manifested in agricultural irrigation areas > agro-pastoral ecotones > grassland sandy areas. The contents of mercury and methylmercury were affected by the temperature, pH, and salinity. The mercury methylation rate of water is controlled by salinity and pH. The content of mercury and methylmercury in sediments is mainly affected by the content of organic matter, redox potential, and acidity and alkalinity of sediments.

10.3. The Impact of Green Algae Blooms on Methylmercury Production in Shallow Lakes in Cold and Arid Regions

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Green algae bloom is a water ecological anomaly characterized by the abnormal proliferation and formation of porous sponge-like floating aggregates through photosynthesis of dominant species in the green algae phylum. It is a major water ecological problem faced by shallow lakes in cold and arid regions. However, the driving mechanism of in situ generation and interfacial migration of methylmercury by algal blooms lacks systematic research. We conducted a two-year experiment on Wuliangsuhai, a typical shallow lake in the cold and arid region of northern China, to investigate the effects of green algal blooms on in situ mercury methylation and sediment–water interface transport. Firstly, through on-site investigation, it was found that during the outbreak of green algae, the total organic carbon content in the water increased by 165.76% to 288.31%, the mercury content increased by 54.34% to 392.27%, and the methylation rate increased by 63.72% to 419.29%. The DOM components indicate that the outbreak of green algae increased the protein-like components in the water by 192.57% to 222.50%. The results of indoor microcosm experiments showed that the outbreak of green algae increased the mercury methylation rate in water by 240.21% and TOC increased by 370.21%. Both on-site and indoor experiments have shown that active components such as tyrosine and tryptophan are key substances driving the in-situ mercury methylation process in water bodies. Following field experiments to monitor the methylmercury content in the gap water at the sediment–water interface during the outbreak of green algae, the results showed that the methylation rate in the interlayer gap water increased over time, with an increase of 58.72% to 326.64%. According to Fick's first law, the calculation of release flux indicates that sediment is a source of methylmercury in water. The outbreak of green algae promotes the migration of methylmercury from interstitial water to overlying water, leading to a significant increase in the methylation rate of water.

10.4. The Melting Cradle: Climate Change and the Unraveling of Glacial Hydrological Systems

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Glaciers are fundamental components of the global cryosphere, acting as critical freshwater reservoirs that regulate river discharge, support ecosystems, and sustain billions of people downstream. This project investigates the profound impacts of anthropogenic climate change on glacial hydrology, arguing that rising global temperatures are not merely causing ice melt, but are systematically dismantling a stable, natural water-regulation

system. This research employs a case study analysis of the Himalayan region, combining a review of the current scientific literature with trend analysis of satellite imagery (Landsat, 1990–2020) to visualize decadal-scale glacier retreat.

The findings confirm a direct correlation between increasing regional temperatures and accelerated glacial mass loss, leading to a shift in hydrological regimes. This manifests as a dangerous transition from a period of increased meltwater (peak water) to an eventual state of significant water scarcity. The project further analyzes the cascading consequences of this shift, including heightened risks of glacial lake outburst floods (GLOFs), altered sediment transport, and severe threats to agricultural and municipal water security downstream.

This unraveling of a millennia-old hydrological balance presents a paramount challenge for the 21st century. This study concludes that while immediate local adaptation strategies such as enhanced water management and early warning systems are urgently required, they are ultimately insufficient. The only permanent solution to mitigating long-term, catastrophic water loss lies in global commitment to aggressive climate change mitigation policies aimed at reducing greenhouse gas emissions and preserving the remaining cryosphere.

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