THESIS OF PhD DISSERTATION

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GÖDÖLLŐ

2025

HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

INTEGRATED ASSESSMENT OF LAND USE IMPACTS ON SURFACE WATER QUALITY IN THE RÁKOS STREAM CATCHMENT USING QUAL2K MODELLING

THESIS OF THE PhD DISSERTATION

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1 INTRODUCTION AND OBJECTIVES

1.1 Introduction

Hungary has abundant freshwater resources, mainly supplied by rivers, lakes, and aquifers. Nearly 95% of the country's drinking water comes from groundwater and riverbank filtration, which makes protecting water quality a national priority. However, about two-thirds of Hungary's water resources are considered vulnerable to pollution. In addition to local pressures, river water quality is strongly influenced by upstream inflows crossing national borders, which carry a variety of contaminants into the country's watercourses.

The Rákos Stream, located in central Hungary, is a small tributary of the Danube. It originates in the Gödöllő Hills and flows through the towns of Isaszeg and Pécel before joining the Danube north of Budapest. Although relatively small, it has both ecological and social importance, supporting local habitats while also serving as a recreational area for nearby residents. At the same time, the stream passes through a diverse mosaic of land uses including agricultural, urban, industrial, and forested areas, and receives treated municipal effluents. These combined pressures make it highly vulnerable to water quality degradation.

Surface water quality is strongly shaped by land use patterns. Agricultural land contributes to elevated nutrient concentrations through fertilizer use and soil disturbance, while urban areas increase pollutant inputs via stormwater runoff and wastewater discharges. In contrast, forested and semi-natural landscapes typically act as buffers, improving water quality by reducing runoff and retaining nutrients. Given these interactions, understanding how land use influences water quality is essential for effective watershed management.

To address this challenge, this study integrates two years of field-based monitoring with GIS-based land use assessment and water quality modelling.

Among the available tools, the QUAL2K model was selected as it is particularly suited for small and medium-sized rivers and provides a practical way to simulate pollutant dynamics in systems influenced by both point and non-point sources. By linking observed water quality patterns with surrounding land use, this research aims to improve understanding of pollution dynamics in the Rákos Stream and provide insights relevant to the management of peri-urban catchments in Hungary.

1.2 Objectives

1.2.1 Main objective

The main objective of this study was to investigate the effects of surrounding land use on water quality in the Rákos catchment and analyze the relationships between different land use types and water quality parameters.

1.2.2 Specific Objectives

To achieve the main objective, the study had the following specific objectives:

- To monitor and assess the physical and chemical water quality parameters of the Rákos Stream through field sampling.
- To evaluate the spatial distribution and extent of land use and land cover (LULC) types in the Rákos catchment using GIS-based analysis.
- To simulate the hydrodynamics and water quality processes of the Rákos Stream using the QUAL2K model, incorporating both field data and land use-derived pollutant loads.

2 MATERIALS AND METHODOLOGIES

This chapter presents the methodological framework used in the study, including an overview of the study area, sampling design, analytical methods, and modeling techniques.

2.1 Description of the Study Area

The Rákos Stream is a small tributary in central Hungary, extending 44.3 km with a drainage area of about 185 km². It originates in the Gödöllő Hills and flows into the Danube north of Budapest. The catchment is characterized by a mixture of urban, agricultural, and forested land uses, making it an ideal site to study land use–water quality interactions (Figure **2-1**).

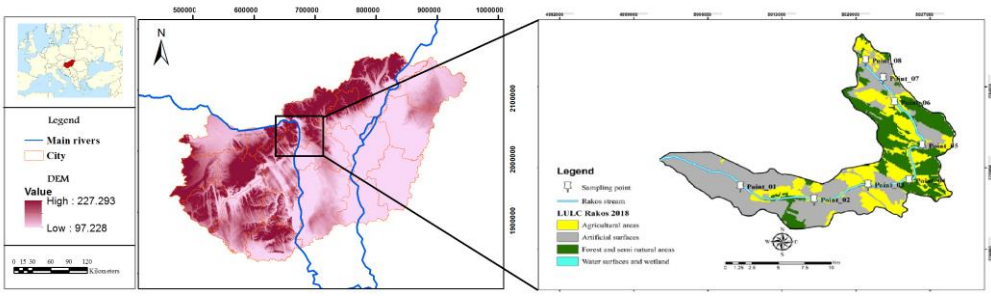

Figure 2-1 Study area location and sampling sites in the Rákos Catchment, Hungary

2.2 Conceptual Model

The conceptual framework of this study provides an overview of the integrated approach used to evaluate the influence of land use and land cover (LULC) on water quality in the Rákos Stream catchment.

As illustrated in Figure 2-2, the framework combines spatial datasets, field measurements, and analytical methods within a unified structure.

LULC classifications, derived from the CORINE database, were used to generate land use maps and delineate the watershed and river network. Field-based water quality monitoring campaigns provided data on both physical parameters (e.g., water temperature, dissolved oxygen) and chemical parameters (e.g., nitrate, ammonium, phosphate). Streamflow records were also compiled to support hydrodynamic and water quality modelling.

These datasets were integrated and analyzed using statistical methods, both univariate and multivariate, to identify patterns in water quality and their relationships with surrounding LULC. In parallel, the process-based QUAL2K model was applied to simulate current conditions in the stream and quantify the influence of land use on selected water quality indicators.

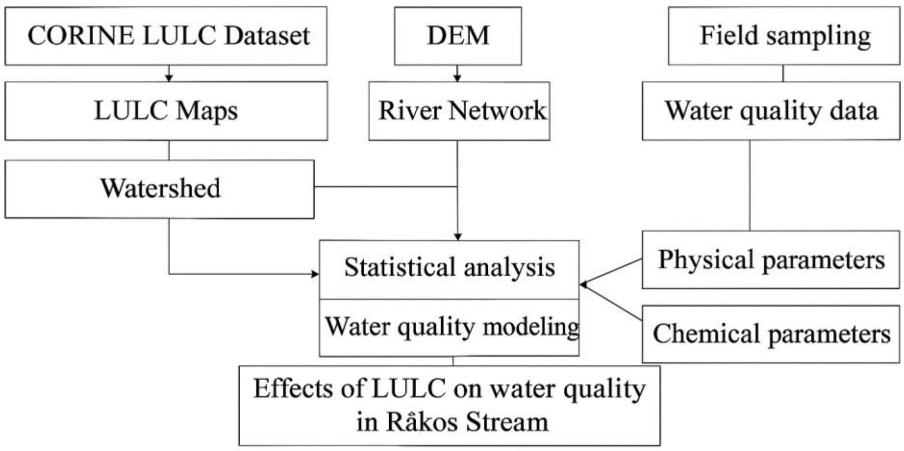

Figure 2-2 The conceptual model within the theoretical framework of the study

2.3 Sampling Design and Data Collection

Eight sampling sites were selected to represent diverse land use conditions, including urbanized, agricultural, and forested reaches. Field sampling was carried out biweekly between November 2019 and October 2021, with consistent timing to minimize variability. Key parameters measured included temperature, pH, dissolved oxygen (DO), ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}), electrical conductivity (EC), and chlorophyll-a.

2.4 GIS-based Land Use Assessment

Land use and land cover data were derived from the CORINE database (2018) and reclassified into three categories: agricultural, artificial (urban), and forest/semi-natural areas. Sub-catchments corresponding to each sampling site were delineated using QGIS, and the proportion of land use types of each zone was calculated. Spatial interpolation of water quality data was performed using the Inverse Distance Weighting (IDW) method to visualize pollutant distribution across the catchment. Accuracy was tested using cross-validation with root mean square error (RMSE) and mean error (ME).

2.5 Statistical Analysis

The dataset was aggregated to monthly and seasonal scales. Normality was tested using the Kolmogorov–Smirnov test, with log transformations applied where necessary. Pearson correlation and Spearman's rank correlation were used to examine relationships between land use proportions and water quality parameters. Differences among sampling sites were tested using one-way ANOVA (or Welch's ANOVA when variance assumptions were not met), followed by Tukey or Duncan post-hoc tests.

2.6 QUAL2K Modelling

The QUAL2K model was applied to simulate hydrodynamics and pollutant dynamics in the Rákos Stream. The modelled reach was divided into seven segments, incorporating both point sources (municipal wastewater from Gödöllő, Isaszeg, and Pécel) and non-point sources (runoff from land use categories). Inputs included hydrological observations, meteorological data (precipitation, air temperature), and pollutant loads derived from land use classification.

2.6.1 Model Calibration

Calibration was performed using July 2021 (wettest month) data, while validation used June 2021 (driest month). Key parameters, including decay rates of ammonium and phosphate and reaeration coefficients, were adjusted during calibration (Table 2-1). Model performance was evaluated using the Normalized Root Mean Square Error (NRMSE) for DO, NH_4^+, PO_4^{3-}, and discharge.

Table 2-1 Calibrated Parameter Values for QUAL2K Model in the Rákos Stream

Reach	k_NH_4 (1/day)	k_PO_4 (1/day)	Reaeration Coef. (1/day)
1	0.35	0.25	1.8
2	0.32	0.22	1.7
3	0.30	0.20	1.6
4	0.28	0.18	1.5
5	0.27	0.16	1.4
6	0.26	0.15	1.3
7	0.25	0.14	1.2

2.6.2 Model Validation

The validation was conducted using data from June 2021, representing the driest month with low flows and minimal runoff influence, to test the model under contrasting hydrological conditions. No parameter adjustments were made after calibration; the calibrated parameters were applied unchanged to the validation dataset to ensure an independent assessment. Model performance was evaluated using the NRMSE for dissolved oxygen, ammonium, and phosphate across all sampling points. This approach allowed for a robust assessment of the model's predictive capability under different seasonal conditions.

2.6.3 Load Contribution Analysis in the Rákos Stream

To quantify the contribution of different land use categories to pollutant loads in the Rákos Stream, GIS-based land use data were integrated with the calibrated QUAL2K model. Each land use type was assigned pollutant input values according to its area and typical nutrient characteristics. The QUAL2K model was then used to simulate the transport and transformation of these inputs along the stream network, accounting for flow conditions, mixing processes, and in-stream transformations. Model outputs were subsequently analyzed to determine the total pollutant load attributable to each land use type, which was expressed as a percentage of the overall catchment load.

3 RESULTS AND DISCUSSION

This chapter presents the results of spatiotemporal variations in water quality across the Rákos Stream catchment over a two-year monitoring period (2019–2021). It integrated field-based measurements with spatial interpolation (IDW), statistical analyses, and process-based modelling using QUAL2K to examine how land use and hydrological dynamics influence pollutant behavior in the catchment.

First, spatial and seasonal variations in water quality parameters, such as ammonium, nitrate, phosphate, dissolved oxygen, electrical conductivity, and chlorophyll-a; were analyzed across eight sampling sites using GIS-based mapping and descriptive statistics. IDW interpolation was applied to visualize the spatial patterns of water quality across the catchment.

Second, the 2018 land use and land cover (LULC) data were evaluated to identify trends in urbanization, agricultural expansion, and forest loss. The impact of LULC on water quality was subsequently assessed using statistical analyses (Pearson and ANOVA) to quantify relationships between specific land use types and pollutant concentrations.

Finally, the QUAL2K model was employed to simulate hydrodynamics and water quality processes under current land use conditions. The model was calibrated and validated using observed field data, and applied to estimate pollutant loads from different land use types.

Together, these analyses provided a comprehensive understanding of the factors shaping water quality in the Rákos Stream. The results offer evidence-based insights to support watershed planning, land use management, and future water quality monitoring efforts in similar peri-urban catchments.

3.1 Statistical Relationships

Correlation and ANOVA analyses confirmed significant associations between land use and water quality. Agricultural land cover showed strong positive correlations with nitrate and phosphate concentrations, while urban land use correlated with elevated ammonium and higher conductivity. Forest cover was negatively correlated with most pollutants, underscoring its protective role. Parameters such as DO, NH_4^+, NO_3^-, NO_2^-, and EC varied significantly among sampling sites ($p < 0.001$), with urban and agricultural points showing the most pronounced impacts.

3.2 GIS Interpolation of Pollutant Distribution

The Inverse Distance Weighting (IDW) maps identified pollution hotspots in areas dominated by agriculture and artificial surfaces, especially near Pécel and in the downstream section close to Budapest. These locations showed high concentrations of NH_4^+, NO_3^-, PO_4^{3-}, and chlorophyll-a, which were consistent with local land use pressures. In contrast, upstream forested and semi-natural areas had the lowest pollutant levels.

To check the reliability of the IDW interpolation, its results for the Rákos Stream were evaluated using two common statistical indicators: Mean Error (ME) and Root Mean Square Error (RMSE) (Table 3-1).

Table 3-1 General results of cross validation analysis for IDW interpolation method used to assess Rákos Stream surface water quality

Criteria	ME	RMSE
NO_3^-	1.83	11.83
NO_2^-	-0.012	0.108
NH_4^+	0.031	0.45
PO_4^{3-}	0.27	2.8
DO	-0.009	8.53
EC	-9.68	239.70
PH	0.002	0.28
Chl-a	-0.55	32.27

The results demonstrate satisfactory predictive accuracy across all assessed parameters, indicating that the IDW interpolation reasonably captured the spatial variation in water quality within the catchment.

The ME values suggest that the model estimates generally align well with observed values, reflecting a good spatial fit.

The relatively low RMSE values across most parameters (with the exception of EC and Chl-a, which are naturally more variable) indicate limited occurrence of extreme deviations, suggesting that the IDW method performs well in reproducing spatial patterns of physicochemical parameters in the Rákos Stream.

3.3 QUAL2K Modelling Outcomes

The QUAL2K model successfully simulated hydrodynamics and pollutant transport under both wet (July 2021) and dry (June 2021) conditions. Calibration results showed good agreement between observed and simulated values (Figure 3-1), with NRMSE values of 0.06 for ammonium, 0.11 for phosphate, and 0.10 for DO, indicating strong model reliability. Validation produced similarly acceptable results, particularly for phosphate and DO (Table 3-2).

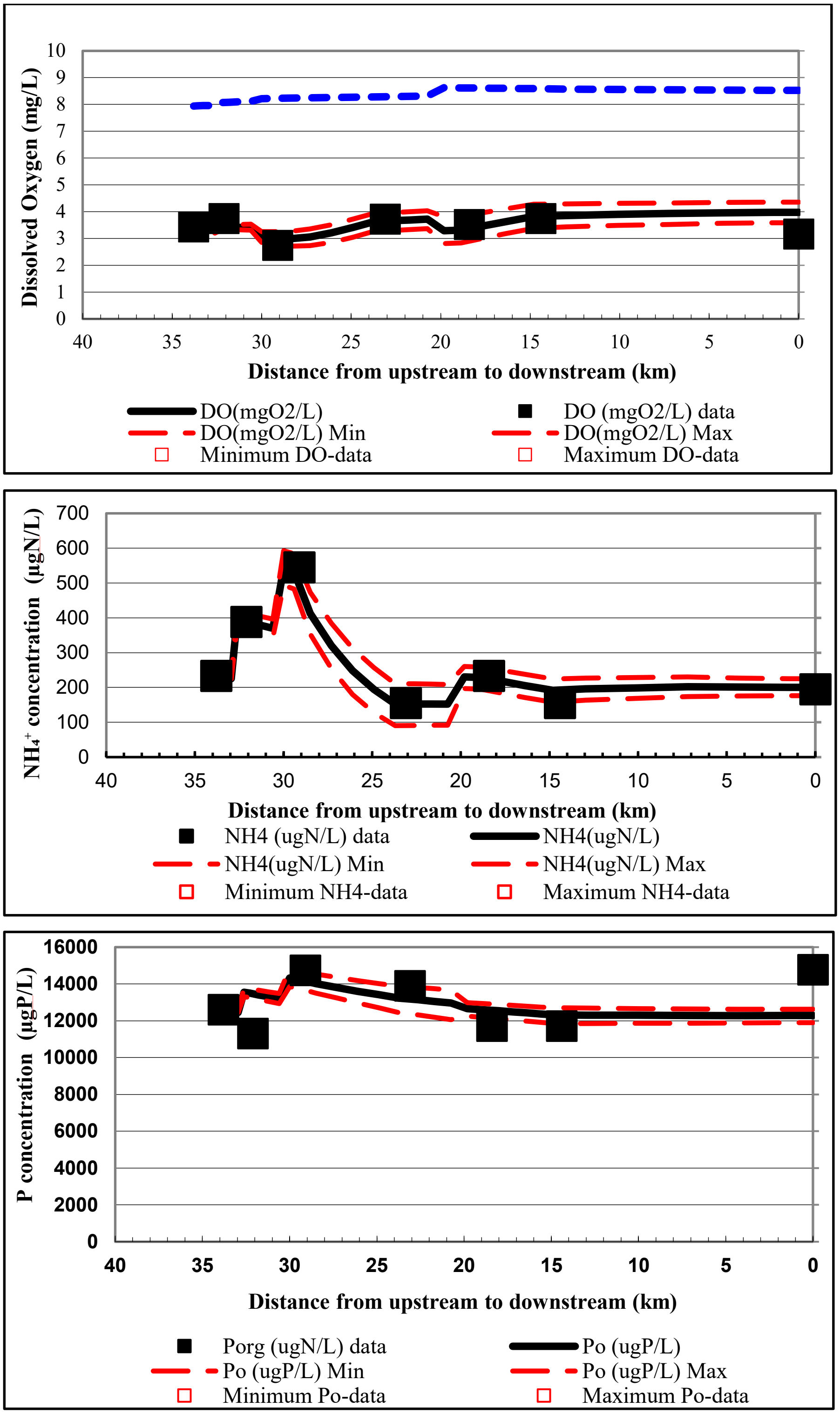

Figure 3-1 PO_4^{3-}, DO, and NH_4^+ profiles in the Rákos Stream, Calibration period (July 2021)

Table 3-2 Calibration errors (NRMSE) between observed and simulated values

Parameter	NRMSE (Calibration)	NRMSE (Validation)
DO	0.10	0.12
NH_4^+	0.06	0.27
PO_4^{3-}	0.11	0.08

Model outputs confirmed that agricultural areas contributed the largest share of nutrient loads, accounting for approximately 60% of NH_4^+ and 46% of PO_4^{3-} inputs. Urban/artificial surfaces contributed around 30% of phosphate and a smaller share of ammonium, while forested/semi-natural areas had the lowest contributions (Figure 3-2). These findings reinforce the dominant role of agricultural practices and urban runoff in nutrient enrichment.

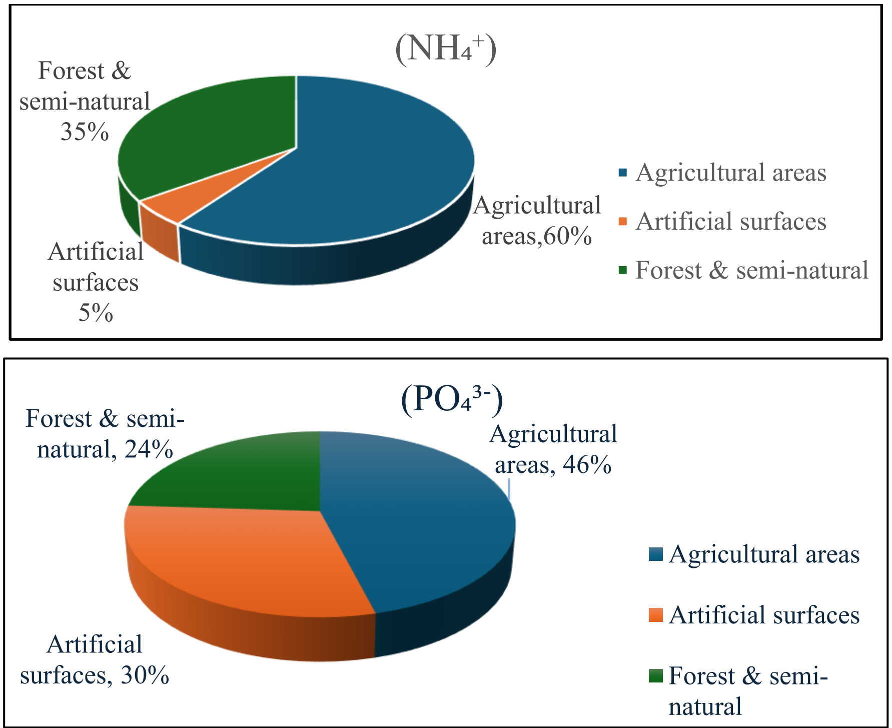

Figure 3-2 Analysis of NH_4^+ and PO_4^{3-} Load Contribution in Rákos Stream

4 CONCLUSION AND RECOMMENDATIONS

This study demonstrates a clear relationship between land use and water quality in the Rákos Stream. Urban and agricultural sites, particularly Points 8 and 3, consistently exhibited elevated nutrient concentrations, higher electrical conductivity, and increased chlorophyll-a, accompanied by reduced dissolved oxygen levels. In contrast, forested and less disturbed reaches, such as Points 4 and 5, showed more stable nutrient dynamics, lower conductivity, and balanced dissolved oxygen and pH values, highlighting the buffering capacity of natural landscapes. These stabilizing effects can be attributed to natural processes such as sedimentation, nutrient uptake, and microbial activity, which contribute to pollutant attenuation.

Seasonal patterns were also evident, with higher nutrient concentrations, chlorophyll-a, and pH typically observed during the summer months. These seasonal peaks were closely linked to warmer temperatures, enhanced biological activity, and greater runoff contributions from urban and agricultural areas.

The QUAL2K model performed well in simulating pollutant concentrations under both high-flow and low-flow conditions, confirming its robustness across contrasting hydrological regimes. Normalized Root Mean Square Error (NRMSE) values indicated strong agreement between observed and simulated data, particularly for ammonium (NH_4^+) and dissolved oxygen (DO), confirming the model's reliability in representing spatial and temporal water quality dynamics. Importantly, the multiple methodological approaches employed—including monitoring, spatial interpolation, statistical analysis, and process-based modelling—produced consistent and mutually reinforcing results. This convergence of evidence strengthens confidence in the study's conclusions.

Based on these outcomes, targeted management actions are recommended. Nutrient reduction measures should be prioritized in high-pressure areas, particularly Points 8 and 3, with special attention to the summer season when pollutant loads are highest. The conservation and enhancement of forested and semi-natural sections should be a management priority, given their demonstrated role in maintaining ecological balance. In addition, the ecological and hydraulic functions of existing structures should be explicitly considered in future planning, as they contribute to both aeration and pollutant attenuation.

For future research, the application of spatially explicit or coupled hydraulic–water quality models, such as HEC-RAS integrated with QUAL2K, could provide a more detailed evaluation of restoration options under varying flow and land use scenarios. Furthermore, the establishment of long-term, continuous monitoring programs for both water quality and meteorological conditions is essential. Such measures would generate valuable data to inform adaptive management and support ongoing restoration efforts in the Rákos Stream and similar mixed-use catchments.

5 NEW SCIENTIFIC RESULTS

1. Quantified, for the first time, the contribution of specific land use types to pollutant loads in the Rákos Stream catchment using a calibrated QUAL2K model, providing a scientifically grounded basis for targeted and evidence-based watershed management.
2. Identified a key in-stream attenuation reach (km 29–23), where hydraulic structures (weirs, sedimentation basins, step-pools, and vegetated banks) coincided with lower ammonium and phosphate levels and higher dissolved oxygen concentrations. Field data combined with model simulations confirm that hydraulic regulation and channel morphology can mitigate nutrient loads and enhance re-aeration under local stream conditions.
3. Developed an integrated methodological framework that combines in-situ water quality monitoring, GIS-based land use classification, and process-

based QUAL2K modeling, offering a transferable approach for similar catchments in temperate urbanizing regions.

4. Quantified seasonal variations in nutrient concentrations and dissolved oxygen (2019–2021) and demonstrated statistically significant land use–driven shifts (e.g., heterogeneous agriculture with NH_4^+ and NO_2^-).
5. Confirmed that EC and nutrient levels are reliable metrics for identifying pollution hotspots and guiding targeted management.

6 PUBLICATION LIST

6.1 Conference abstracts/ papers/ oral and poster presentations

Saeidi, S., Mosallaei, A., Harsini, J.I., Grósz, J. and Waltner, I., 2023, October. Assessing the impact of land use and land cover on water quality: A case study of the Rákos catchment in Hungary. In ARPHA Conference Abstracts (Vol. 6, p. e108160). Pensoft Publishers.

Saeidi, S., Grósz, J., Harkányiné Székely, Z. & Waltner, I. (2022) 'The effects of land use and land cover on water quality in the Rákos catchment, Hungary'. In: Futó, Z. & Bodnár, K. (eds.) Proceedings of the 5th International Scientific Conference on Water, 22–24 March 2022, Szarvas, Hungary. Gödöllő: MATE, pp. 221–224.

Saeidi, S. & Waltner, I. (2020) 'Comparison of land cover changes in Pest and Békés counties in Hungary'. In: Jakab, G. & Csengeri, E. (eds.) Water management: Focus on Climate Change: 3rd International Conference on Water Sciences: Conference volume. Szarvas: Szent István University Institute of Irrigation and Water Management, pp. 138–143.

Deganutti de Barros, V., **Saeidi, S.**, Amekelew, S., Grósz, J., Sebők, A. & Waltner, I. (2020) 'Water quality monitoring for Rákos stream in the winter of 2019/2020'. In: Jakab, G. & Csengeri, E. (eds.) Water management: Focus on Climate Change: 3rd International Conference on Water Sciences: Conference volume. Szarvas: Szent István University Institute of Irrigation and Water Management, pp. 178–184.

Saeidi, S., Waltner, I. & Centeri, C. (2019) 'Application of hydrodynamic and quality modeling of water resources'. In: Jakab, G. & Csengeri, E. (eds.) XXI. Századi vízgazdálkodás a tudományok metszéspontjában: II. Víztudományi Nemzetközi Konferencia. Szarvas: Szent István Egyetem Agrár- és Gazdaságtudományi Kar, pp. 338–342.

Saeidi, S., Grósz, J., Centeri, C. & Waltner, I. (2019) 'Analysing land use change and geomorphometric parameters in small watersheds'. In: Hatvani, I.G., Tanos, P. & Fedor, F. (eds.) GEOMATES 2019. International Congress on Geomathematics in Earth & Environmental Sciences: Abstract book. Pécs: Regional Committee of the Hungarian Academy of Sciences at Pécs, p. 51.

6.2 Peer-reviewed journal articles

Waltner, I., **Saeidi, S.**, Grósz, J., Centeri, C., Laborczi, A. & Pásztor, L. (2020) 'Spatial assessment of the effects of land cover change on soil erosion in Hungary from 1990 to 2018', ISPRS International Journal of Geo-Information, 9(11), p. 667. https://doi.org/10.3390/ijgi9110667.

Naderi, M.H., **Saeidi, S.** & Imani Harsini, J. (2020) 'Implementation of the environmental flow regime in the improvement of river environment', Journal of Wetland Ecobiology, 11(4), pp. 35–52.

Saeidi, S., Grósz, J., Sebők, A., Deganutti de Barros, V. & Waltner, I. (2019) 'Területhasználat-változás a Szilas-patak vízgyűjtő területén 1990-től', Tájökológiai Lapok / Journal of Landscape Ecology, 17(2), pp. 265–275.

Saeidi, S., Grósz, J., Sebők, A., Deganutti de Barros, V. & Waltner, I. (2019) 'A területhasználat változása a Rákos-patak vízgyűjtőjén 1990-től', Tájökológiai Lapok / Journal of Landscape Ecology, 17(2), pp. 287–296.