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The supply of total nitrogen and total phosphorus from small urban catchments into the Gulf of Gdańsk

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Abstract The main goal of work was to quantify the nitrogen and phosphorus loads transported by small streams to the Gulf of Gdańsk. The research aims to determine wastewater release volumes over time, instead of focusing only on spatial distributions. Another aim is to identify the main determinants potentially affecting water quality in rivers flowing across the city of Sopot. The study area consists of six small river catchments located in the city of Sopot, each with an open flow channel, which lies along the bay. Studies were conducted 12 times per year in the period from March 2014 to February 2015. Laboratory analyses were performed to determine the concentration of both total nitrogen and total phosphorus. In order to calculate pollutant loads, discharge was also measured in each of studied rivers. Conducted research has shown that all analyzed streams were characterized by low total nitrogen and total phosphorus concentrations. The mean annual values ranged from 0.60 to 1.28 mg·dm^{-3} in case of total nitrogen and from 0.066 to 0.100 mg·dm^{-3} in case of total phosphorus. In 2012, the total nitrogen load from Poland to the Baltic Sea was 210.768.000 kg N while the total phosphorus load was 15.269.000 kg P, which means that streams analyzed in this paper supplied barely 0.002 % of the biogenic load supplied to the Baltic Sea by Poland as a whole.

Keywords *• city of Sopot • the Gulf of Gdańsk • total nitrogen • total phosphorus • loads, water pollution*

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INTRODUCTION

The Baltic Sea is the second largest brackish sea in the world and its hydrographic and environmental conditions are strongly dependent on the frequency of saline water inflows from the North Sea (Binczewska *et al.* 2018). The waters of the Gulf of Gdańsk are one of the most eutrophic coastal areas of the Baltic Sea. This is confirmed by studies by Tomczak *et al.* (2016) who observed changes in the fauna and flora, resulting from anthropogenic pressures, e.g. nutrient loadings and possible interactions with climatic disturbance. Research on marine sediments also indicates a strong eutrophication of the Baltic Sea caused by man (Warnock *et al.* 2018). The influence of bottom sediments on the quality of the Baltic Sea was also described by Vallius (2016) or Ryabchuk *et al.* (2017). Climate disturbances are extremely important in the aspect of emerging extreme phenomena. This applies in particular to extreme rainfall, which can cause in urban areas an increased surface runoff of contaminated waters (often linked to the phenomenon of floods). This can be confirmed by research in the Potok Oliwski catchment, which carries away significant amounts of water from the city of Gdańsk. According to Matej-Łukowicz *et al.* (2018), the Potok Oliwski supplies to the Gulf of Gdańsk 4 tons of total nitrogen and 2 tons of total phosphorus during the year. The largest amounts of nutrient loads are delivered in summer and autumn, i.e. during the period of the most intense precipitation. The amount of nutrient loads according to Bowes *et al.* (2015) will grow when an agricultural area is run in the catchment area. Also, do not forget about global climate change (Čerkasova *et al.* 2016). According to Wu and Malmström (2015), nitrogen is the most sensitive to climate change, with a considerable increase and seasonal redistribution of loadings. For phosphorus, loadings by different pathways are less sensitive to climate change.

In 1993, nutrient loads to the Baltic Sea were 1,022,754 tons of nitrogen and 38,888 tons of phosphorus as estimated by Turner *et al.* (1999). The largest basin of the Baltic Sea, the Baltic Proper, received 85% of the total load of both nitrogen and phosphorous. According to Turner *et al.* (1999), direct discharges, mainly from sewage treatment plants in the coastal zone, corresponded to about 10% of the total load. To quote Turner *et al*. (1999), "Poland is the largest discharging country with respect to total nitrogen loading (28.5%), followed by Sweden (10.4%) and Germany (10.2%). Poland is also the country providing the largest load of phosphorous to the Baltic Sea, approximately 50% of total load". An analysis provided by Andrulewicz and Witek (2002) shows that the average input of total nitrogen from the Vistula River was 118,000 tons per year (15% of the total) and the input of total phosphorus was 7,000 tons per year on average, which is 19% of the total riverine discharge into the Baltic Sea. According to Svendsen *et al*. (HELCOM 2017), the inputs of nitrogen and phosphorous to the Baltic Sea sub-basins have decreased significantly in recent years, comparing the years 2012–2014 with the reference period 1997–2003. The total nitrogen input was reduced by 14% while the total phosphorus input was reduced by 11% in the Baltic Proper. The total nitrogen and total phosphorus inputs fell during the period for the entire Baltic Sea, with the share of direct point-sources experiencing greatest changes (Fig. 1). Nitrogen was reduced from 1,056,922 tons in 1995 to 825,825 tons in 2014, while phosphorus was reduced from 41,163 tons in 1995 to 30,939 tons in 2014 (Table 1) (HELCOM 2018).

According to the HELCOM report (2018), in 2014, 169,941 tons of total nitrogen and 12,776 tons of total phosphorus were supplied from Poland to the Baltic Sea, but 140,371 tons (or 82.6%) of total nitrogen was riverine nitrogen and 12,699 tons (99.4%) of the total phosphorus load was riverine phosphorus (Table 1).

The obtained results confirm the observations of

Table 1 Total nitrogen and total phosphorus sources and loads [tons] from Poland to the Baltic Sea according to HELCOM (2018)

Year	1995	2000	2006	2012	2014
Total nitrogen	262,159	201,049	207,057	107,647	169,941
Total phosphorus	14,846	11,490	11,651	6,863	12,776

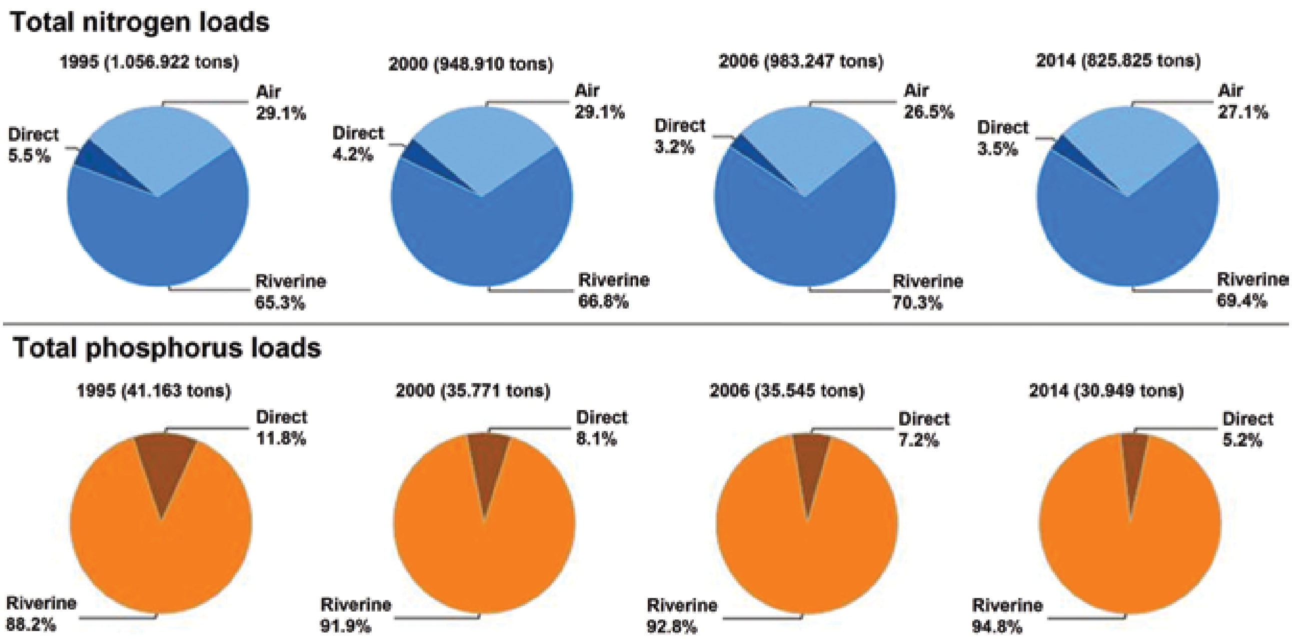

Fig. 1 Sources and input of nutrients to the Baltic Sea. Sonesten *et al.* (HELCOM 2018–changed)

Beusen *et al.* (2016) that watercourses have been the main source of nutrients to the sea since the 20th century, which should be considered on a global threat scale. The management of the Baltic Sea area should be based on the removal of either N or P from sewage, and differences between sub-basins and between polluted coastal and offshore areas should be taken into consideration (Granéli *et al.* 1990). According to Maximov *et al.* (2015), large amounts of nitrogen and phosphorus are deposited in sediments. Phosphorus retention in these sediments for a long time and the amount of nitrogen streams from sediments increase. There are several studies showing the internal loading of phosphorus in the Baltic Sea, for example Puttonen *et al.* (2014). According to these authors, the uppermost 2 cm of sediments were calculated to contain 126,000 tonnes of phosphorus in the northern Baltic Sea covering 19,200 km^2 of the seafloor. Subtracting the assumed average background content (i.e. that assumed to be buried) from this total phosphorus content gave an estimation of 31,000−37,000 tons of potentially mobile phosphorus at the sediment surface. Understanding the factors responsible for regional and long-term variations of nutrients is a basic condition for understanding the large-scale eutrophication of the Baltic Sea (Wulff *et al.* 1990). The lagoon and estuaries are transition zones in which we observe influences of the aquatic and terrestrial, as well as freshwater and marine environment (Perez-Ruzafa *et al.* 2011). In those areas, the effects of human activities are the most marked (Kornijów 2018). The main factor contributing to the increased nutrients content and other substances in the coastal waters of the southern Baltic is the impact of rivers, which carry loads of pollutants. Significant sources of pollutants entering the marine bodies are small river catchments. The quality of water in such catchments is often poor in terms of water chemistry and various physical attributes. Sopot rivers are an example of small rivers, their natural character slowly disappears. The channels are regulated, often covered, some of their sections are rectilinear with artificially shaped edges and rainwater drainage outlets. They are rainwater receivers, but pollution reaching them can affect their qualitative and quantitative state for a diversified period of time.

The objective of the study was to specify the nitrogen and phosphorus loads transported by small streams to the Gulf of Gdańsk. Urbanization of the catchment causes changes in hydrological conditions and changes significantly groundwater and surface water outflow to the watercourse. This paper presents the volume of selected pollutant indices carried out by 6 watercourses located in the coastal city of Sopot, each with an open flow channel. The research also aims at analyzing seasonal changes in the inflow of substances to the receiver and the spatial variation of the exports of substances carried out in association with hydrological factors. The aim is to determine wastewater release volumes during the research period, focusing on changes over time, instead of focusing only on spatial distributions. Moreover, an additional goal of the presented study is to identify the main determinants potentially affecting water quality in rivers flowing across the city of Sopot.

A large-scale eutrophication of the Baltic Sea is an effect of the regional and long-term variations of nutrients. The drainage area of the Baltic Sea is about four times as large as the surface area of 373,000 km^2 (Wulff *et al.* 1990). The Polish Baltic coast receives freshwater from two large rivers – the Vistula and the Odra – as well as several small rivers reaching the sea along the central part of the coast and the Gulf of Gdańsk. Hence, the entire Polish coastline remains strongly affected by human impact, and the variability of the nutrient concentration in the region is high. Sopot, as one of Poland's best-known recreational cities found on the Gulf of Gdańsk, is crisscrossed by 12 watercourses collecting rainwater from the moraine hills surrounding the city. After construction of the weirs and locks blocking the inflow of the Vistula River to the lagoon in the early 20th century, the inflow decreased over the last 100 years. According to Glasby and Szefer (1998), the reduction of the inflow of the Vistula River to the lagoon, in the period from the 1970s to the 1990s saved the ecosystem from total degradation when the inflowing rivers were extremely polluted and resembled sewers (Glasby, Szefer 1998).

Sopot is a city where the authorities take good care of the quality of water discharged from the city area to the Gulf of Gdańsk and thus the quality of the water in the bathing area. It is the only city in which the drainage system operates so far down the bay. The local government began a reconstruction program in the last decade designed to help eliminate all potential sources of water pollution in the city area, which consists of the reconstruction of the local water and sewer system as well as the construction of collection vessels funnelling polluted water far into the Gulf of Gdańsk. Urban catchments are characterized by the fact that through the construction of the catchment rivers and channels are covered in a large part. In addition, there is not as much pressure on the part of agriculture as we can observe in other catchments such as the Piaśnica or Płutnica draining water directly to the Baltic Sea or the Gulf of Gdansk.

MATERIALS AND METHODS

Analyses of the variability of pollutant transport in the streams of the city of Sopot were made on the basis of systematic measurement of discharge and nutrients concentrations. Laboratory analyses were performed to determine the concentration of both total nitrogen and total phosphorus. In order to calculate pollutant loads, discharge was also measured in each of studied rivers. The study period covered the period from March 2014 to February 2015. The choice of water quality indicators was related to the need to take into account both organic and biogenic substances that contribute to the progressive eutrophication of the receiver. The study area consisted of the catchment area of streams flowing via uncovered channels across the city of Sopot: Swelina, Kamienny Stream, Grodowy Stream, Babidolski Stream, Haffnera Stream, and also included the catchment of drainage ditches in Northern Park (Fig. 2). Sampling points were located within a distance of not more than 1.5 km from estuaries to the sea. In this work, out of the inventoried 11 watercourses, 6 were selected and studied because of the full spectrum of data and specific morphological characteristics (these watercourses flow from the edge zone of the Gdańsk Upland).

Discharge measurement and water sampling were performed once a month. Water samples were taken from the surface. A chemical analysis was performed at the Hydrochemical Laboratory of the Department of Hydrology at the University of Gdańsk within 24 hours after sampling. The resulting data consisted of the concentrations of total nitrogen and total phosphorus. Stream discharge was measured using an electromagnetic flat sensor gauge of the Valleport model 801. The flow rate was calculated using the accounting method. The WTW PhotoLab Spektra spectrophotometer was used to determine the total nitrogen and total phosphorus values. The pollutant loads were calculated using the formula (Gulliver *et al.* 2010):

$$L_i = C_i \cdot O_{i,}$$

where:

L_i – pollutant load [$g \cdot s^{-1}$],
C_i – concentration of the analyzed substance (water quality indicator) [$mg \cdot dm^{-3}$],
Q_i – flow rate at the sampling time [$m^3 \cdot s^{-1}$].

Unit loads of pollutants in the river catchments were calculated according to the formula:

$$E = \frac{L_a}{A \cdot 1000},$$

where:

E – pollutants load unit [$kg \cdot km^{-2} \cdot year^{-1}$],
L_a – annual load [$ton \cdot year^{-1}$],
A – catchment area [km^2].

CHARACTERISTICS OF THE STUDY AREA

Sopot is a tourist city with a lot of recreational options, and since 1999 it has the status of a health resort. The city area is 17.31 km^2, of which 60% is covered by forests and green areas. This coastal city

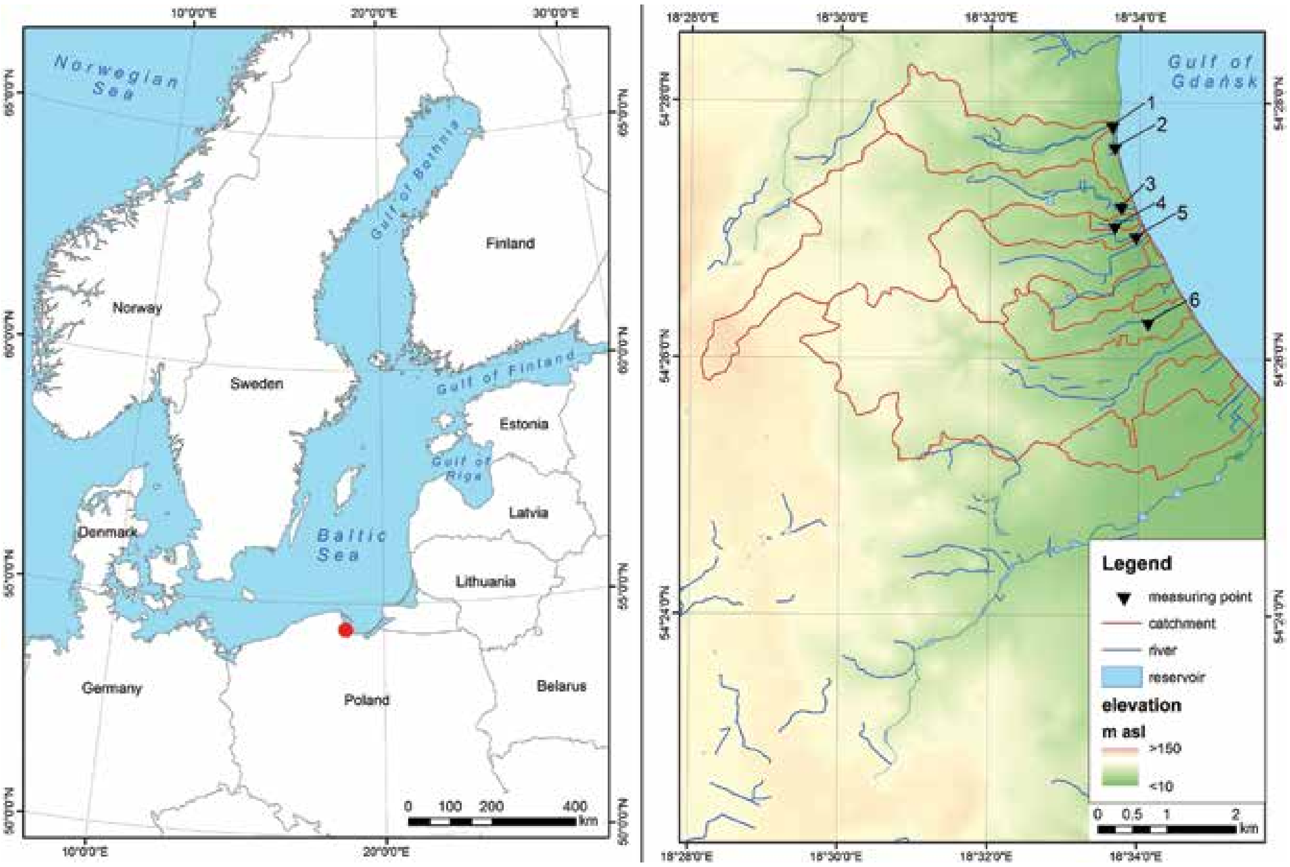

Fig. 2 Location of the research area. 1 – Swelina; 2 – Ditches; 3 – Kamienny; 4 – Babidolski; 5 – Grodowy; 6 – Haffnera

is attractive mainly because of its close proximity to the beach and bathing areas along the Gulf of Gdańsk. This is why the city has been focusing for years on maintaining good water quality in the bay. In order to increase the attractiveness of the region and promote economic development, the city took steps which are also positively impacting the state of the natural environment in the region. The study area is part of the Baltic Sea's direct basin. A characteristic feature of this area is the occurrence of numerous short watercourses draining the local uplands and flowing into the Gulf of Gdańsk. The springs located at the bottom of Sopot valleys and in the hollows of the moraine hills are the outflows of 12 natural streams with a constant flow and a number of temporary watercourses.

The analyzed streams varied in terms of length. The shortest were melioration ditches (0.4 km), while the longest was the Kamienny Stream (2.9 km), the catchment of which also covered the largest area of 3.2 km^2 (Table 2).

Streams in Sopot are receivers of water from the rainwater management system. The total length of the rainwater drainage system in the city of Sopot is about 59,000 m, while the volume of retained water is 15,000 m^3. In order to limit the inflow of pollutants with rainwater, pollution filters and separation vessels are installed in places of rainwater meets wastewater.

Sopot's rainwater management system (70 km long) is linked directly with streams in the city. In the past, these streams were recharged mostly by drainage water and groundwater flowing down from the local uplands. At the present time, the primary source of recharge is water flow from the city's rainwater collection system. As rain falls in the city, it washes out pollutants that make their way via local streams to the Gulf of Gdańsk. This process used to cause the closures of coastal bathing areas just a few years ago. Water quality norms were often exceeded, which forced such closures. In 2008, the local government initiated a project called "Funnelling Sopot stream water far into the Bay of Gdańsk". This is part of an European Union project promoting the cross-border protection of coastal waters in the Baltic Sea. The project is partly funded by an EU operating program called "Infrastructure and the Environment". The purpose of this project is to improve water quality along the Sopot coastline and limit flooding in the lower part of the city. The first stage of the project was completed in late 2009 and included the construction of System A – an underground water collection system that links three watercourses (Graniczny, Bezimienny, Karlikowski), as well as System B, which collects water from Potok Haffnera, Potok Środkowy, and Potok Boh. Monte Cassino. The two systems are equipped with parallel pipes running underneath the Bay of Gdańsk and terminating in an underground reservoir located 345 m and 380 m from the beach (Fig. 3). The second stage occurred in 2011 and 2012 and resulted in System C, which connects four other streams (Kuźniczy, Babidolski, Grodowy, Kamienny) and then funnels their waters – via underground pipes – into the Bay. The total length of the pipes constituting collection systems A, B, and C is 2.230 m. All three pipe systems are found under the Bay of Gdańsk. The Swelina Stream is not part of the funnelling system, as it is partly located in the city of Gdynia.

This stream was fitted with a hydrophytic system designed to purify surface runoff, and this step greatly improved water quality in the Sopot Kamienny Potok bathing area. As part of this project, a total of 32 devices were installed on rainwater and snowmelt funnelling pathways leading to streams. The devices consist of sedimentation tanks and separation tanks for oil-derived compounds, which secure stream waters from at least part of the pollutants washed off street and parking surfaces. In accordance with assumptions made in the project, these types of devices made it possible to reduce the level of pollution by oil-derived material in precipitation and snowmelt waters flowing from the city of Sopot into the Gulf by 97%.

RESULTS

The total catchment area of all analyzed streams entering the Gulf of Gdańsk was 10.32 km^2 (Table 2). In the years 2014–2015, the average annual flow from the catchments was 23 m^3·s^{-1}, of which

Table 2 Selected characteristics of the analyzed streams in the city of Sopot

Stream	Length [km]			Catchment area [km^2]	Mean flow [m^3·s^{-1}]	Mean specific runoff [dm^3·s^{-1}·km^{-2}]
	Covered-channel	Open channel	Total stream			
Swelina	0.2	2.4	2.6	2.89	30.79	10.65
Drainage ditches	0.0	0.4	0.4	0.17	1.83	10.76
Kamienny Stream	1.7	1.2	2.9	5.68	40.52	7.13
Babidolski Stream	0.7	0.8	1.5	0.77	26.50	34.42
Grodowy Stream	0.5	0.2	0.7	0.12	15.31	127.58
Haffnera Stream	1.3	0.2	1.5	0.69	23.06	33.42

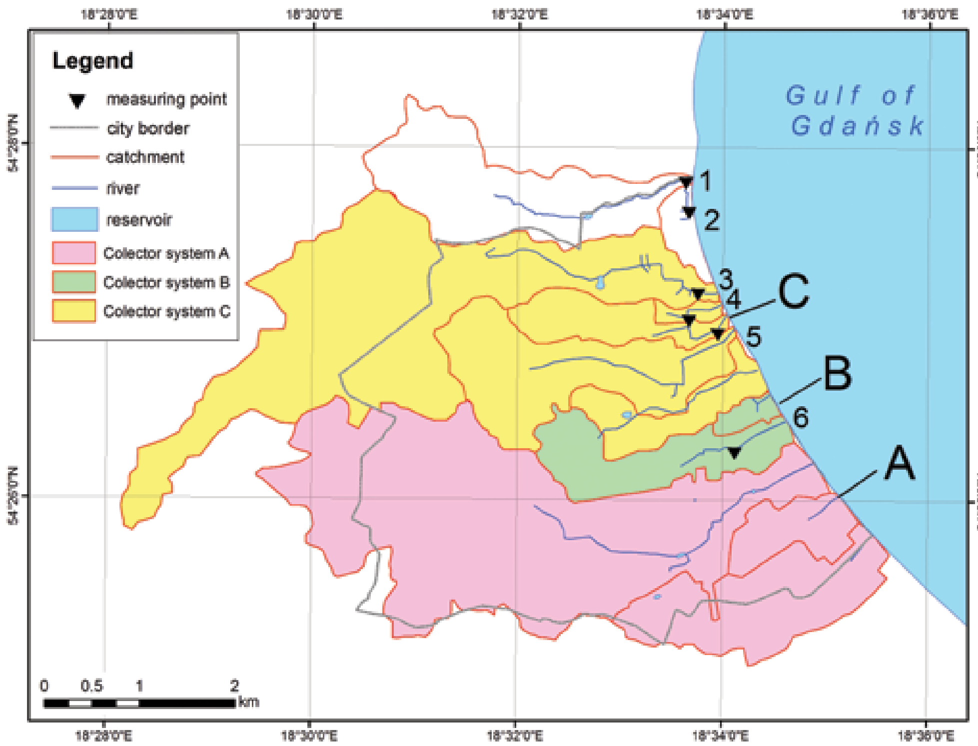

Fig. 3 Water collection systems in Sopot. 1 – Swelina; 2 – Ditches; 3 – Kamienny; 4 – Babidolski; 5 – Grodowy; 6 – Haffnera

the flow of the Kamienny Stream was 56.7 %. The highest river resources were observed in the Kamienny Stream catchment (40.52 $dm^3 \cdot s^{-1} \cdot km^{-2}$), while the lowest river discharge was found in a drainage ditch (1.83 $dm^3 \cdot s^{-1} \cdot km^{-2}$). The highest value of the mean specific runoff was observed in the Grodowy Stream (127.58 $dm^3 \cdot s^{-1} \cdot km^{-2}$). The discharge of the studied watercourses varied in the course of the year (Fig. 4). In the case of the Grodowy Stream, the maximum flow culmination occurred once – in October. In the Haffner Stream, the culmination of the flow was observed twice – in March and October.

Moreover, in the case of the Kamienny Stream and Swelina, the first maximum occurred in June and the second in October. Completely different flow changes were characteristic of drainage ditches, where the flow values were aligned throughout the year. Minimum flow values in all waterways, except for the Haffner Stream (minimum in November), were recorded during the summer season. Variation in the water content of the catchment is largely determined by the amount of precipitation, whose annual sums do not exceed 550 mm in the catchment area of the Gulf of Gdańsk. Taking into account variation in rainfall within a year, the highest rainfall occurred between May and October, with the maximum in August, and the least rainfall occurred between November and April, with the minimum in February (Fig. 5).

The natural variability of hydrometeorological processes occurring in the catchment affect the stream

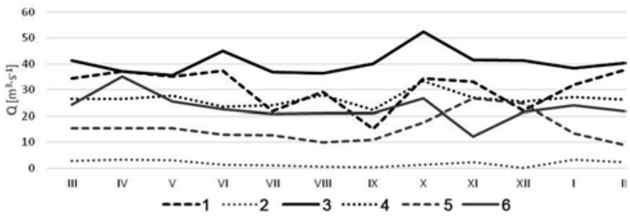

Fig. 4 Changes in water discharge in analyzed streams within a year. 1 – Swelina; 2 – Ditches; 3 – Kamienny; 4 – Babidolski; 5 – Grodowy; 6 – Haffnera

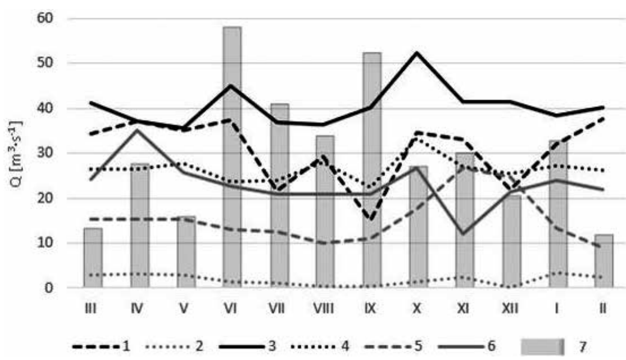

Fig. 5 Instantaneous discharge in the studied watercourses on the day of measurements and monthly sums of precipitation. 1 – Swelina; 2 – Ditches; 3 – Kamienny; 4 – Babidolski; 5 – Grodowy; 6 – Haffnera

discharge volume. This causes changes in the speed of pollution migration. Figure 5 shows instantaneous discharge in the studied watercourses on the day of measurements in combination with monthly sums of precipitation. The sums of precipitation refer to the month preceding the flow measurement. For example, the monthly sum of precipitation marked on the chart on 3 April was calculated on the basis of data from 2–3 April.

Nitrogen and phosphorus are the basic elements determining the existence and development of living organisms. However, their excessive abundance in aquatic ecosystems leads to eutrophication (Volk *et al.* 2008). The sources of nitrogen in surface waters are urban and industrial sewage, surface runoff from the catchment and atmospheric precipitation (Destouni *et al.* 2006). According to the Polish law relating to the quality of inland surface water, first-class water quality should not contain instantaneous nitrogen concentrations in excess of 5 mg·dm^{-3} (Resolution of Poland's Minister of the Environment, Journal of Laws No. 162, Item 1008). Figures 6 and 7 show the instantaneous biogenic substances concentration in the studied watercourses.

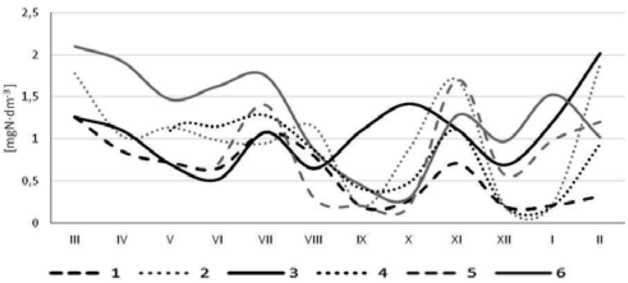

Fig. 6 Instantaneous concentration of total nitrogen in the studied watercourses in Sopot. 1 – Swelina; 2 – Ditches; 3 – Kamienny; 4 – Babidolski; 5 – Grodowy; 6 – Haffnera

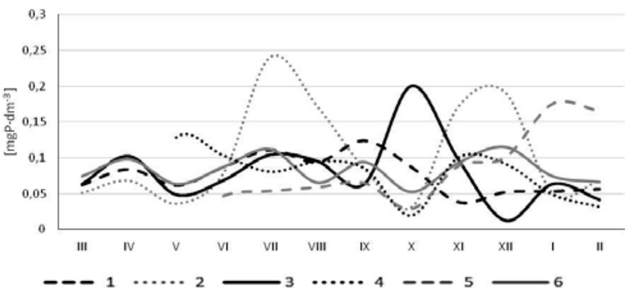

Fig. 7 Instantaneous concentration of total phosphorus in the studied watercourses in Sopot. 1 – Swelina; 2 – Ditches; 3 – Kamienny; 4 – Babidolski; 5 – Grodowy; 6 – Haffnera

The conducted research showed that total nitrogen content in all measuring points did not exceed the norms established by the Polish Law for first-class water quality. Fluctuations in the mean values of nitrogen concentrations in the studied watercourses ranged from 0.60 mg·dm^{-3} (Grodowy Stream) to 1.28 mg·dm^{-3} (Haffnera Stream) within a year. The range of variance for instantaneous nitrogen concentrations for the studied watercourses was also similar (Fig. 6). For each studied stream, the nitrogen concentration varied substantially from season to season. Studies showed that no single overarching trend existed in total nitrogen content. The highest values were noted in February and March in most of the analyzed streams, while the lowest were recorded in September, October, December, and January.

Another ion analyzed in this study was phosphorus. Phosphorus enters surface waters in the form of mineral and organic compounds (Abel 2014). According to the Polish law relating to the quality of inland surface water, first-class water should not contain instantaneous phosphorus concentrations exceeding the value of 0.2 mg/ml (Resolution of Poland's Minister of the Environment, Journal of Laws No. 162, Item 1008).

Global water security depends upon sustainable phosphorus (P) management. The river catchment scale provides an ideal unit of focus for studying this, and analytical developments in in-field measurements have promoted interest in short-term temporal dynamics (Haygarth *et al.* 2014). Phosphorus concentration in the analyzed streams did not exceed the Polish norm for first-class water quality. The mean value ranged from 0.066 mg·dm^{-3} (Babidolski Stream and Grodowy Stream) to 0.1 mg·dm^{-3} (drainage ditches). The range of variance for instantaneous phosphorus concentrations for the studied watercourses was similar (Fig. 7). As in the case of nitrogen concentration, no single overarching trend in total nitrogen content existed in any analyzed stream.

Based on the obtained nitrogen and phosphorus concentrations and carried out flow measurements, the annual and average monthly total nitrogen and phosphorus loads were calculated. The annual load supplied by analyzed streams during the study period was 4,066 kg for total nitrogen and 352 kg for total phosphorus per year. Analyses indicate that the largest nitrogen and phosphorus loads from the city of Sopot are supplied to the Gulf of Gdańsk by the Kamienny Stream (Table 3). Cf. the load supplied by the entire territory of Poland in 2012 was 210,768,000 kg of total nitrogen and 15,269,000 kg of total phosphorus. The studied watercourses provide about 0.002% of the biogenic mass that is supplied to the Baltic Sea from Poland's territory as a whole (Cieśliński *et al.* 2017).

Seasonal changes in the total nitrogen and total phosphorus loads in watercourses showed that larger loads of nitrogen could occur in the winter months, but in some cases there is no seasonal variances in the phosphorus load (Silva, Williams 2001).

The study was able to show that nitrogen load exhibited seasonal changes, but no discernible seasonal pattern was detected for pollutants found in Sopot watercourses.

Figure 6 shows the range of variation and the average monthly values of nitrogen loads. The largest to-

Table 3 Annual total nitrogen and total phosphorus loads [kg·year^{-1}]

Ion \ River	Swelina	Ditches	Kamienny	Babiodolski	Grodowy	Haffnera
Nitrogen	607	66	1373	646	425	949
Phosphorus	71	5	106	66	44	60

tal nitrogen loads in the analyzed watercourses were noted in spring for the Swelina Stream with the highest value in March (0.04 g·s^{-1}) and for the Haffnera Stream with the highest value in April (0.07 g·s^{-1}). The lowest loads of total nitrogen for Swelina occurred in September (0.003 g·s^{-1}) while for the Haffnera Stream in October (0.01 g·s^{-1}). The lowest pollutant concentration was observed in September for the Grodowy Stream (0.002 g·s^{-1}). Not long after that observation, in November, the Grodowy Stream was observed to have the largest pollutant concentration (0.05 g·s^{-1}). In the case of the Kamienny Stream, the largest value of nitrogen load was noted in February (0.08 g·s^{-1}), but the smallest total nitrogen load (0.02 g·s^{-1}) occurred in June and August. For the Potok Babidolski Stream, the lowest total nitrogen loads occurred in December and January (0.005 g·s^{-1}), while the largest load (0.03 g·s^{-1}) was noted in May, July, and October. The loads of total nitrogen in drainage ditches were quite small and aligned over the entire research period (Fig. 8).

The average monthly values and the range of variation of phosphorus loads in studied watercourses are shown in Figure 9. The largest phosphorus load values occurred in May in the Babidolski Stream and in April in the Haffnera Stream (approx. 0.003 g·s^{-1}). The largest amount of total phosphorus loads in the Grodowy Stream was noted in November (approx. 0.002 g·s^{-1}). In case of Swelina, the smallest instantaneous phosphorus loads were noted in the winter months, while in the other seasons of the year, Swelina transported a similar load of approx. 0.002 g·s^{-1}. The largest instantaneous total phosphorus load occurred in Kamienny Potok in October (0.01 g·s^{-1}).

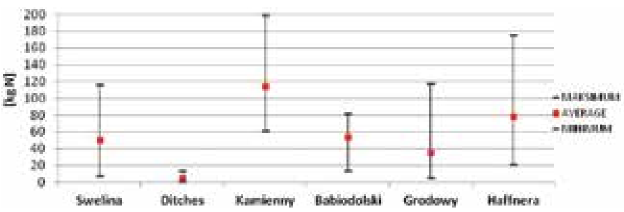

Fig. 8 The range of variation and the average monthly values of nitrogen loads

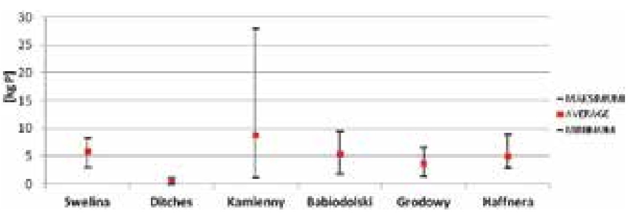

Fig. 9 The range of variation and the average monthly values of phosphorus loads

DISCUSSION

The quality of surface water and degree of water pollution depend on many factors. The decomposition of organic matter leads to increase in phosphorus and nitrogen concentrations in aqueous environments (Chatterjee 2009). According to Andrulewicz (1996), proposals for the Baltic Monitoring Programme – HELCOM BMP should introduce new measurement techniques which may affect changes in monitoring strategy towards the measurement of the biological effects of pollution. Definitely, monitoring should also include small urban basins, seemingly not carrying a risk of pollution of the Baltic Sea, but presented in large numbers in the coastal zone. In the Baltic Sea area, the external nitrogen and phosphorus loading ratios are generally well above the 16:1 Redfield ratio for all subareas (Granéli *et al.* 1990). Currently, nitrogen supply is probably increasing more rapidly than phosphorus supply and the management of the Baltic Sea area cannot be based on the removal of those elements in wastewater, but must also take into account the differences between catchments and polluted coastal and offshore areas (Granéli *et al.* 1990). According to the HELCOM report (2018) of sources and pathways of nutrients to the Baltic Sea, nutrient loads from Poland are characterized by comparatively large proportions from agriculture and from point-sources. In case of phosphorus loads, the point-sources share is even larger than the agricultural share (42%, and 34%, respectively). While in case of nitrogen loads, the contrary occurs with 31% from point-sources, and 45% from agricultural activities.

In Poland, during the summer period there are mainly torrential and heavy rainfall, immediately followed by a rapid increase in flows in rivers. In the autumn season, large sums of precipitation (150–200 mm) are characteristic in the areas of Polish coastal zone of the Baltic Sea (Wibig, Jakusik 2012). During this period, rainfall is more evenly distributed over time, the supply of nitrogen and phosphorus from the catchment is less because of the effect of diluting substances dissolved in water with larger water flows. Among the studied watercourses, the Kamienny Stream was characterized by a high correlation of precipitation and outflow, which means that the conditions prevailing in its catchment allow its quick reaction to precipitation. Increased content of nitrate ions at the beginning (in March) and at the end (in February) of the research period may result from the transport of nitrates washed away from the surface of thawing soils, surface runoff waters and ground and soil waters during the snow melting before vegetation starts.

Many researchers such as Boyer *et al.* (2002) and Alvarez-Cobelas *et al.* (2008) showed that the main source of nitrogen in the catchment is agriculture. In urban catchments, the supply of nitrogen to surface waters is more important in the supply of atmospheric supplies, while the studied urban catchments do not show excessive concentrations of this element.

Watercourses in urban catchments, especially in large cities, become the main receivers of sewage and highly contaminated surface runoff, which results in deterioration of their chemical and hygiene-sanitary conditions. In the aspect of phosphorus loads in the course of the year, only in drainage ditches two distinct peaks were noticeable during the research period (the first in July and the second in November). Research conducted by Dondajewska *et al* (2009) confirmed that the highest concentrations of phosphorus in water occurred in the areas of housing estates. According to Gilbert and Clausen (2006), this is related to the fact that the main sources of phosphorus in urbanized areas are lawns and gardens, and there is also surface runoff from roads, particularly marked during intense rainfall, which is also clearly visible in the case of the Kamienny Stream.

Considering the problem of nutrient supply from small catchments to the Baltic Sea and in the case of the watercourses presented in this article – to the Gdansk Bay, the aspect of water and sea exchange between the Gulf of Gdansk and the Baltic Sea, which in his research was more widely considered by Jankowski (1985), should also be noted. The 2D depth-averaged model of the Gulf of Gdańsk applied by Jankowski (1985) can be used for steady-state water circulation calculations with the wind as the main forcing phenomenon. Beside river discharge and water exchange between the Gulf and the open sea, hydrodynamics of the Gulf of Gdańsk is also forced by the wind conditions and water density stratification. The results from the 2D hydrodynamic models can be used to estimate the seasonal changes in inorganic and total nitrogen or inorganic and total phosphorus.

The direct discharges, mainly from sewage treatment plants in the coastal zone, correspond to about 10% of the total load. We should note that provided studies show that the relationship between the catchments land use and nitrogen and phosphorus supplied by the analyzed rivers is very poor. The reason for the lack of this relationship is primarily the fact that 52% of the studied watercourses flow underground, and there are no significant sources of pollution located within the surveyed catchments, and the only sources of pollution are the communication routes. The nutrient loads from Poland are characterized by comparatively large proportions from agriculture and from point-sources. In 2012, the total load of nitrogen from Poland to the Baltic Sea was 107,647 tons, from which 48,656 tons (45.2%) from agricultural activities. The total load of phosphorus in the same year was 6,863 tons, from which 2,327 tons (33.9%) from agricultural activities (HELCOM 2018).

On the other hand, the local government began a reconstruction program to help eliminate all potential sources of water pollution in the city area. The local water and sewer system as well as the construction of collection vessels funnelling polluted water far into the Gulf of Gdańsk. The conducted research showed that because of the low water content, the analyzed watercourses are not a significant threat to the waters of the Gulf of Gdańsk, and the pollution supplied to the bay from the city of Sopot is small. Perhaps it will change as a result of climate change. The fact that the climate warming process is taking place is evidenced by the increase in the average air temperature on the Earth, which in the years 1906–2005 amounted to 0.74 ° C ± 0.18 ° C (IPCC 2007). Further forecasts indicate that the global average air temperature on the Earth by the end of the 21st century will rise by 1.4 to 5.8 ° C (BACC Author Team 2008, 2014). As a consequence, changes will be noticed not only in air and water thermoelectricity as well as in the amount of rainfall, but also in the size of evaporation, potamical inflow from the catchments and in wind speeds. It can therefore be concluded that the changes will have a very wide range, which will cause changes in air circulation and changes in the balance of the Baltic Sea. The ice regime will also change. It is predicted that when the temperature increases by 2 to 4 ° C by the end of the 21st century, the area of ice reduction will reduce by 50 to 80%. With the same temperature rise, the Baltic's salinity will decrease by 8 to 50% (BACC Author Team 2008, 2014). Another consequence of global warming will be the increase in surface water pollution resulting from the accelerated eutrophication process. As a result, the marine ecosystem and the waters of the coastal zone will change (BACC Author Team 2008, 2014).

The nutrients mass supplied by those six rivers during the research period was 4066 kg for total nitrogen and 350 kg for total phosphorus. According to HELCOM report (2018) about the sources and pathways of nutrients to the Baltic Sea, the total nitrogen and total phosphorus inputs fall during the recorded period for the entire Baltic Sea, with the share of direct point-sources experiencing the greatest change. The reduction of nitrogen inflow is similar for all pools in the southern part of the Baltic Sea and correlates with the decrease in production from Denmark, Germany, Poland and Sweden. The pollutant load supplied by the studied watercourses stands at about 0.002% of the total pollutant mass supplied to the Baltic Sea by the entire territory of Poland. Despite the fact that small streams from the city of Sopot do not provide a large load of pollutants, we cannot ignore the numerous small streams flowing into the Baltic Sea, a large number of watercourses transporting inconveniently small amounts of pollutant loads is a significant threat to the quality of the Baltic Sea.

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