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Original Research

Assessing the Impact of Wastewater Effluent Diversion on Water Quality

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Abstract

The aim of this study was to determine the change of water quality in the Trzemna River after modernisation of the wastewater treatment plant (WWTP) in Gołuchów and wastewater effluent diversion (WED) to the Prosna River in 2008. Data was acquired from the State Environmental Monitoring database for the period before and after changing the location of discharge from the treatment plant. The before-after (BA) and before-after-control-impact (BACI) analyses were used to determine the effectiveness of applied solutions. The BA study covered 12 physicochemical parameters and showed improvement of water quality in terms of phosphorous compounds, EC, ammonium nitrogen, TKN, TN, and BOD_5. Lack of statistically significant differences for nitrates, pH, and TOC were noted. The BACI analysis was only applicable for six physicochemical parameters, and statistically significant differences were shown for TN, TKN, ammonium nitrogen, and TP. There were no differences in the case of nitrates and DO. After wastewater effluent diversion, a high concentration of nitrates in Trzemna water was still observed, with a statistically confirmed increasing trend. This is an effect of the negative impact of agricultural diffuse pollution. Modernisation of a WWTP and wastewater effluent diversion positively affected the quality of Trzemna water. The BA and BACI analyses in relation to statistical tests applied in hydrology can be successfully used to evaluate the impact of changes in the environment on water quality. In the case of BA design it was possible to analyse 12 parameters, whereas in BACI analysis it was only half of them. However, this method is recognised as more reliable and eliminates the impact of natural temporary variations.

Keywords: eutrophication, wastewater effluents, wastewater treatment plant, surface water quality, impact assessment

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Introduction

Municipal wastewater effluents contain many toxic substances that degrade aquatic environments, first and foremost nutrients as well as pharmaceuticals, hormones, pathogens, and chlorides. Untreated or insufficiently treated wastewater has been the source of surface water pollution for many years on all inhabited continents, and nutrients included in them affect intensification of rivers, reservoirs, and the sea's eutrophication process [1-7]. In Europe, the Water Framework Directive (WFD) and the necessity to achieve good quality water by the EU states has necessitated modernisation of many wastewater treatment plants (WWTPs) with insufficient technology and construction of modern efficient WWTPs. These actions will significantly contribute to the recovery of water bodies. However, even effluents from modern WWTPs may cause a hazard if the receiving watercourse is small in relation to the amount of effluents [3, 5, 8-9].

The impact of human operations on water resource quality and quantity engages scientists for over 100 years, but quantitative evaluation is frequently inconvenient [5, 10-12].

Comparative methods are used to evaluate the positive or negative impacts by humans on the environment. Green [13] has presented a few types of such methods. Since the 1970s they were used mostly to evaluate the degree of environmental degradation by humans. Today, they are also used to analyse positive changes in the environment related to limitation of emissions, restoration of water bodies, or integrated catchment management [9, 14-16]. Scientific literature presents many methods aimed at the limitation of pollutant discharge into freshwater and marine receiving environments; however, only a few studies have related to evaluating the effectiveness of analysed methods [14], which is why studies on developing methods concerning river restoration are necessary [16].

The prevention of eutrophication processes should be based first and foremost on understanding nutrient migration and transfer in a catchment and then on sustainable water management to local, regional, and cross-border scales [4].

Problems related to determining the impact of operations undertaken in order to improve water quality are frequent in small agricultural catchments, where water quality monitoring is not regular and performed at a small number of locations. Most frequently these are ungauged catchments and under such circumstances one can only estimate, not calculate, the pollution load [17]. The approaches to water quality data must be different than in environmental studies based on the monitoring of animal or plant populations. This data often does not meet the parametric test assumptions of normal distribution and variance homogeneity. Often the studies are interrupted and there are values below the limit of detection [12].

The purpose of our study was to evaluate Trzemna River water quality after wastewater effluent diversion in terms of parameters that can be obtained from State Environmental Monitoring.

Among the available statistical methods, the ones that allow for developing data based on the existing monitoring systems of surface water were proposed, considering the gaps in measurement strings, lack of normal distribution and variance homogeneity as well as utilisation in analyses of impact assessment such as before-after and before-after-control-impact research design.

Materials and Methods

Study Site

The Trzemna River is one of the most polluted lowland watercourses in Poland [17-18]. It is a left tributary of the Prosna River; the total area of its catchment is 119.2 km^2 and the average inclination is 5.48‰. The headwaters of the river are located near the Czachory village at the altitude of 126.50 m a.s.l. and its mouth is at the ordinate 91.10 m a.s.l., river length is ca. 21 km, which gives a longitudinal inclination of the watercourse of 1.73‰. At 5.6 km of the river, there is an earth dam of the Gołuchów Reservoir. Mean annual flow in the Gołuchów Reservoir cross-section is 0.37 m^3·s^{-1} and the reservoir area at normal water level is 51.5 ha. About 12,500 people live within the area of the catchment. The largest settlement is Gołuchów, populated by 2,300 people. Ciemna watercourse, which is the tributary of the Ołobok River, flows southeast in the same area as the Trzemna. Both watercourses clearly bifurcate in the watershed [17-20]. The analysed area can be characterised by low annual precipitation (ca. 517 mm) compared to other regions of Poland and very intensive agricultural production. In 2005-14 annual consumption of nitrogenous fertilisers increased here from 65 to 90 kg·ha^{-1}, and in 2011-13 it amounted to 94 kg·ha^{-1}. Arable land represents 80% and forests 8.6% of the total catchment area. The catchment consists of glacial sands and tills covering the area of Wysoczyzna Kaliska,

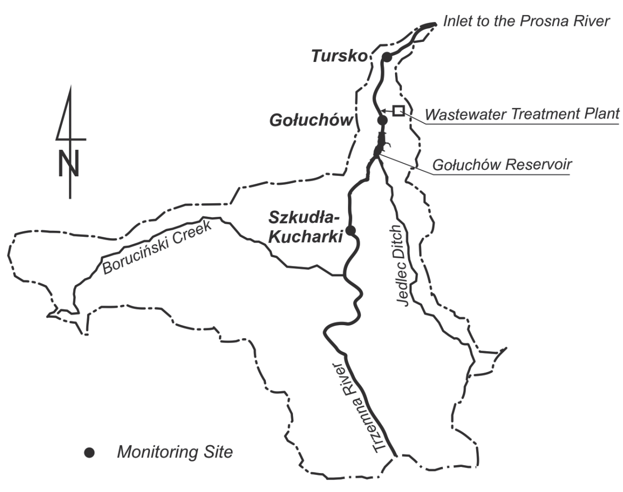

Fig. 1. The Trzemna River catchment

and there are no significant water and wind erosion phenomena [18-20].

Although a WWTP was built in Gołuchów in 1992, the sewage system was not developed back then and wastewater was not regularly delivered to the plant. The WWTP was found to be one of the main sources of river pollution. For many years it worked ineffectively and the actual quantity of treated wastewater was only 25% of the 1,131 $m^3 \cdot d^{-1}$ permissible pursuant to binding law [21]. A thorough modernisation of the WWTP was initiated in 2007. The modern treatment plant can collect 800 m^3 of wastewater per day. The sewage system covers an area populated by 3,000 people and is still being developed. Since 2008, treated wastewater is discharged to the Prosna River, bypassing the Trzemna River [18].

The Trzemna is monitored for water quality at three monitoring sites (MS): MS Szkudła-Kucharki, MS Gołuchów, and MS Tursko (Fig. 1). MS Szkudła-Kucharki closes a fragment of the catchment of area 82 km^2, MS Gołuchów 114 km^2 (area larger by 32 km^2), and MS Tursko 118 km^2 (area gain of 4 km^2). MS Gołuchów was liquidated in 2007 due to changes in surface water monitoring principles in Poland. WWTP discharge is located between MS Gołuchów and Tursko (Fig. 1). Studies performed before treatment plant modernisation by Dąbrowska [18] in 2004-06 showed that contamination of N and P in the Trzemna River in MS Tursko significantly varied from concentration in other sites. In the case of MS Szkudła-Kucharki and MS Gołuchów, nitrates were the predominating form of nitrogen, and in Tursko ammonium and organic nitrogen. Average annual concentration of phosphates increased in MS Tursko by up to eight times compared to values measured in Gołuchów.

MS Gołuchów is located below the town, between it and MS Tursko, a gain of the catchment was only 4 km^2, and P concentration increased three times (and N more than two times) – disproportionate to the gain of the catchment area (Table 1). The sole meaningful source of pollution was the discharge from a treatment plant. Forest and parks dominate within the analysed section of the catchment. It is not extensively agriculturally used and sources of pollution negligibly affect the water quality of this small area. The influence of the Gołuchów Reservoir on water quality is not significant. No major nutrient accumulation or release was observed there [18]. The slight, but first of all, constant influence of the reservoir on river water quality enabled us to conduct analyses with use of the selected BA and BACI methods.

Water Quality Data

Data from the State Environmental Monitoring database was used in the study. All available data series for the analysed area from 2005-14 were obtained from the Voivodeship Inspectorate for Environmental Protection in Poznań. Studies were performed in 2004, 2005, 2006, 2008, 2009, 2010, and 2013; N = 74 determinations were available for each examined index. Data was divided in the middle to the "pre-WED" (since January 2004 to June 2008) and "post-WED" periods (July 2008 to December 2013). According to general monitoring principles concerning measurements below the limit of determination, the value corresponding to half of the limit of detection was used in statistical analyses. Within 2005-14 it was only possible to compare physicochemical parameters, and biological hydromorphological quality elements were not measured within the whole study period.

Methods

Before-After and Before-After-Control-Impact Research Designs

The easiest way to detect changes in an aquatic environment caused by the sudden change of a factor or factors affecting the surroundings (e.g., by point sources of pollution) is the before-after design (Fig. 2). The situation where in small catchments there is data from only one monitoring point before and after an event that affects the environment is very frequent. The impact of an event on the environment is determined by comparing observations before and after using a two-sample test [22]. The weakness of this method is that the difference in the analysis is attributed to the examined activity. Observed changes can also be caused by natural temporal variations [23-24]. The study can be developed by trend analysis before and after the event [14].

To improve sensitivity of this method and exclude natural temporal variations, samples also can be taken at the control sites. This extended method is called before-after-control-impact (BACI) design (Fig. 2). In the case of BACI, data is collected in a control and impact zone before and after impact. The simplest example of a BACI experiment is water quality monitoring on spots upstream and downstream of the facility discharging pollutants

Table 1. Concentrations of nitrogen and phosphorous in the Trzemna River [18].

Year	MS Szkudła-Kucharki		MS Gołuchów		wastewater effluent impact	MS Tursko	
	Total P mg $P \cdot dm^{-3}$	Total N mg $N \cdot dm^{-3}$	Total P mg $P \cdot dm^{-3}$	Total N mg $N \cdot dm^{-3}$		Total P mg $P \cdot dm^{-3}$	Total N mg $N \cdot dm^{-3}$
2004	0.39	7.98	0.66	6.69		2.01	15.56
2005	0.42	9.10	0.61	10.88		2.37	18.95
2006	0.38	11.31	0.33	9.01		1.51	13.09

to a river, before and after construction of the given factory or treatment plant. Most often, the analysis

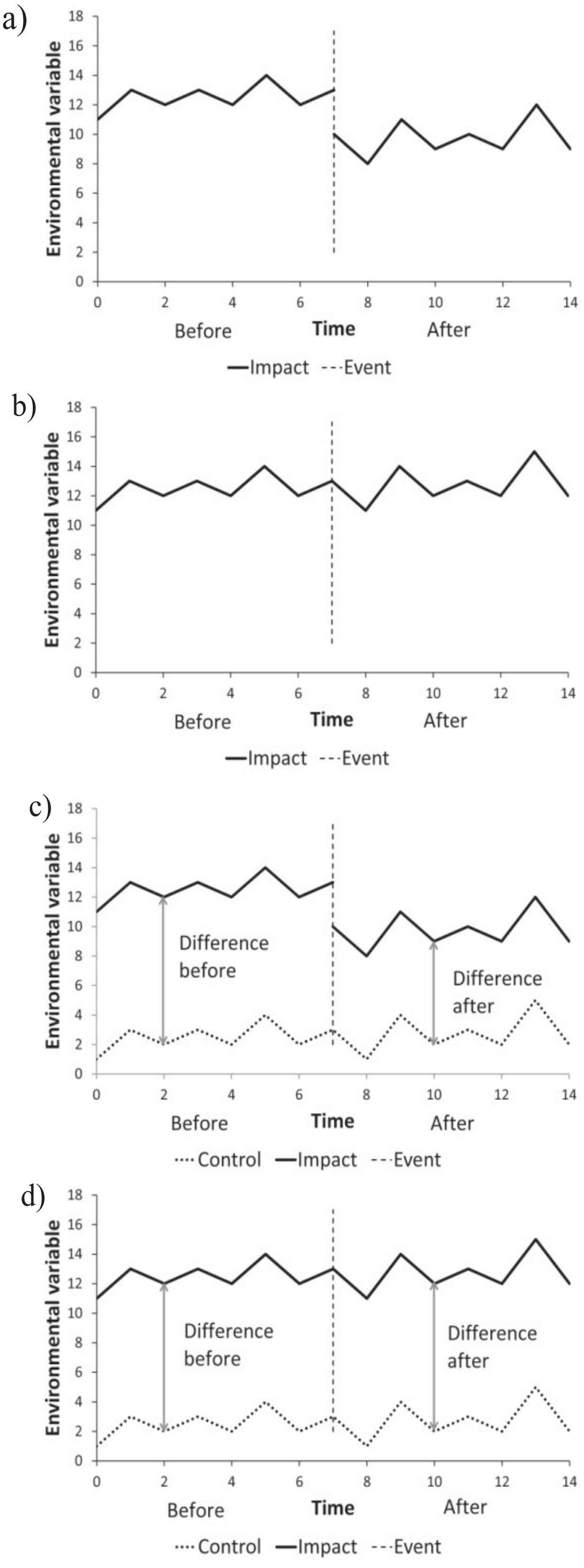

Fig. 2. Simplified data profiles for: a) BA analysis assuming impact, b) BA analysis assuming no impact, c) BACI analysis assuming impact, d) BACI analysis assuming no impact [23-24].

consists in the calculation of differences between data pairs (BACI paired) from the control and the impact sites. Then one compares the *before* differences against the *after* differences [23, 25]. To develop data in BACI analysis of variance, ANOVA or nonparametric tests are used depending on data type [14, 22-23]. Based on this method, multiple site experiments are developed along with other more complicated solutions where multivariate analysis of ecological data is used. These are known as "beyond BACI" designs [22-23, 26].

Our paper concerns the BA and BACI concept to examine the *before* (pre-WED) and *after* (post-WED) conditions of the Trzemna River (MS Tursko), as well as to compare a *control* (MS Szkudła-Kucharki) with the *impact* site (MS Tursko).

Statistical Analysis

Analyses were conducted with the use of Statistica v. 12 and XLSTAT 2015 software. Levene's test showed that data does not have homogeneous variances, thus to compare water quality differences before and after the WED period we used a nonparametric U Mann-Whitney test. The measurement of central tendency for this test is median in the case of data related to water quality outliers affecting the mean.

To identify trends we used the Mann-Kendall test – a commonly used nonparametric hydrological test. It can be applied when the gap in data string does not exceed one-third of the total record, which allows for the use of monotonic trend analysis [12, 27].

The verification of the hypothesis is based on Mann-Kendall statistic *S* [28-29]:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k)$$

…where x is the observed value in the time sequential order, n is the number of observations, and $sgn(x_j - x_k)$ is an indicator function:

$$\begin{cases} sgn(x_j - x_k) = 1 \; if \; x_j - x_k > 0 \\ sgn(x_j - x_k) = 0 \; if \; x_j - x_k = 0 \\ sgn(x_j - x_k) = -1 \; if \; x_j - x_k < 0 \end{cases}$$

The non-parametric equivalent of the correlation coefficient used in the Mann-Kendall test is Kendall's tau. The positive value of Kendall's tau demonstrates an increase of one variable with the increase of the other. The negative value of Kendall's tau demonstrates a decrease with the increase of the other. If one of the variables is time, the positive value of Kendall's tau means a tendency to increase in time while a negative value indicates a decrease in time. The p-value is calculated to determine the statistical significance of Kendall's tau [28-29].

Table 2. Results of BA analysis for MS Tursko.

Parameter	Pre-WED period	Post-WED period	p-value
	Median Mean±SD		
pH	7.7 -	7.5 -	0.385
Dissolved Oxygen DO (mg $O_2 \cdot dm^{-3}$)	6.6 6.9±3.2	8.1 8.5±3.1	0.033*
BOD_5 (mg $O_2 \cdot dm^{-3}$)	7.0 8.3±4.4	4.0 4.2±1.9	0.000*
Total Nitrogen TN (mg $N \cdot dm^{-3}$)	14.2 15.8±3.2	7.5 11.7±9.9	0.028*
Nitrate (mg $NO_3^- \cdot dm^{-3}$)	18.2 26.7±25.4	24.1 43.8±45.3	0.178
Nitrite (mg $NO_2^- \cdot dm^{-3}$)	0.5 1.0±1.3	0.2 0.2±0.2	0.000*
Ammonium Nitrogen (mg $N \cdot dm^{-3}$)	4.1 6.6±8.4	0.1 0.1±0.1	0.000*
Total Kjeldahl Nitrogen TKN (mg $N \cdot dm^{-3}$)	5.6 9.5±9.6	1.5 1.5±0.6	0.000*
Total Phosphorus TP (mg $P \cdot dm^{-3}$)	1.2 1.8±1.6	0.2 0.3±0.2	0.000*
Phosphate (mg $PO_4^{3-} \cdot dm^{-3}$)	2.8 4.4±4.1	0.4 0.5±0.5	0.000*
Total Organic Carbon TOC (mg $C \cdot dm^{-3}$)	10.7 11.8±4.3	10.1 10.1±2.1	0.134
Electrical Conductivity at 20ºC EC ($\mu S \cdot cm^{-1}$)	862.5 891.8±170.6	730.5 754.7±134.3	0.000*

*statistically significant difference

Results and Discussion

Before-After Design

Concentration of nutrients determined in the river in the period pre-WED is very high compared to other watercourses in this part of Europe [4-5, 8, 30-34]. For example, mean concentrations in Serafa watercourse, also affected by wastewater effluents, were as follows: TN 10.9 mg $N \cdot dm^{-3}$, TKN 5.6 mg $N \cdot dm^{-3}$, nitrate 22.0 mg $NO_3^- \cdot dm^{-3}$, ammonium nitrogen 3.5 mg $N \cdot dm^{-3}$, TP 1.1 mg $P \cdot dm^{-3}$, phosphate 1.4 mg $PO_4^{3-} \cdot dm^{-3}$, BOD_5 11.7 mg $O_2 \cdot dm^{-3}$, and DO 5.8 mg $O_2 \cdot dm^{-3}$ [8]; in the small polluted lowland Dębina River, DO was 7.7 mg $O_2 \cdot dm^{-3}$, BOD_5 2.5 mg $O_2 \cdot dm^{-3}$, nitrate 31.0 mg $NO_3^- \cdot dm^{-3}$, and nitrite 0.3 mg $NO_2^- \cdot dm^{-3}$ [34]. A similar impact of insufficiently treated wastewater on water quality in receiving water was proven by many authors [7-9, 35-36]. Most studies present the statistically significant impact of introducing insufficiently treated wastewater on nitrate concentration in receiving waters; in case of the Trzemna there is no statistical significance for this parameter.

In the post-WED period, concentrations of most nutrient forms, EC, and BOD_5 are comparable with those analysed in the literature. The exception is high nitrate concentration. Furthermore, the concentration of nitrates and TN in the Trzemna after wastewater effluent diversion is characterised by a rising trend (Table 3) caused by the dynamic increase in agricultural nitrate pollution in the catchment. The aforementioned significant increase in the annual consumption of nitrogenous fertilizers seems to play an important role in the occurring process. Due to this, in 2012 the analysed area was classified as a nitrate-vulnerable zone by the director of the Regional Water Management Board in Poznań [37].

BA analysis in the case of 12 physicochemical parameters of the Trzemna water using the nonparametric U Mann-Whitney test showed that water quality with respect to most of the examined parameters has improved within the post-WED period (Table 2). Statistically, no significant differences were detected for nitrate, pH, and TOC.

Analysis of trends of the remaining parameters using the Mann-Kendall test showed that within the pre-WED period, pH, concentration of ammonium nitrogen, and TKN had a decreasing trend. Within the post-WED period in relation to pH and concentrations of TN and nitrate, a rising trend was observed, and in case of concentrations of TP and phosphate a decreasing trend (Table 3).

Based on the average concentrations of N and P in the Trzemna River measured in MS Tursko (Table 2) in the pre-WED (15.8 mg $N \cdot dm^{-3}$, 1.8 mg $P \cdot dm^{-3}$) and post-WED periods (11.7 mg $N \cdot dm^{-3}$, 0.3 mg $P \cdot dm^{-3}$), we found N:P = 9:1 in the pre-WED period, and 39:1 in the post-WED period. The N:P ratio decides which of the nutrients stimulate algae development. When the N:P ratio < 10 the development of algae is limited by nitrogen, when it is 10-20 a cumulative limitation by both these elements is perceived, and when N:P > 20 the amount of algae is limited by phosphorus [38-39]. Wastewater effluent diversion not only caused improvement of water quality, but also the element limiting algae development in the river from nitrogen to phosphorus.

Before-After-Control-Impact Design

The BACI could be performed for six physicochemical parameters (Table 4), because only in this case were measurements taken in pairs within the same period *before* (pre-WED) and *after* for the *control* (MS Szkudła-Kucharki) and the *impact* site (MS Tursko). The nonparametric U Mann-Whitney test was used to analyse statistical significance of differences among the tested parameters in the control and impact sites, before and after WED. It was shown that there are no statistically significant differences for DO and nitrate concentrations, and differences in the remaining parameters were statistically

Table 3. Results of trend analysis in water quality in MS Tursko.

Parameter	Pre-WED period				Post-WED period			
	Mann-Kendall statistic	Kendall's tau	p-value	Trend nature	Mann-Kendall statistic	Kendall's tau	p-value	Trend nature
pH	-203	-0.272	0.018*	decreasing	205	0.378	0.002*	increasing
Dissolved Oxygen DO (mg $O_2 \cdot dm^{-3}$)	-52	-0.067	0.552	no trend	117	0.209	0.086	no trend
BOD_5 (mg $O_2 \cdot dm^{-3}$)	65	0.084	0.465	no trend	97	0.173	0.155	no trend
Total Nitrogen TN (mg $N \cdot dm^{-3}$)	-74	-0.095	0.398	no trend	177	0.316	0.008*	increasing
Nitrate (mg $NO_3^- \cdot dm^{-3}$)	92	0.118	0.291	no trend	191	0.341	0.005*	increasing
Nitrite (mg $NO_2^- \cdot dm^{-3}$)	126	0.162	0.146	no trend	70	0.125	0.306	no trend
Ammonium Nitrogen (mg $N \cdot dm^{-3}$)	-189	-0.242	0.028*	decreasing	74	0.132	0.279	no trend
Total Kjeldahl Nitrogen TKN (mg $N \cdot dm^{-3}$)	-179	-0.230	0.038*	decreasing	5	0.009	0.953	no trend
Total Phosphorus TP (mg $P \cdot dm^{-3}$)	-97	-0.124	0.263	no trend	-172	-0.307	0.011*	decreasing
Phosphate (mg $PO_4^{3-} \cdot dm^{-3}$)	-114	-0.146	0.189	no trend	-198	-0.353	0.003*	decreasing
Total Organic Carbon TOC (mg $C \cdot dm^{-3}$)	111	0.143	0.200	no trend	-9	-0.016	0.906	no trend
Electrical Conductivity at 20ºC EC ($\mu S \cdot cm^{-1}$)	-116	-0.149	0.180	no trend	26	0.046	0.711	no trend

*statistically significant difference

Table 4. Results of BACI analysis: control site MS Szkudła-Kucharki vs. impact site MS Tursko.

Parameter	Szkudła-Kucharki Control Pre-WED period	Szkudła-Kucharki Control Post-WED period	Tursko Impact Pre-WED period	Tursko Impact Post-WED period	Differences comparison (p-value)
	Median Mean±SD		Median Mean±SD		
Dissolved Oxygen DO (mg $O_2 \cdot dm^{-3}$)	9.0 8.3±3.7	8.9 8.8±2.4	6.6 6.9±3.2	8.1 8.5±3.1	0.235
Total Nitrogen TN (mg $N \cdot dm^{-3}$)	8.1 10.5±7.6	12.1 14.4±8.8	14.2 15.8±3.2	7.5 11.7±9.9	0.000*
Nitrate (mg $NO_3^- \cdot dm^{-3}$)	26.6 39.7±35.6	43.9 57.7±40.3	18.2 26.7±25.4	24.1 43.8±45.3	0.065
Ammonium Nitrogen (mg $N \cdot dm^{-3}$)	0.2 0.3±0.4	0.1 0.2±0.2	4.1 6.6±8.4	0.1 0.1±0.1	0.000*
Total Kjeldahl Nitrogen TKN (mg $N \cdot dm^{-3}$)	1.7 1.8±0.7	1.3 1.3±0.6	5.6 9.5±9.6	1.5 1.5±0.6	0.000*
Total Phosphorus TP (mg $P \cdot dm^{-3}$)	0.3 0.4±0.2	0.3 0.3±0.2	1.2 1.8±1.6	0.2 0.3±0.2	0.000*

*statistically significant difference

significant. The WWTP in Gołuchów was not a significant source of nitrate pollution. Main nitrate pollution sources are situated in the area of the catchment controlled by MS Szkudła-Kucharki, where cultivated fields are located. Below that point there are mainly non-agricultural areas [17-18]. Thus, the concentration of nitrates in the Trzemna decreases along its course, and in MS Szkudła-Kucharki it is higher than that in MS Tursko in both the pre-WED and post-WED periods (Table 4). Similar relations were also found by Dąbrowska [18] in her earlier studies conducted before the modernisation of the WWTP.

Differences between BA and BACI analysis were found for DO, and in BACI analysis no impact of WED was detected on the change of this parameter. BACI design eliminates the impact of climatic and other factors not related to discharge of wastewater, thus the results of this method are found to be more reliable. The BACI analysis usually provides less probability of detecting changes compared to BA. In their works, Korman and Higgins [40] noted a 10-15% lower probability of detecting a population change in the case of the BACI method unless the degree of covariation in survival rates between the control and treatment stocks was very strong. In the case of the Trzemna water quality tests, the difference between the highest p-values for BACI and BA methods were detected for DO; it is also worth noting that in the BA method p-value for DO was the closest to 0.05 of all parameters whose differences were statistically significant.

Summary and Conclusions

BA analysis showed that as a result of WWTP modernisation in Gołuchów and wastewater effluent diversion, Trzemna River water quality has improved with respect to phosphorus compounds, EC, ammonium nitrogen, TKN, TN, and BOD_5. The change did not affect concentrations of nitrate, TOC, and pH. Due to the necessity to compare data pairs measured within the same time at the control and the impact sites, BACI analysis could be performed for six out of 12 parameters. It has also demonstrated a significant impact of WED on the concentration of TN, TKN, ammonium nitrogen, and TP in the Trzemna River. Differences between these two methods were noticeable for DO. In the BA analysis, changes of concentration of DO were statistically significant while in BACI they were not. The BA and BACI analyses can be successfully used to detect positive changes in river water quality (i.e., for the control of restoration measures) and to support integrated catchment management. BACI requires more data, which in some cases of its gathering from the State Environmental Monitoring nets will reduce the number of parameters for which comparison can be performed. Due to the nature of data, nonparametric tests should be performed.

The performed studies show that despite significant improvement of water quality in the river resulting from improved wastewater management, high concentrations of nitrates related to agricultural pollution are a current problem in the case of the Trzemna River catchment.

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