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Biophysical Assessment of Lake Ecosystem Services for Flood Regulation

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SUMMARY

Lakes and adjacent wetland networks provide essential benefits for flood protection, but climate change and rapid urbanisation increasingly strain these ecosystems and their services. Traditional approaches to planning and management primarily rely on subjective, qualitative assessments of ecosystems, neglecting the relationship between supply and demand. However, accurately quantifying and mapping the benefits that can be delivered to people is important for supporting their health and well-being. This study presents a framework for high-resolution mapping of lake ecosystem services (ES) for flood regulation and coastal protection across two urban lake basins in Lithuania. A framework is proposed, and a geographic information system (GIS)-based analysis is utilised to prepare, process, and integrate geospatial data layers representing biophysical characteristics at 10-meter resolution within a 5-km buffer around the lakes. To model flood-regulation supply and demand, 13 variables representing soil, land, population, and built-area characteristics were used. Using Spearman's rank correlation, redundant variables were identified and removed. After reclassification, a weighted-sum function in ArcGIS Pro was used to combine the variables and create supply and demand models. Correlation analysis further identified the indicators that contributed most to each model. Finally, a surplus/deficit map was created by subtracting demand from supply using the Raster Calculator tool. Results revealed a spatial concentration of deficit areas in the northern part of Lake Mastis. This study provides municipalities with a powerful analytical tool for evidence-based planning decisions to safeguard vulnerable communities.

Keywords: Lake ecosystem services mapping; Flood regulation; Biophysical modelling; GIS analysis; Lakes Go Digital.

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Introduction

Lakes are crucial ecosystems for maintaining the hydrological cycle and ecological condition of Earth, which have been disturbed by human activities such as urbanisation (Dubey & Dutta, 2020). They provide various services, such as crop production, regulation of water quality and quantity, maintenance of biodiversity, and improvement of human health and well-being (Xia et al., 2025). Lakes and their adjacent ecosystems have a natural, biophysical capacity to moderate, absorb, and temporarily store excess water flows, which is critical for reducing flood risks, coastal protection, and property damage in adjacent urban areas (Inácio et al., 2022). Although numerous studies on mapping lake ecosystem services (ES) have been conducted across Asia, Europe, and America (Inácio et al., 2022), lakes' contribution to hydrological regulation and water-related services like flood control remains underexplored (Montenegro-Díaz et al., 2025) and hard to quantify (Sterner et al., 2020). Furthermore, mapping and assessment of ESs have increasingly shifted from qualitative estimates to quantitative, biophysical, and process-based models that improve scientific robustness and reduce the high degree of uncertainty that is critical for sound decision-making and management (Pereira et al., 2024). Studies on a global scale have shown that the combined effects of climate change and human activities can alter supply-demand patterns, leading to surplus or deficit imbalances (Tian et al., 2025; Sidemo-Holm & Kristensen, 2025). Mapping the supply and demand using relevant indicators is a powerful approach to uncover spatial mismatches (Syrbe & Grunewald, 2017; Yang et al., 2025). The study aims to quantify and map the lake ecosystem's capacity to regulate floods and protect coastal communities using an integrated biophysical and GIS-based analysis.

Method and Theory

As part of the Latvia-Lithuania Interreg project Lakes Go Digital, this study focuses on two urban lakes in Lithuania, as shown in Figure 1.

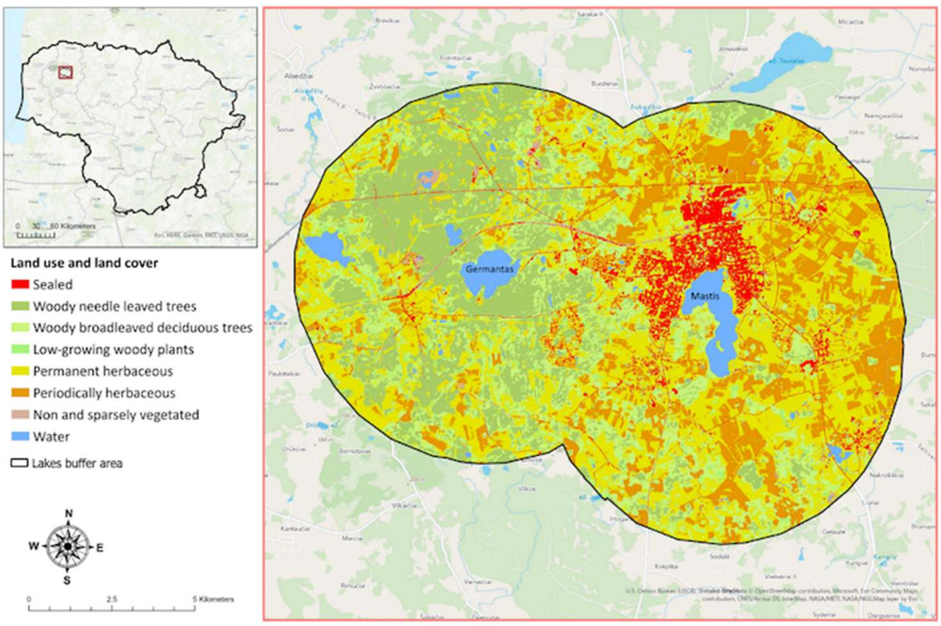

***Figure 1**. Study area*

We then adapted the framework proposed by Pereira et al. (2022) and presented in Figure 2. It quantifies and spatially distributes both Flood Regulation Supply (the ecosystem's capacity to provide services) and Flood Regulation Demand (physical and social vulnerability) in seven steps: (1) **Flood regulation supply variables**: Adjust the environment's capacity to handle excess rainfall and runoff. It is modelled using spatial variables, processed in raster format: soil texture, soil thickness, slope (derived from a Digital Elevation Model), tree cover density, grassland coverage, and imperviousness density. (2) **Flood regulation demand variables**: Identify risk areas where societal assets or landscape characteristics increase flood pressure. It integrates nine variables: slope, topographic wetness index, waterline density, building density (derived from centroids and the Kernel Density function), population density, distance to lakes, distance to waterlines, and historical flooded areas. (3) **Multicollinearity test**: After all variables are resampled to a uniform 10-meter spatial resolution, a spatial point grid is established to extract variable values, which are tested for multicollinearity in JASP (https://jasp-stats.org/) using a Spearman correlation analysis. Variables with a correlation coefficient above 0.8 are redundant and thus removed. (4) **Reclassification**: The variables are reclassified to scale from 1 (low supply/demand) to 5 (high supply/demand) using the Reclassify tool and Natural Breaks (Jenks). (5) **Applying the weighted sum function** to generate supply and demand models. Weights are assigned to variables based on their relative importance (the sum of weights in each model should be 1). (6) **Spearman's rank correlation** is used to identify the indicators most strongly correlated with the supply and demand model, thereby identifying the dominant and most contributing factors. (7) **Subtracting the demand model from the supply** (Supply model – Demand model) in the Raster Calculator in ArcGIS Pro. In this way, the ES deficit and surplus areas are illustrated. In deficit areas, the landscape's capacity to retain and infiltrate water into the soil is low, while there is a need for flood regulation to safeguard people and urban infrastructure. Surplus areas are natural buffer zones that can effectively regulate floods, reducing exposure for people and urban infrastructure. Areas where supply and demand are equal are balanced areas.

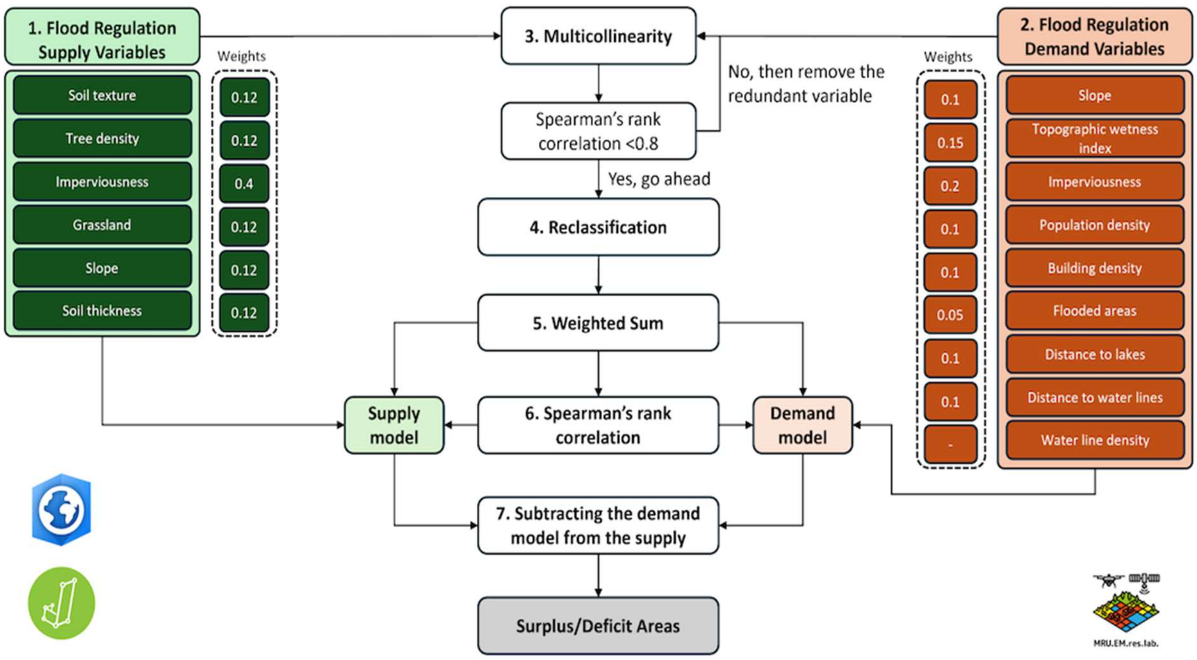

***Figure 2**. Methodological framework*

Results

Figure 3 displays the results, including a) surplus/deficit area map and spatial distribution, ranging from -2.36 (deficit areas where demand exceeds supply, in red) to 3.86 (surplus areas where supply exceeds demand, in dark green), and b) Spearman's ρ correlation between the supply and demand model and their indicators. It was observed that there is a concentration of deficit areas around the northern part of Lake "Mastis". However, Lake 'Germantas' is mainly characterised by surplus areas. The statistical metrics along the spatial distribution confirm a predominantly positive imbalance (more supply) across the study area. A mean of 2.21 and a median of 2.32 indicate an average ES surplus in the study area. Min/Max range (-2.36 to 3.86) shows considerable contrast between the deficit and surplus areas. A skewness of -2.36 indicates that while most of the area has high surplus values, there is a tail of severe deficits. A Kurtosis of 11.39 (peak) indicates a high concentration of deficit values rather than a normal distribution. The correlation analysis demonstrated that grassland coverage was significantly correlated with the supply model ($\rho=0.524$, $p<.001$), followed by soil texture (ρ=0.401, p<.001) and imperviousness (ρ=0.400, p<.001). This suggests that land cover and soil properties are the predominant biophysical factors influencing water retention capacity. Conversely, in the demand model, 'distance to lakes' emerged as the primary determinant, exhibiting a strong correlation (ρ = 0.643, p < .001). This was followed by 'distance to water lines' (ρ=0.473, p<.001) and 'building density' (ρ=0.446, p<.001).

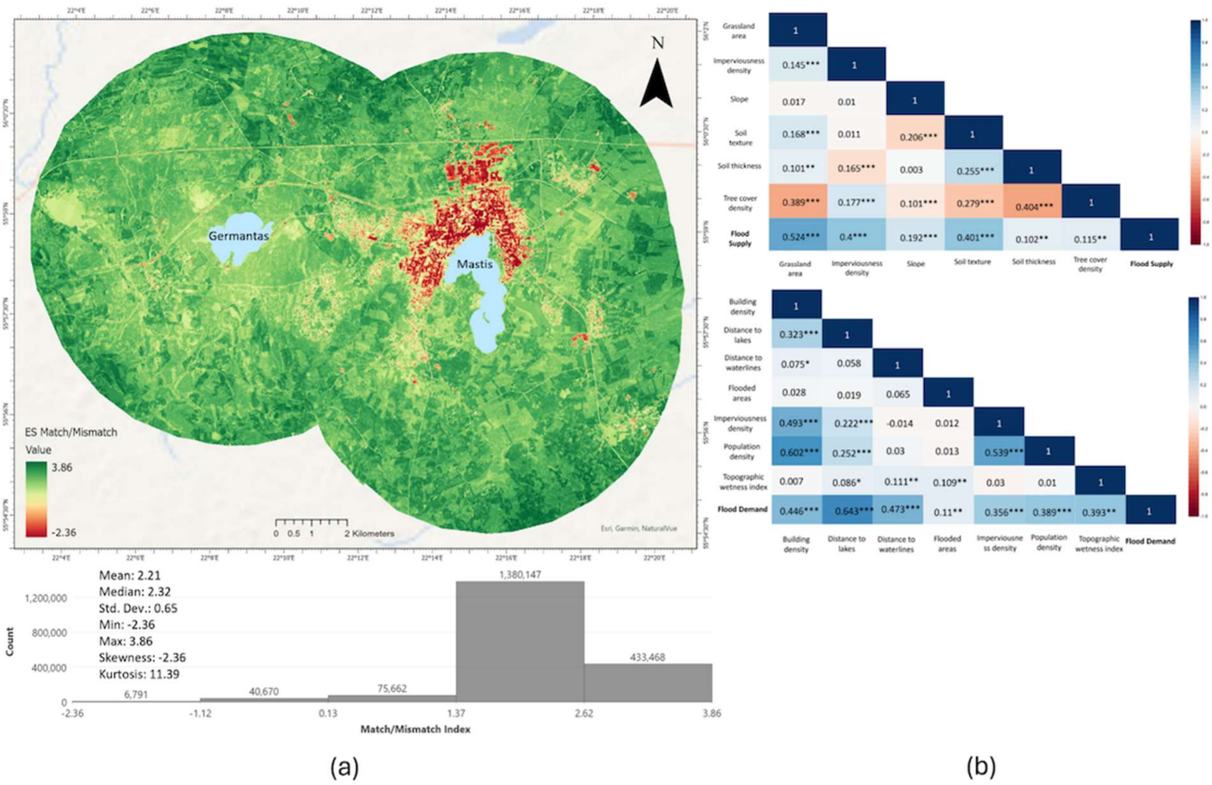

__Figure 3.__ (a) Surplus/Deficit areas for flood regulation Ecosystem Services (ES) within a 5-km buffer around Lakes Germantas and Mastis, Lithuania. Positive values (green) represent an ES surplus where natural supply capacity exceeds the risk of flooding, whereas negative values (red) highlight ES deficit areas concentrated within urbanised areas. (b) Spearman's ρ correlation for supply (Upper panel) and demand (Bottom panel) models and their indicators (p < .05, ** p < .01, *** p < .001)*

Conclusions

Our study provides insight into the critical balance of lake ecosystem services (ES) through a biophysical assessment and geospatial and statistical analyses, which are crucial for management and planning. We analysed the flood regulation services of two lakes in Lithuania. This analysis identified deficit areas around Lake Mastis, characterised by urbanisation, and surplus areas surrounding Lake Germantas. Correlation analysis provides clear guidance for targeted land-use management. Interventions should focus on conserving grasslands and enhancing soil-vegetation conditions, since grassland extent and soil texture are key factors for natural water retention (ES supply). On the other hand, urban planning must account for proximity to water bodies, as "distance to lakes" and "building density" are primary drivers of ES demand. The findings highlight that managing lake ecosystems requires an advanced understanding of a lake's capacity, social vulnerability, and the gaps between them to sustainably manage ecosystem services.

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References

Dubey, D., & Dutta, V. (2020). Nutrient Enrichment in Lake Ecosystem and Its Effects on Algae and Macrophytes. In V. Shukla & N. Kumar (Eds.), *Environmental Concerns and Sustainable Development: Volume 2: Biodiversity, Soil and Waste Management* (pp. 81–126). Springer. https://doi.org/10.1007/978-981-13-6358-0_5

Inácio, M., Barceló, D., Zhao, W., & Pereira, P. (2022). Mapping lake ecosystem services: A systematic review. *Science of The Total Environment*, *847*, 157561. https://doi.org/10.1016/j.scitotenv.2022.157561

Montenegro-Díaz, P., Crespo, P., Jaramillo, F., & Ochoa-Sánchez, A. (2025). Water-related ecosystem services of lakes worldwide: A comprehensive meta-analysis. *Environmental Research Communications*, *7*(11), 112003. https://doi.org/10.1088/2515-7620/ae1d28

Pereira, P., Kalinauskas, M., Das, M., Bogdzevič, K., Inácio, M., & Barcelo, D. (2022). Chapter Six—Mapping and assessment of flood regulation supply and demand in Vilnius (Lithuania). In P. Pereira & C. S. S. Ferreira (Eds.), *Urban Soil and Water Degradation* (Vol. 8, pp. 113–133). Elsevier. https://doi.org/10.1016/bs.apmp.2022.10.015

Pereira, P., Kalinauskas, M., Pinto, L. V., Barcelo, D., Zhao, W., & Inacio, M. (2024). A simple method for mapping winter recreational fishing ecosystem services supply in lakes. A contribution to mapping freshwater ecosystem services. *MethodsX*, *12*, 102764. https://doi.org/10.1016/j.mex.2024.102764

Sidemo-Holm, W., & Kristensen, J. A. (2025). A framework to identify and value ecosystem services and disservices with supply and demand. *Environmental Challenges*, *20*, 101306. https://doi.org/10.1016/j.envc.2025.101306

Sterner, R. W., Keeler, B., Polasky, S., Poudel, R., Rhude, K., & Rogers, M. (2020). Ecosystem services of Earth’s largest freshwater lakes. *Ecosystem Services*, *41*, 101046. https://doi.org/10.1016/j.ecoser.2019.101046

Syrbe, R.-U., & Grunewald, K. (2017). Ecosystem service supply and demand – the challenge to balance spatial mismatches. *International Journal of Biodiversity Science, Ecosystem Services & Management*, *13*(2), 148–161. https://doi.org/10.1080/21513732.2017.1407362

Tian, S., Wu, W., Chen, S., Li, Z., & Li, K. (2025). Global mismatch between ecosystem service supply and demand driven by climate change and human activity. *Environmental Science and Ecotechnology*, *26*, 100573. https://doi.org/10.1016/j.ese.2025.100573

Xia, P., Peng, J., Gu, T., Yu, S., & Xu, Z. (2025). Lake-related ecosystem services facing social–ecological risks. *People and Nature*, *7*(4), 734–751. https://doi.org/10.1002/pan3.70015

Yang, M., Wang, M., Cao, L., & Zhang, H. (2025). Integrating trade-offs and supply-demand into ecosystem service zoning management to provide more targeted management strategies from the water-food-ecosystem nexus perspective. *Scientific Reports*, *15*(1), 33957. https://doi.org/10.1038/s41598-025-11536-3