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ASSESSING THE IMPACT OF THE TURBULENCE OF RIVER FLOW ON VARIATIONS IN THE CONCENTRATIONS OF NUTRIENTS

The fourth-order stream of the Baltic Sea has been analysed, which is a tributary which remained in the riverbed as a result of natural river stretches not corresponding to the status of good water quality. The authors examined separate river stretches representing maximum changes in the hydraulic gradient and investigated the dependence of variations in the concentrations of biogenic nutrients on river flow velocity, i.e., turbulence, defining it by the Reynolds criterion. The calculation of the coefficient of self-purification provides that the river flowing downstream is 100% self-purified and removes all nitrates and 61% of phosphates. The content of dissolved oxygen at the confluence of the river in spring was by 5.5% larger than that at the headwaters, whereas in the summer season, the difference in the content of dissolved oxygen in river water between the headwaters and confluence increased and made 25%. The conducted research has disclosed that the dynamics of river flow affects water quality, and therefore, for selecting monitoring places, land use structure or economic entities situated around the sampling point as well as the nature of the river flow itself must be considered.

1. INTRODUCTION

Recently, the number of proposed solutions for improving the ecological status of rivers, lakes as well as the Baltic Sea has substantially increased. With reference to data suggested by the *Lithuanian Fund for Nature* [1], over the last century, the Baltic Sea water has become heavily eutrophic and oversaturated with nutrients. According to the Council of the European Union, the encountered problems should be solved at the national, regional and municipal levels. To ensure a good or excellent ecological status of the Baltic Sea, similar conditions have to be created for the rivers that flow in the Baltic Sea, including the first-, second- and fourth-order streams.

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Foreign and Lithuanian scientists [2–6] described changes in nutrients under varying factors such as leakage, watershed land use and sediments, water content, physical and geographical properties. Nevertheless, the impact of the slope and overfall has not been properly investigated.

The authors suggest that water quality depends on a number of factors such as the height of flow, geology, flow character, flow velocity and wetland in the watershed [7, 8]. Water quality is also affected by the season of the year, as, amounts of nutrients in water may differ depending on temperature. At low water flow (sometimes even lower than environmental discharge), water quality decreases, as, under such conditions, particles are tend to sink [9]. Meanwhile, although the silt washed from adjacent surfaces appear in the river in the run of flooding, a permanent mix of water flow naturally purifies itself, and therefore the particles do not sink to the bottom of the river.

A turbulent water flow, compared to the laminar one, has many advantages that were analysed by Vaikasas [6] and other authors [10]. During turbulent and mixed flow, water better absorbs oxygen and is less contaminated with nutrients, as the permanent circulation of air takes place on the surface. Self-purification processes (denitrification, oxidation) are more intensive in the flow containing contaminants. Moreover, flowing water is an important medium for transporting and distributing suspended and organic nutrients.

The questions what impact the turbulence of river flow has on nutrients and if monitored sample points are wisely selected taking into account the chemical properties of nutrients have not been considered. The paper is aimed at assessing variations in the concentrations of nutrients in view of the turbulence of river flow.

2. OBJECT OF RESEARCH AND METHODOLOGY

The object of the research covers the watershed of the Širvinta River that is 129 km long and covers the area of 918 km². The river has been chosen due to natural stretches that have remained in the riverbed, which, however do not correspond to good water quality.

8 sample points (Fig. 1) embracing the entire length of the river from the headwaters to the confluence were chosen. The points were selected to represent a maximum fluctuation in the hydraulic gradient. The samples of water were taken 1–1.5 m away from the bank of the river and in the middle of the river once per season in the sample point. Ammonium molybdate spectrometric method LST EN ISO 6878:2004 was used for determining phosphorus, electrotechnical probe method LST EN ISO 5814:2012 was employed for defining dissolved oxygen, while nitrogen was determined as bound nitrogen (TNb), by following oxidation to nitrogen oxides LST EN 12260:2004. The coordinates of the points, distances to the confluence and the length of the stretches are provided in Table 1.

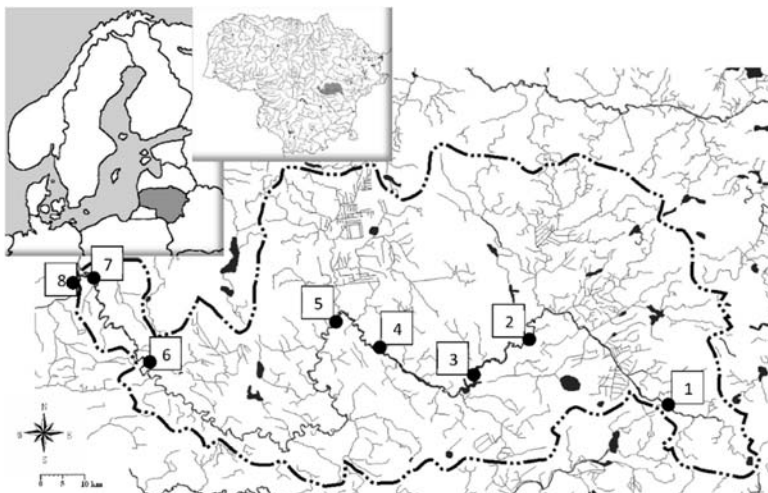


Fig. 1. The watershed of the Širvinta

Table 1

Sample points

No.	Coordinates according to LKS	Distance to the estuary [km]	Altitude [m]	Distance between the points [km]
1	55.077, 25.127	121.5	129.2	
2	55.062, 25.192	112.7	124.2	8.8
3	55.025, 25.027	91.6	115.5	21.1
4	55.046, 24.954	83.4	109.5	8.2
5	55.072, 24.870	70.8	100	12.6
6	55.026, 24.671	24.4	85.3	46.4
7	55.111, 24.562	3.3	47.9	21.0
8	55.108, 24.562	0.0	41.7	3.3

Sample point 1 was situated in the woodland. Sample point 2 was surrounded by cultivated fields on one side, and an urbanized area on the other. Sample points 3 and 4 were close to hydro power plants. In the latter case, the impact of the ponds constructed next to the plants on water quality has been assessed. The rest of the points were located in the areas of cultivated fields. Under the varying hydraulic gradient and turbulence of the flow, for the examination of changes in nitrates, phosphates and dissolved oxygen, defining the Reynolds criterion and a factor in self-purification is an important task. The Reynolds criterion is more frequently calculated to analyse fluid flow in circular pipes. Therefore, to estimate it in open and wide riverbeds, the radius is accepted as a hydraulic radius.

For assessing the general self-purification of the river, the following equation has been used:

$$\frac{C_L}{C_0} = \exp(-K_T t) \quad (1)$$

where C_L is the nutrient concentration in the examined point, mg/dm^3 , C_0 – nutrient concentration in the sample place 1 following the gradient after a complete mix with generated pollution, mg/dm^3 ; K_T – an empirical coefficient indicating physicochemical and biological self-purification processes and determined from field study and measurement data, day^{-1} , t – time for the uptake of a nutrient, day.

Time for uptake a nutrient [11] is calculated according to the formula

$$t = \frac{LWyn}{Q} \quad (2)$$

where L – the length of the river section, m, W , y – the average width and depth of the riverbed, respectively, m, n – the degree of the free flow of water expressed in parts of the unit under no inference of vegetation or debris, Q – average river discharge, m^3/day .

The degree of the free flow of water was not measured, and therefore time for the nutrient staying underwater was calculated assuming that $n = 1$. The application of Eqs. (1), (2) enable one to establish the coefficients K_T for the self-purification of the river [11].

$$K_T = \frac{1}{t} \ln \frac{C_0}{C_L} \quad (3)$$

3. RESULTS AND DISCUSSION

Due to the fact that the riverbed is wide enough, it can be accepted that a hydraulic radius is equal to the maximum depth of the estimated point. Rates were measured during spring and summer seasons under differences in the water content of the river: the average discharge of the river in spring made $7.9 \text{ m}^3/\text{s}$, whereas that in summer – $3.94 \text{ m}^3/\text{s}$. Data and findings employed in calculations are presented in Table 2. It shows that the river flow is turbulent in all analyzed points and makes $Re > 4000$. The calculations support the idea expressed by Tsujimoto [12] claiming that flows swirl in the turbulent flow.

According to Alian [13], in case any nutrient is poured into the river subsequently measuring downstream, after a while, it will change differently. In order to mathematically describe the process, nutrient flow and distribution should be considered thus taking into account the dimensions of the riverbed and water rate. The thesis by Bagdžiūnaitė-Litvinaitienė [14] presents that the examination of nutrients leads to a question about what method for estimating self-purification and variations in nutrients

should be employed so that the obtained results adequately reflected the real situation. Certainly, though changes in the concentrations of nutrients are affected by a number of factors, however, all aspects can be difficult to assess.

Table 2

Data and results of calculating the Reynolds criterion

No.	Spring season			Summer season		
	Depth [m]	Velocity [m/s]	Re	Depth [m]	Velocity [m/s]	Re
1	0.47	0.12	30 412	0.20	0.01	11 647
2	1.00	0.25	147 059	0.50	0.13	37 647
3	1.40	0.23	189 412	1.25	0.18	95 588
4	1.67	0.25	255 412	1.20	0.30	211 765
5	1.40	0.22	181 176	1.10	0.19	122 941
6	1.60	0.25	235 294	1.40	0.22	181 176
7	1.00	0.30	176 471	0.80	0.25	117 647
8	1.00	0.36	211 765	0.90	0.34	180 000

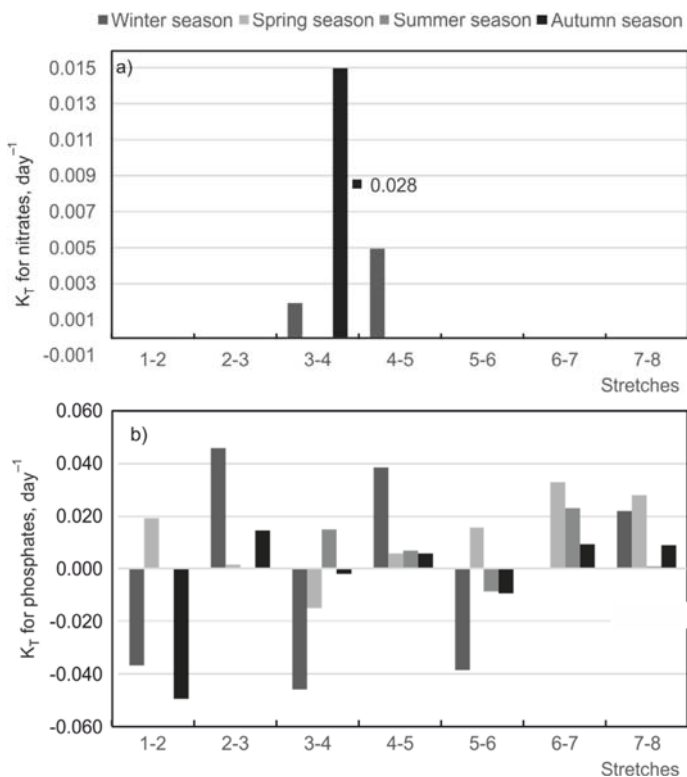


Fig. 2. Results of calculating the self-purification coefficient of: a) nitrates, b) phosphates

While analysing self-purification in the river and employing Eq. (3), the coefficient of self-purification K_T has been estimated. The received findings are shown in Fig. 2. The received negative values of the self-purification coefficient show that the process takes the direction opposite to purification.

Table 3

Concentrations [$\text{mg O}_2/\text{dm}^3$] of dissolved oxygen in sample points

Sample points		Winter	Spring	Summer	Autum
1	before the fall	3.60	8.50	8.10	10.00
	within the fall	4.60	6.90	7.20	8.20
	after the fall	7.30	9.00	8.20	6.10
	average	5.17	8.13	7.83	8.10
2	before the fall	7.09	7.70	6.25	6.00
	within the fall	7.20	5.80	6.54	8.90
	after the fall	7.00	6.50	6.26	10.00
	average	7.10	6.67	6.35	8.30
3	before the fall	7.30	7.40	8.70	8.62
	within the fall	8.00	8.10	8.80	10.00
	after the fall	8.70	6.80	10.00	5.40
	average	8.00	7.43	9.17	8.01
4	before the fall	7.70	1.60	8.00	7.80
	within the fall	8.90	8.90	8.00	7.60
	after the fall	9.20	7.10	4.20	5.30
	average	8.60	5.87	6.73	6.90
5	before the fall	3.80	9.70	6.80	8.80
	within the fall	8.30	9.80	6.30	9.20
	after the fall	0.70	7.90	6.35	9.60
	average	4.27	9.13	6.48	9.20
6	before the fall	8.00	8.60	6.25	8.40
	within the fall	8.70	7.00	6.57	10.00
	after the fall	3.70	10.00	6.39	8.40
	average	6.80	8.53	6.40	8.93
7	before the fall	10.00	7.56	9.20	6.30
	within the fall	8.40	8.96	8.10	7.90
	after the fall	9.70	7.77	6.70	5.70
	average	9.37	8.10	6.50	6.63
8	before the fall	3.50	8.10	7.20	8.10
	within the fall	7.80	9.38	8.60	10.00
	after the fall	9.10	8.36	8.60	9.30
	average	6.80	8.61	5.88	9.13

The content of dissolved oxygen at the confluence of the river in spring was only by 5.5% larger than that at the headwaters, whereas in the summer season, the difference in the content of dissolved oxygen in river water between the headwaters and confluence

increased and amounted to 25%. The content of dissolved oxygen at the confluence of the river in autumn was by 11% larger than that at the headwaters while in the winter season, the difference in the content of dissolved oxygen in the river water between the headwaters and confluence increased and was equal to 25% (Table 3).

Due to high nutrient pollution in the river, the content of dissolved oxygen was not sufficient to oxidize them. It was diminished by a reduction of dissolved oxygen in overfall, a more intensive vegetation period in summer and soil fertilization or other economic activities in autumn. As for nitrates (Fig. 3), it should be noted that the river fully purifies itself; nevertheless, it must be emphasized that changes in nitrate concentrations in water were not recorded in spring and summer seasons. Processes of vegetation and intensive photosynthesis are also responsible complete consumption of nitrates in the system. The other reason is river water rich of nitrogen that is soluble, consisting of ammonium, nitrite and nitrate ions and could be found as gaseous nitrites. Nitrogen fixation is observed, which occurs when bacteria convert gaseous nitrogen into ammonia and store inside their biomass; then, ammonium appears in water as bacterium excretes, and a part of it is taken by clay particles [15].

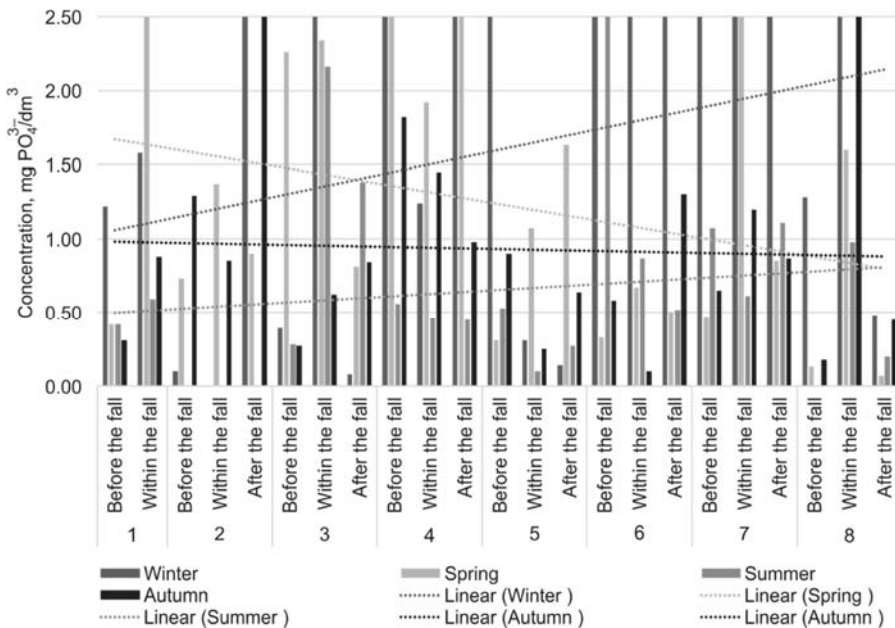


Fig. 3. Variations in the concentrations of nitrates

Figure 3 shows that the content of nitrates is always lower on average by 1–4 times before the fall of water than that within it. Falling water is highly turbulent, and consists predominantly of dissolved oxygen; therefore, the content of nitrates decreases again up

to the initial or even lower concentration. In Figure 3, sample points 3 and 7 are distinguished. The content of nitrates in sample point 3 where Re makes 95 000–190 000 is by 14 times higher even after the fall than before it. Sample point 3 is close to the hydro power plant in Motiejūnai where the settlement (urban area) is found on one side of the river and forests are located on the other.

The obtained result seems to be interesting due to the fact that the river flowing towards turbines spreads nutrients throughout the pond, and thus a variation in nitrates should be lower by 2–3 times. However, the findings indicate that a change in the concentrations of nitrates is 7 times higher after the fall than within the process of falling. Such drastic change could be influenced by instantaneous pollution from the concentrated source of contamination.

As for sample point 7, variation in the content of nitrates from the initial position has increased up to 4 times after the fall (Re criterion varies from 110 000 to 180 000). Sample point 7 is surrounded by cultivated fields, the banks of the river are covered with abundant vegetation and no urbanized areas are observed. Thus, the latter two factors determine a higher content of nitrates after the fall.

During spring and summer seasons, nitrate flows remained unchanged. One of the reasons for the obtained results is a higher temperature, whereas the other is a decrease in the concentration of ammonium ions in spring and summer, as aquatic vegetation intensively assimilates them during the growing season. Though the turbulent flow in the river can be observed in both summer and winter, however, in our case, the latter factor had no impact. The concentration of ammonium ions increases 2–3 times in autumn and winter and is affected by the decomposition of organic matter in summer.

From the headwaters to the confluence, the river itself removes 41% of phosphates during the winter season, whereas 82% of those are taken away in autumn. As for spring and summer, the coefficient of self-purification is higher by 47% in spring and by 1% in summer at the headwaters rather than at the confluence; nonetheless, a comparison of the stretches between sample points 6, 7 and 7, 8 reveals that the concentration of phosphates decrease by 1.18 times in spring and by 23 times in summer. The places that have not faced self-purification processes could be influenced by instantaneous pollution from diffused contamination sources in spring and a small leak in the summer season, which, according to Lysoviene [11], impedes the possibilities of natural self-purification (Fig. 4).

A variation in phosphates defined before and after the fall fluctuates from 2 to 5 times, but sometimes, a change of 25 times can be noticed. Falling water is dynamic, contains much oxygen and involves very intensive self-purification processes. Thus, the water flowing further includes a lower amount of phosphates

The content of phosphates increases from 16 to 25 times after the fall starting from the initial concentration at sample points 2 (Re between 37 000 and 150 000) and 5 (120 000–190 000). An interesting argument is that this increase was recorded in the winter season when vegetation could not have influence. These points are surrounded

by cultivated fields and residential areas, and therefore it could be instantaneous pollution from the concentrated contamination source, as in other seasons, no increase has been recorded at this point.

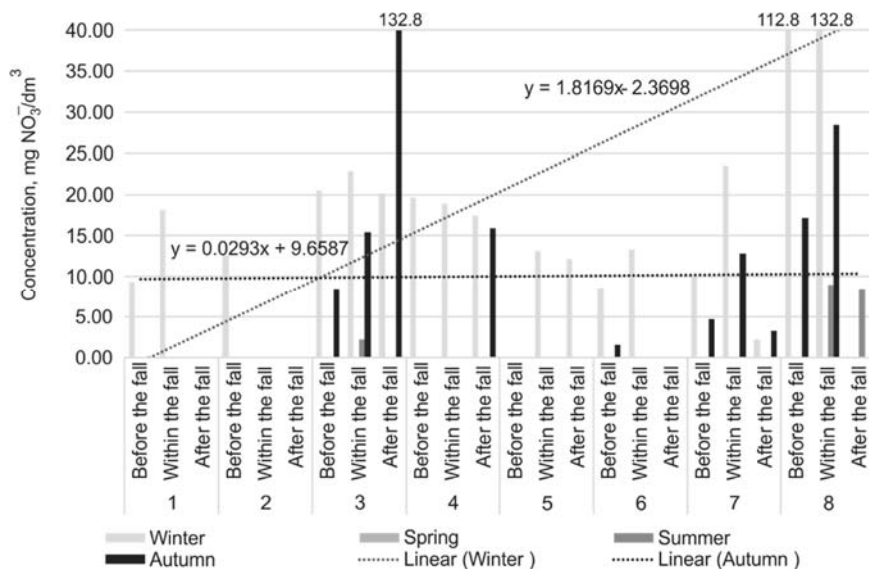


Fig. 4. Variations in the concentrations of phosphates

Sample point 8 (180 000–210 000) is situated in the woodland, and therefore this factor has determined a spike in a variation in the content of phosphates: the amount of phosphates is 13 times lower that that before the fall. However, under turbulent processes (compared to other points, the river is the most torrential at this point), after the fall at the final point, the content of phosphates has decreased by 3 times.

The analysis of variations in the content of dissolved oxygen (Table 3) reveals that, on the contrary to comparing variations in the contents of nitrates and phosphates, the content of oxygen is the highest in falling water due to the intensive water mixing. The content of dissolved oxygen within the water falling process is 2–6 times higher than that before or after it. In the summer season, the content of oxygen remains reduced because the riverbed is covered by vegetation. Therefore, oxygen is used for photosynthesis, and the content of oxygen dissolved in water is lower by 2 times compared to other seasons (Table 3).

A comparison of the overfall of the river from the headwaters to the confluence shows that the velocity of the river increased by 3.2 times in the spring season and 3.4 times in summer, which obviously had an impact on turbulence. Nevertheless, the impact of turbulence can also be observed between adjacent points; for example, investigation on variations in the concentrations of phosphates in sample points 3 and 4

demonstrates that a change in the concentration of phosphates has decreased from 7 to 1.5 times during the fall while velocity between these points has increased 2.3 times.

Thus, a summary of the obtained results provides that the physical-geographical characteristics of the watershed [16–19] and the turbulence of the river have an impact on variations in the concentrations of nutrients. Therefore, for developing an operational monitoring network of sample points, not only standard rivers should be considered but also the turbulence of the river should be carefully analysed and representative places indicating variations in nutrients should be selected. For example, if the monitored sample point is chosen when Re criterion is within the range of 30 000–150 000, then, a possible decrease in nutrients makes about 34%, whereas, if Re criterion is within the range of 180 000–220 000, then, it decreases to 64%. Having selected the above introduced sample points and permanently monitoring variations in the levels of nutrients in water, more accurate identification of water quality and the efficiency of measures for improving it could be made.

4. CONCLUSIONS

With reference to the turbulence, overfall and gradient of the river, the analysis of variations in concentration of nutrients discloses that changes in the concentration of nutrients before and after the fall differ on average by 1–6 times.

The calculation of the coefficient of self-purification provides that the analysed river flowing downstream fully self-purifies and removes all nitrates and 61% of phosphates. The content of dissolved oxygen at the confluence of the river in spring was only by 5.5% larger than that at the headwaters, whereas in the summer season, the difference in the content of dissolved oxygen in river water between the headwaters and confluence increased and made 25%.

On the basis of the obtained results, it was concluded that the flow of the Širvinta River was turbulent. When Re criterion is within the range of 30 000–150 000, the concentrations of nutrients increase by 34%, whereas when Re is within the range of 180 000–220 000, the concentrations reach 64%.

In the light of the findings and obtained research results, a hydraulic gradient and river turbulence make an impact on variations in the concentrations of nutrients. The concentrations of nutrients after the hydraulic gradient are lower due to ongoing self-cleaning processes taking place in the river. Therefore, for selecting monitoring sites, the most representative sections of the hydraulic gradient closest to reference conditions are recommended.

ACKNOWLEDGEMENTS

The authors are grateful to Ieva Apanavičiūtė for field and laboratory assistance.

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