Modelling Monthly Concentration of Ammonium and Nitrate Nitrogen in The Hron River Basin: Integration of Time Series of Environment Factors

Veronika Bačová Mitková[1*)], Pavla Pekárová[2)], Dana Halmová[3)]

[1*)] Institute of Hydrology, SAS, Dúbravská cesta 9, 841 04 Bratislava, Slovakia, mitkova@uh.savba.sk; 0000-0001-6650-9182
[2)] Institute of Hydrology, SAS, Dúbravská cesta 9, 841 04 Bratislava, Slovakia, pekarova@uh.savba.sk; 0000-0002-1180-2215
[3)] Institute of Hydrology, SAS, Dúbravská cesta 9, 841 04 Bratislava, Slovakia, halmova@uh.savba.sk; 0000-0003-1461-6394

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Abstract

As a vital hydrological unit in Slovakia, the Hron River basin is fundamental to regional water governance, agricultural activities, and biodiversity conservation. While our previous research was concentrated mainly on oxygen regime, water temperature (Tw) and pH, this study shift the focus toward ammonia nitrogen ($N\text{-}NH_4^+$) and nitrate nitrogen ($N\text{-}NO_3^-$) on the Hron River. With this new focus, the study aims to assess long-term trends in nitrogen compounds in the Hron River at two key sampling sites: Valaská (upper basin) and Kamenica nad Hronom (lower basin). The analyzed period from 1992 to 2021 captures the impact of socioeconomic transitions, industrial activities, and the progressive implementation of environmental mitigation measures. Using statistical methods, long-term trends were assessed, indicators such as pH, BOD, Do, and Tw exhibit distinct seasonal fluctuations, which serve as key drivers for biochemical processes affecting nitrogen compounds. The second part of the work focuses on mathematical modelling of the nitrogen compounds such as $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$. Based on simple regression analysis, the relationships between nitrogen concentrations and quality indicators such as DO, BOD, Tw, pH, and discharge Qd were derived. Derived regressions were than used as exogenous values for constructing a Seasonal Autoregressive Integrated Moving Average (SARIMA) model. An innovative aspect of this study is the integration of these derived regression parameters as external regressors within the ARIMA framework to enhance the predictive accuracy of $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ concentrations. While the chemical purity (less waste, more oxygen) has improved significantly since 1992, the Hron River is now facing new challenges associated with environmental changes (water warming and pH changes). Water quality in the upper reaches (Valaská) responds more sensitively to cleaning measures, while the lower reaches (Kamenica) show a more stable but still warming environment. The resulting predictive model enables the simulation of future pollution trends, providing a valuable tool for water management and river basin planning in the context of climate change.

Keywords: *Hron River, long-term trend changes, Nitrogen dynamics, water quality, autoregressive modeling.*

1. Introduction

Surface water protection and sustainable water resource management represent key priorities of European environmental policy. The legislative foundation for achieving good ecological and chemical status of water bodies is established by the Water Framework Directive (WFD 2000/60/EC), which integrates water quantity, water quality, ecological condition, and hydromorphological status into a unified management approach. One of its fundamental principles is the "one-out-all-out" concept, meaning that good water status can only be achieved when all monitored quality elements comply with the required standards [1]. Effective water management requires the recognition that water quantity and water quality are strongly interconnected and should be assessed together rather than separately. This integrated approach is emphasized in the EU Water Resources Concept [2] and further supported by the European Commission's Zero Pollution Action Plan for Air, Water and Soil, adopted in 2021, which aims to reduce environmental pollution and strengthen ecosystem protection [3]. Recent legislative updates have further reinforced European water policy. Directive (EU) 2026/805 introduced amendments to Directive 2000/60/EC, as well as to Directives 2006/118/EC and 2008/105/EC, with the objective of improving groundwater protection, strengthening environmental quality standards, and supporting more effective long-term water management across EU Member States.

Based on analyses of long-term data, it is possible to identify trends in certain environmental parameters with good accuracy. In the 20th century, an increase in nitrate concentrations was observed in waters flowing through agricultural landscapes [4], while ammonia concentrations increased in urban areas [5]. At the turn of the 20th century, a decrease in phosphorus and nitrogen concentrations (mainly in the form of orthophosphates, nitrates and ammonia) was observed in surface waters [6]. In recent decades, nitrate pollution of freshwaters has increasingly become a pervasive global problem [7]. In addition, we are also experiencing an increase in biochemical oxygen demand [8]. These changes may also be exacerbated by a long-term trend of decreasing discharge due to increasing drought, which is also reflected in an increase in chloride concentration and electrical conductivity as well as an overall deterioration in surface water quality, particularly in urbanized landscapes ([9]. Recent studies focusing on Slovak river basins have addressed various aspects of surface water quality, including the transport and transformation of pollutants in aquatic environments [10–12]. These investigations generally indicate an overall improvement in water quality conditions after 1989. Despite this positive development, continuous monitoring of key parameters such as water temperature, pollutant loads, and the presence of both organic and inorganic contaminants remains essential, particularly in smaller river systems.

The composition and concentrations of physicochemical indicators in surface waters are governed by a combination of natural processes and anthropogenic pressures, both of which are continuously evolving. As a result, systematic monitoring of long-term changes in water quantity and quality is crucial for understanding potential risks to the stability of riverine systems.

The interactions between water quality components are complex and require integrated analysis. Climate change, together with ongoing human activities, significantly influences both water quantity and quality, thereby affecting the overall hydrological regime of river basins. A detailed understanding of these interdependencies is therefore necessary for effective risk assessment, prevention of adverse environmental impacts, and timely implementation of mitigation measures.

Although the effects of climate change on water availability have been extensively investigated in recent decades, its influence on surface water quality remains comparatively less explored. This highlights the need for further research focusing on the combined impacts of climatic and anthropogenic drivers on river water quality dynamics. Our previous research primarily focused on assessment of the oxygen regime or water temperature (Tw) and pH, whereas the present study emphasizes the analysis of ammonia nitrogen (N-NH4+) and nitrate nitrogen (N-NO3−).

Consequently , the main objectives of the present paper are:

- to detect and analyse of the changes in nitrogen compounds, specifically ammonia nitrogen (N-NH_4^+) and nitrate nitrogen (N-NO_3^-), of surface water in the Hron River;
- to investigate the relationships between nitrogen concentrations and selected physicochemical and hydrological indicators, such as dissolved oxygen (DO), biochemical oxygen demand (BOD), water temperature (Tw), pH, and discharge (Q), using regression analysis in order to explain and predict nitrogen dynamics;
- to use the derived regression relationships as exogenous variables for the validation and improvement of the predictive performance of the Seasonal Autoregressive Integrated Moving Average (SARIMA) model. Modelling of hydrospheric processes is essential for effective water resources management and planning.

2. Description of the Catchment and Data

The Hron River is the second longest watercourse in Slovakia, spanning a total length of 298 km with a basin area of 5 465 km². Flowing exclusively through Slovak territory, it eventually joins the Danube near Štúrovo. The river originates in the Horehronie valley, at the intersection of the Low Tatras and the Spiš-Gemer Karst, and is classified as a nivo-pluvial (snow-rain) type river. As a vital hydrological unit in Slovakia, the Hron River basin is fundamental to regional water governance, agricultural activities, and biodiversity conservation. Despite its regional importance, the river continues to grapple with environmental challenges, specifically pollution originating from industrial activities and agriculture. Following a period of severe contamination, the overall pollution levels of the Hron River began to gradually subside during the 1990s. Peak concentrations of pollutants were primarily recorded during the 1970s. This was subsequently mitigated in the 1980s through a significant reduction in industrial and agricultural discharge, alongside the implementation of a comprehensive network of wastewater treatment plants [13]. Despite these improvements in the surface water quality, the river's recovery has been periodically compromised by ecological disasters. Among the most serious incidents after 2000 was the ecological accident on July 18, 2003, upstream from Banská Bystrica, where a combination of industrial toxins (ammonia) and summer heatwaves demonstrated the river's extreme vulnerability to human negligence. Yet, the absolute worst disaster occurred near Budča (in July 2021). The leakage of hundreds of cubic meters of digestate from a biogas station led to the death of more than 40 tons of fish, ranking it among the largest ecological accidents in the modern history of the Hron River [14].

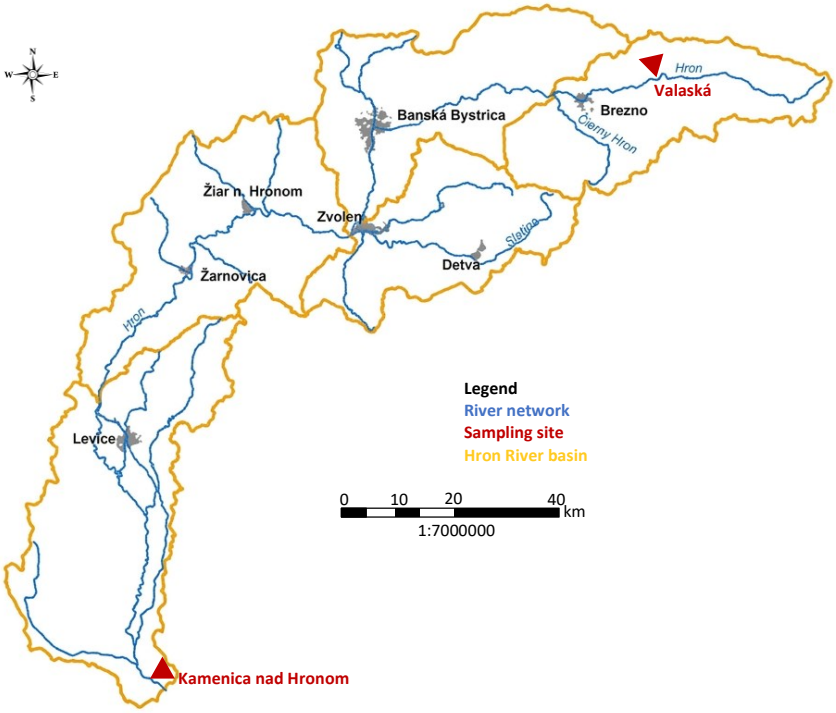

Fig. 1. Scheme of the Hron River basin with selected sampling sites.

In our study, monthly concentration of the monthly concentrations of ammonium nitrogen (N-NH_4^+) and nitrate nitrogen (N-NO_3^-) in the surface water were used. The two sampling sites were chosen for our analysis, the one from upper part of the Hron River: Valaská and the second one from lower part of the Hron River: Kamenica nad Hronom to quantify the possible threat to balanced regime for the period 1992–2021. Daily discharges used in this study were sourced from the gauging stations located nearest to the selected sampling points, the maximum distance was below 10 km. Water temperature data correspond to measurements taken

at the exact time of water quality sampling. The geographical scheme of the Hron River within Slovakia is illustrated in Figure 1. Figure 2 illustrate seasonal regime of long-term monthly discharges and long-term monthly concentrations of ammonium nitrogen ($N\text{-}NH_4^+$) and nitrate nitrogen ($N\text{-}NO_3^-$) in the Hron River during the period 1992–2021, together with daily discharges recorded on sampling days from the nearest gauging stations selected sampling points.

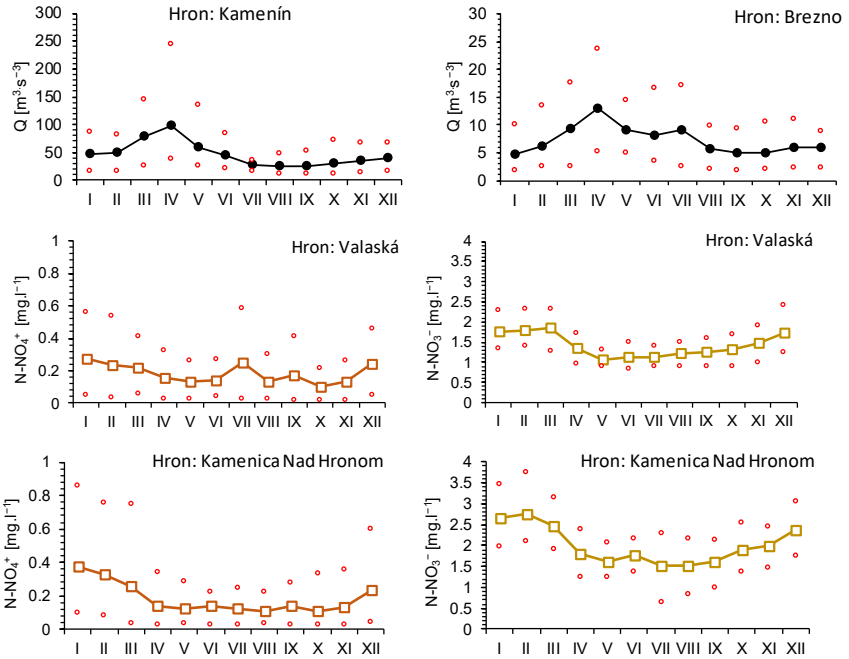

Fig. 2. Seasonal regime of long-term monthly discharges and long-term monthly concentrations of ammonia nitrogen ($N\text{-}NH_4^+$) and nitrate nitrogen ($N\text{-}NO_3^-$) in the Hron River at Valaská and Kamenica nad Hronom during the period 1992–2021 (red points are 10th and 90th percentile).

3. Methods

Traditional Mann-Kendall trend test is commonly employed to analyse trends within entire time series, categorizing the data. This statistical tool identifies trends at four levels: $\alpha = 0.001$, 0.01, 0.05 and $\alpha = 0.1$. An interpretation of the $\alpha = 0.001$ level indicates only a 0.1% probability that the observed data originate from a random distribution, thereby minimizing the risk of incorrectly rejecting the null hypothesis H0. Conversely, at the 0.1 level, this risk (Type I error) stands a 10% probability that we make a mistake if we reject the hypothesis H0. Using the Mann-Kendall test, we test the null hypothesis H0 of no trend, i.e., that the observations xi are randomly ordered in time, against the alternative hypothesis H1, which assumed presence of an increasing or decreasing monotonic trend. For n (number of tested values) ≥ 10, the statistic S is approximately normally distributed with the mean and variance as follows:

$$E(S) = 0 \tag{1}$$

$$VAR(s) = \frac{1}{8}\left[n(n-1)(n-2) - \sum_{p=1}^{q} t_p\,(t_p-1)(t_p+5)\right] \tag{2}$$

Where, n denotes number of tested values, q – represents the number of tied groups, and t_p is number of observation in the p group. Consequently, values S and VAR(S) are used for Z computation. The standard test statistic Z is computed as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & if\ S < 0 \end{cases} \tag{3}$$

A hydrological time series is first divided into two equal parts covering the full observation period. Both resulting sub-series are then independently arranged in ascending order. The first sub-series (X_i) is plotted on the x-axis, while the second sub-series (X_j) is plotted on the y-axis within a Cartesian coordinate system. If the data points lie approximately along the 1:1 (45°) line, the time series is considered trendless. Points located below this diagonal indicate a decreasing trend, whereas points above the line indicate an increasing trend in the analysed time series [15, 16]. The significance of detected trends was assessed using predefined significance levels. The classification is as follows:

*** corresponds to $\alpha = 0.001$, indicating that null hypothesis is unlikely;
** corresponds to$\alpha = 0.01$, 1% risk in rejecting H0;
* corresponds to $\alpha = 0.05$, 5% risk in rejecting H0;
+ corresponds to $\alpha = 0.1$, 10% error in rejecting H0;
no symbol indicates that the significance level exceeds 0.1, meaning that H0 cannot be rejected.

The strongest trends are marked with three asterisks (***), with decreasing statistical significance reflected by a lower number of symbols. Trend significance was evaluated based on the Z statistic, where positive values indicate an increasing trend and negative

values indicate a decreasing trend. Values of |Z| below the critical significance threshold indicate the absence of a statistically significant trend.

Individual physicochemical indicators of surface water quality exhibit mutual relationships and dependencies, which can be observed using regression analysis. Correlation analysis examines the relationship between two random variables xi and yi. The correlation coefficient r(x, y) is used to quantify the dependence between quantities, if it exists.

$$r_{x,y} = \frac{\sum_{i=1}^{n}(x_i - x)(y_i - y)}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{4}$$

Unlike correlation analysis, regression analysis allows for determining the nature of the mutual relationship and the optimal way of describing it. It consists of determining the type of the regression function equation and calculating its parameters. Among the basic regression equations used in the hydrology are linear, multiple regression linear, and nonlinear (quadratic, polynomial, hyperbolic, power, exponential, logarithmic).

For the modelling of nitrogen compounds in surface water, a Seasonal Autoregressive Integrated Moving Average SARIMA model with and without selected regressor was applied. The model is designed to capture patterns and dependences in time series data based on past behaviour data [17, 18]. Parameter estimation is typically performed using the maximum likelihood estimation method. In practice, identifying an appropriate SARIMA model involves several steps: (1) trend analysis, (2) selection of model structure and order, (3) estimation of parameters, and (4) model validation. The seasonal component is an important part of the SARIMA framework, as it enables modelling data with periodic fluctuations and cycles. The general form of the SARIMA (p, d, q)x(P, D, Q)$_L$ model is given as:

$$\phi(B)\mathbf{\Phi}(B^L)(1-B)^d(1-B^L)^D Y_t = \Theta(B)\Theta(B^L)E_t \tag{5}$$

The model parameters define both non-seasonal and seasonal dynamics. The parameter *p* defines the order of the non-seasonal autoregressive components, *d* determines the degree of non-seasonal differencing applied to achieve stationarity and q represents the order of the non-seasonal moving average components. Seasonal behaviour is captured by parameters P, D, and Q, which correspond to the seasonal autoregressive, seasonal differencing, and seasonal moving average orders, respectively.

The error term E_t is assumed to follow a normal distribution with zero mean and constant variance σ_E^2. The parameter L denotes the length of the seasonal period, such as L=12 for monthly data exhibiting yearly seasonality. The backshift operator *B* is defined as $BY_t = Y_{t-1}$, while differencing operator expressed as (1-B) for non-seasonal and (1-B^L) for seasonal transformation.

4. Results

The Mann-Kendall non-parametric test detected the various significant long-term trends and course of these trends in analysed physicochemical indicators of surface water quality such as dissolved oxygen, biochemical oxygen demand, pH and water temperature. To evaluate the long-term trends in selected physicochemical indicators of surface water quality the monthly and annual concentrations from the Hron River at selected sampling sites (Valaská and Kamenica nad Hronom) were used (period 1992–2021). Increasing long-term trends of DO concentrations were detected in the winter months at significance levels $\alpha = 0.001(^{***})$ at the Valaská sampling point, and in the winter and spring months at significance levels $\alpha = 0.05(^{**})$ and $\alpha = 0.01(^{*})$ at the Kamenica nad Hronom sampling point. Very significant ($\alpha = 0.001^{***}$) decreasing long-term trends in BOD concentrations were detected in all months of the year at the Valaská sampling point, in the case of Kamenica nad Hronom a significant long-term trend was detected only in May ($\alpha = 0.001^{***}$). The pH values showed increasing long-term trends also in all months of the year at $\alpha = 0.01(^{*})$ and $\alpha = 0.1(^{+})$ in Valaská, but a very significant increasing long-term trend at $\alpha = 0.001(^{***})$ was detected in annual values. In the case of the Kamenica nad Hronom the very significant increasing long-term pH trends were detected in the months of August and December. Increasing long-term trends in water temperature were detected in month of April ($\alpha = 0.05(^{**})$) in Valaská, and in months of June ($\alpha = 0.01(^{*})$) and October $\alpha = 0.05(^{**})$ in Kamenica nad Hronom. Annual values of the water temperature showed an increasing long-term trend at the significance level ($\alpha = 0.01(*)$) in both sampling points.

A detailed analysis of long-term trends in chemical surface water quality indicators, specifically ammonium nitrogen N-NH_4^+ and nitrate nitrogen N-NO_3^-, was conducted in this section of the study. The results of the Mann-Kendall non-parametric test for the period 1992–2021 indicate a positive long-term trend in surface water quality at the selected sampling points of the Hron River. This improvement is evidenced by significant decreases in both indicators' ammonium nitrogen N-NH_4^+ and nitrate nitrogen N-NO_3^-. However, the observed decline in concentrations exhibits varying levels of significance (intensity) and seasonal variability. The decrease in nitrogen compounds is less consistent in upper sampling point Valaská. For N-NH_4^+, a decreasing long-term trend ($\alpha = 0.05(^{**})$ and $\alpha = 0.01(^{*})$) was detected primarily from July to September, as well as in annual concentrations ($\alpha = 0.05(^{**})$) (Table 1). Regarding N-NO_3^-, the decline is concentrated mainly in the first half of the year (January–July), while the trend is absent during the autumn months (Table 1). Consequently, the overall annual trend is decreasing at a significance level of $\alpha = 0.05(^{**})$. A significantly higher consistency in surface water quality improvement was observed at lower sampling point Kamenica nad Hronom for the analysed period. For N-NH_4^+ concentrations, a downward trend was detected across all months, with 8 months showing a significant long-term trend at the $\alpha = 0.001(^{***})$ significance level (Table 1). The annual Pearson correlation coefficient R=0.83 indicates a strong relationship between time and the decrease in concentration. Similarly, for nitrates, a decreasing trend is present almost year-round, except for May and August. In the annual N-NO_3^- concentrations the significant ($\alpha = 0.001(^{***})$) decreasing trend was detected for Kamenica nad Hronom (Table 1).

The annual concentrations of the analysed nitrogen forms and their long-term trends for the selected period (1992–2021) at the Valaská and Kamenica nad Hronom sampling sites are illustrated in Figure 3.

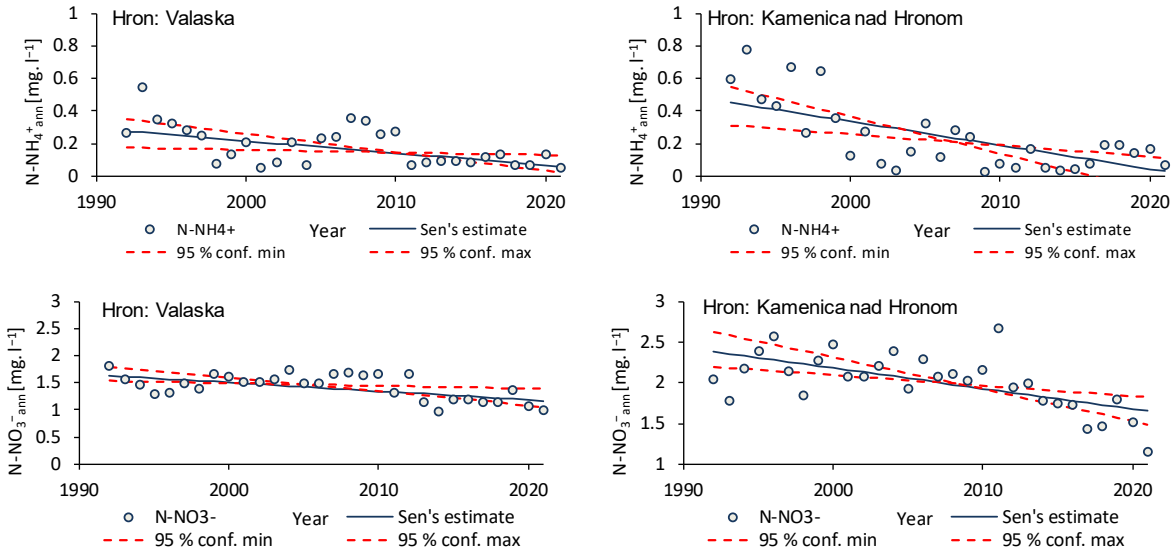

Fig. 3. Long-term annual concentrations of the ammonium nitrogen N-NH_4^+ and nitrate nitrogen N-NO_3^- in the Hron River at Valaská, and Hron: Kamenica nad Hronom, including the fitted Sen's slope estimate (solid black line) and the corresponding 95% confidence limits (red dashed line) (1992–2021).

Tab. 1. Assessment of long-term trends in monthly and annual concentrations of N-NH_4^+ a N-NO_3^- based on the Mann-Kendall test in the Hron River at Valaská and Kamenica nad Hronom sample points during the period 1992–2021 (no symbol - no sign. trend).

		N-NH_4^+			N-NO_3^-		
Hron: Valaská							
month	n	Significance	skewness	Pearson correl.	Significance	skewness	Pearson correl.
January	30		-	-	**	-0.027	0.62
February	30		-	-	**	-0.023	0.53
March	30	*	-0.007	0.43	*	-0.026	0.54
April	30		-	-	***	-0.024	0.61
May	30	+	-0.002	0.4	*	-0.009	0.11
June	30		-	-	**	-0.016	0.44
July	30	*	-0.005	0.42	**	-0.013	0.45
August	30	*	-0.005	0.5		-	-
September	30	**	-0.009	0.55		-	-
October	30	+	-0.003	0.37		-	-
November	30	**	-0.006	0.55		-	-
December	30		-	-		-	-
Annual	30	**	-0.007	0.58	*	-0.016	0.59
Hron: Kamenica nad Hronom							
January	30	***	-0.014	0.60	*	-0.028	0.43
February	30	***	-0.017	0.70	**	-0.032	0.46
March	30	***	-0.013	0.62	**	-0.033	0.56
April	30	*	-0.005	0.45	**	-0.024	0.4
May	30	**	-0.006	0.59		-	-
June	30	***	-0.005	0.41	*	-0.020	0.45
July	30	***	-0.004	0.58	*	-0.029	0.47
August	30	**	-0.004	0.41		-	-
September	30	**	-0.006	0.62	*	-0.023	0.4
October	30	***	-0.007	0.72	*	-0.023	0.29
November	30	***	-0.007	0.66	+	-0.020	0.34
December	30	***	-0.015	0.72	***	-0.043	0.68
Annual	30	***	-0.012	0.83	***	-0.025	0.62

Cross-corelation analysis of our data revealed relatively weak linear dependences (r<0.3) of the monitored nitrogen compounds, particularly on discharge (Qd). Cross-corelation for the Hron River in the Valaská also detected a correlation between BOD and N-NH_4^+ (r=0.258) suggesting that ammonium nitrogen may originate from gross organic pollution where ammonification primarily occurs (Figure 4a). The weak correlation (near zero) between Do and NH_4^+ indicates that the oxygen regime is not a limiting factor for nitrification, rather, the concentration of the ammonium nitrogen is primarily driven by external sources (Figure 4a).

In contrast, N-NO_3^- exhibits a moderate corelation with DO (r = 0.347), confirming its stability in the well-oxygenated environment of the upper part of the river. A strong negative corelation between nitrates and surface water temperature (r = -0.547) points to intensive biological nitrogen assimilation by vegetation during warmer periods. Overall, the results indicate a river with good assimilatory capacity, where water quality is determined by biotransformation processes rather than by flow dilution.

In the case of the Kamenica nad Hronom sampling site in the lower section of the river, cross-correlation showed a moderate

negative dependency between N-NH_4^+ and water temperatureTw (r=-0.337), suggesting more efficient nitrification, especially at higher temperatures. For nitrates (N-NO_3^-), the temperature dependency at the lower sampling site is even stronger (r = -0.617). This phenomenon is explained by the process of denitrification and seasonal nitrogen uptake by vegetation, which are more pronounced in the lower, slower flowing sections with a developed floodplain. Additionally, the correlation between nitrates and oxygen (r = 0.490) confirms that ammonia is successfully transformed into nitrates in the lower reach (Figure 4b)

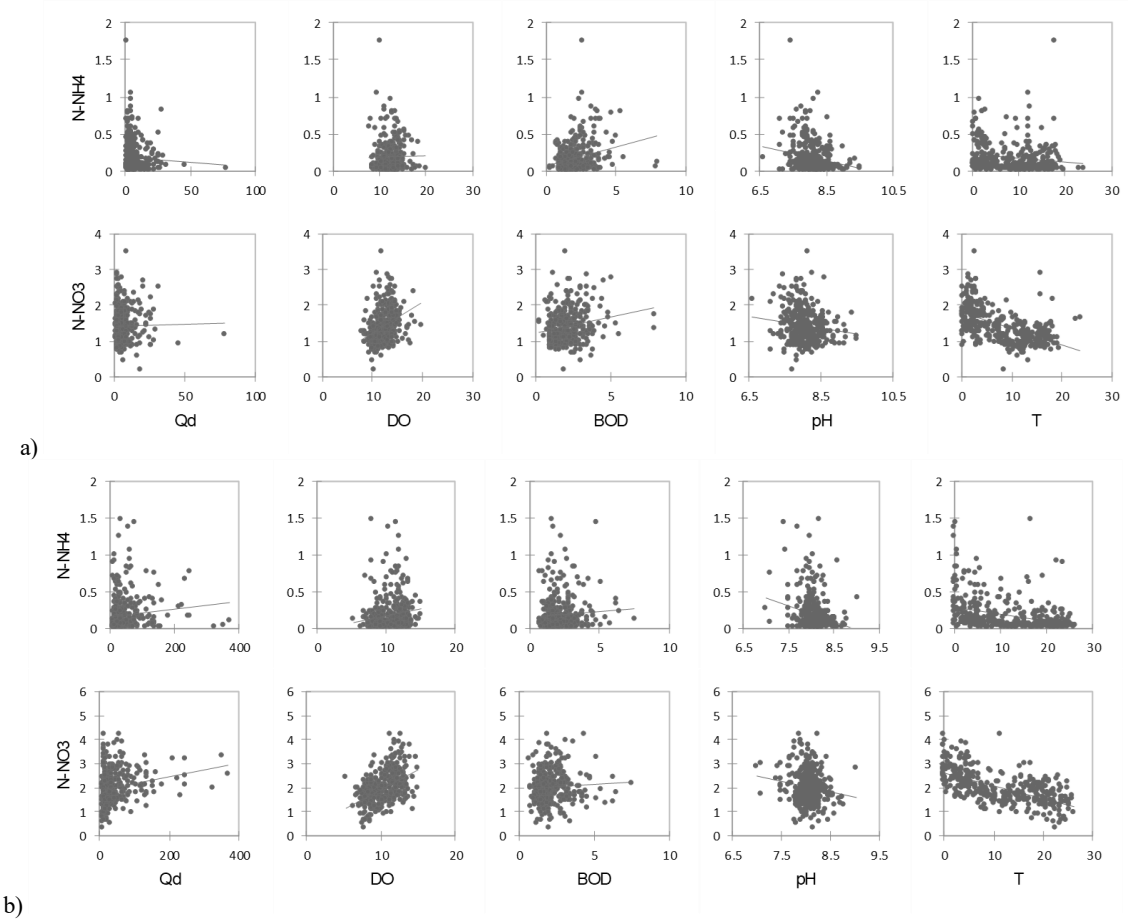

Fig. 4. Pearson cross-correlation between monthly N-NH_4^+ and N-NO_3^- concentrations and main analyzed hydro-environmental drivers influencing nitrogen transformation processes for Hron River a) in the Valaská and b) in the Kamenica nad Hronom sampling sites (period 1992–2021).

To determine the optimal method for describing the relationships between N-NH_4^+ a N-NO_3^- and the selected regressors (exogenous parameters), we defined the types of multiple linear or nonlinear regression functions and calculated their parameters. For the Valaská sampling site, we tested the derived equations (6) and (7) as a multiple nonlinear regression relationship within the model; for Kamenica nad Hronom, equations (8) and (9) were used. Subsequently, we incorporated these derived relationships into the SARIMA model as exogenous parameters and tested the modelling of the given variables. Histograms of the analysed surface water quality are not normally distributed; therefore, logarithmic or square root transformations were applied to the SARIMA modelling to stabilize the data.

Exogenous regressor for the Hron River: Valaská

$$N - NH_4^+ = 1.46 - 1.16pH - 0.024BOD \quad (6)$$

$$N - NO_3^- = 1.86 - 0.0063DO + 0.0039Tw^2 - 0.112Tw \quad (7)$$

Exogenous regressor for Hron: Kamenica nad Hronom:

$$N - NH_4^+ = 0.16 + 0.057BOD - 0.034e^{0.081Tw} \quad (8)$$

$$N - NO_3^- = 2.40 - 0.0062DO - 0.066Tw \quad (9)$$

The measured monthly concentrations of ammonium nitrogen (N-NH_4^+) and nitrate nitrogen (N-NO_3^-) at the Hron: Valaská and Hron: Kamenica nad Hronom stations for the period 1992–2021 were then modelled using the SARIMA method. The last 24 months of the measured data were used to validate the model. Individual model parameters (including exogenous regressors) were significant at the level of $\alpha < 0.05$. The model parameters were estimated using maximum likelihood estimation, and model accuracy was evaluated using various statistical criteria (Table 2). The model reliably extracts the seasonal cycle and trend, with the mean absolute error (MAE) during the validation period not exceeding 0.06 mg.l^{-1} for N-NH_4^+ and 0.25 mg.l^{-1} for N-NO_3^-. Correlations between

the measured and modelled concentrations achieved values of over 60%, further confirming the model's utility for long-term forecasting of surface water quality. Figure 5 illustrates the best-fit SARIMA models, incorporating the derived regressors and measured concentrations of ammonium and nitrate nitrogen at the selected sampling sites (Valaská and Kamenica nad Hronom). Subsequently, the selected SARIMA models were used to predict $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ concentrations for a 36-month period (Figure 6).

Tab. 2. The best-fit SARIMA models, math adjustment, MAE – mean absolute error, and corelation between modelled and measured concentrations in the Hron River at the Valaská and Kamenica nad Hronom sampling points (2000–2021)

Sampling site	$N\text{-}NH_4^+$ [mg. l^{-1}]	$N\text{-}NO_3^-$ [mg. l^{-1}]
Hron: Valaská	$(1,1,1)x(0,1,0)_{12}$+1multiregressor	$(1,1,1)x(0,1,1)_{12}$+1multiregressor
Math adjustment	Natural log	Natural log
MAE [mg.l^{-1}]	0.053	0.20
$R_{measured/modelled*}$	0.62	0.74
Hron Kamenica nad Hronom	$(1,0,1)x(1,1,1)_{12}$+1multiregressor	$(1,0,2)x(0,1,1)_{12}$+1multiregressor
Math adjustment	Natural log	Natural log
MAE [mg.l^{-1}]	0.026	0.24
$R_{measured/modelled*}$	0.74	0.81

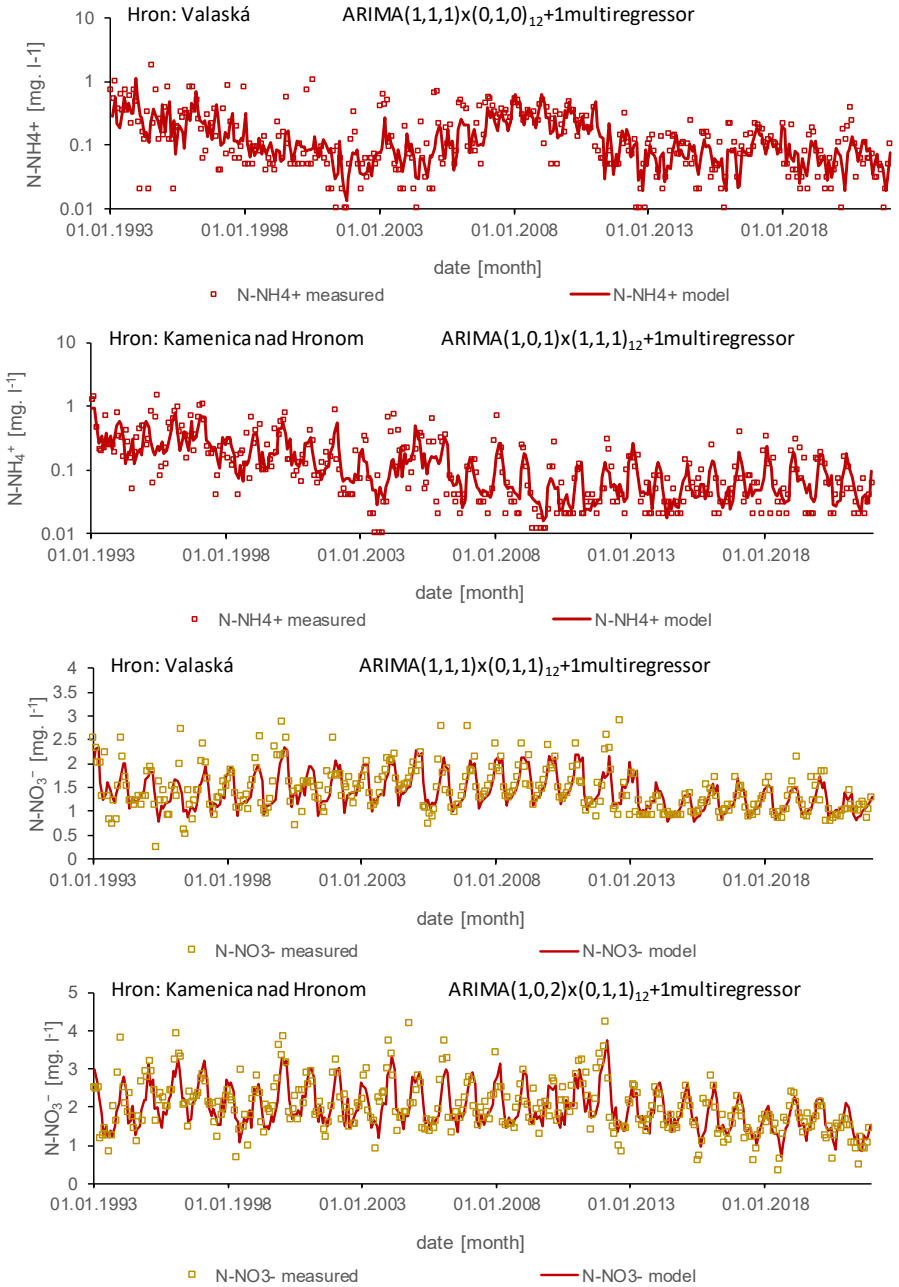

Fig. 5. Modelling of the monthly concentration of ammonium nitrogen $N\text{-}NH_4^+$ and nitrate nitrogen $N\text{-}NO_3^-$, of the surface water quality at study sampling sites by using the selected best fit ARIMA models for Hron River a) in the Valaská and b) in the Kamenica nad Hronom sampling sites (period 1992–2021)

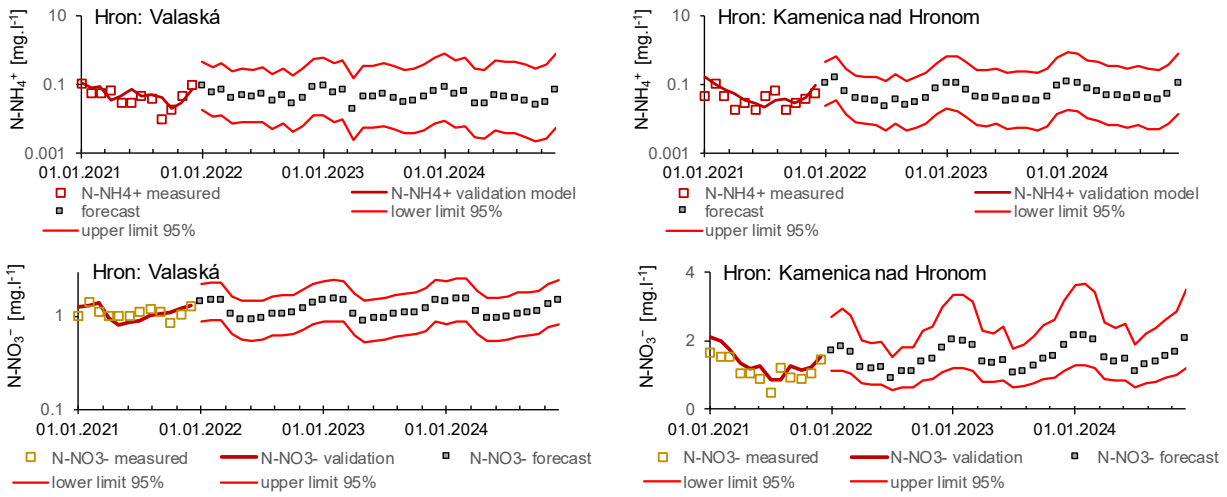

Fig. 6. Validation and prediction (36 months) of the monthly concentration of ammonium nitrogen N-NH_4^+ and nitrate nitrogen N-NO_3^- of surface water at study sites by using the selected best fit ARIMA models for Hron River a) in the Valaská and b) in the Kamenica nad Hronom sampling sites (period 2020–2024).

5. Conclusion

The first part of this study presents a comprehensive assessment of long-term changes in surface water quality in the Hron River at two key sampling sites: Valaská (upper basin) and Kamenica nad Hronom (lower basin) during period 1992–2021. The study was particularly focused on the behaviour of nitrogen forms, ammonium nitrogen (N-NH_4^+) and nitrate nitrogen (N-NO_3^-), and their relationship with selected hydrological parameter and physicochemical indicators (dissolved oxygen (DO), biochemical oxygen demand (BOD), water temperature (Tw), and pH. The result show that surface water quality has generally improved over time, mainly due to the gradual reduction of industrial and agricultural pollution, as well as the implementation of environmental measures. Long-term trend analysis indicates a significant reduction in both ammoniacal and nitrate nitrogen concentrations across the monitored reaches. The more pronounced and consistent decline observed at the downstream station (Kamenica nad Hronom) compared to the upstream profile (Valaská) underscores the river system's inherent capacity for longitudinal recovery following systematic nutrient load reductions. While Valaská reflects the conditions of a relatively cleaner mountain region with lower anthropogenic pressure, Kamenica summarizes the positive changes across the entire Hron river basin over the last three decades. The analysis of the other physicochemical indicators of the surface water quality revealed significant seasonal as well as long-term trends. A positive finding is the increase in dissolved oxygen concentration and the decrease in BOD, indicating an improvement in the river's self-purification capacity. On the other hand, the increasing trend in water temperature and changes in pH point to ongoing environmental changes, likely associated with climate change, which may have negative impacts on aquatic ecosystems in the future.

Correlation and regression analyses demonstrated that the relationships between nitrogen compound concentrations and the observed environmental factors are complex and often nonlinear. While biological assimilation and nitrogen transformation processes dominate in the upper reach, nitrification and denitrification processes are more pronounced in the lower reach, influenced by temperature and oxygen regime. An important contribution of this work is the application of modelling using SARIMA model with exogenous variables derived from regression relationships. This approach improved the accuracy of nitrogen concentration predictions and captured both seasonal and trend components of time series. Model validation confirmed their good reliability and applicability for short- and medium-term forecasts of water quality development.

The obtained results have significant implications for water resource management. They show that long-term monitoring and trend analysis are essential for understanding the development of aquatic ecosystems and for effective planning of water protection measures. At the same time, they highlight the need for an integrated approach that considers not only chemical indicators but also hydrological and climatic factors.

In conclusion, despite the demonstrated improvement in water quality in the Hron River, challenges related to climate change, extreme events, and potential sources of pollution persist. Future research should focus on more detailed modelling of climate scenario impacts and on expanding the analysis to include additional water quality indicators in order to enable more accurate predictions and the design of effective adaptation measures.

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