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Nutrient loss from three small-size watersheds in the southern Baltic Sea in relation to agricultural practices and policy

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ABSTRACT

Agriculture is the major contributor of waterborne nutrient fluxes into the Baltic Sea, one of the world's most eutrophication-sensitive areas. Poland, as a large, densely populated state ohf the Baltic Region, with dominating agricultural land use, largely contributes to riverborne loads of N and P. The aim of our study was to examine the input of nutrients from three small first-order agricultural watersheds (Bladzikowski Stream, Gizdepka river and Mrzezino canal) in the Pomerania region, into the Bay of Puck, inner part of the Gulf of Gdansk. This study attempts to give a partial answer as to the question if inputs of nutrients from the 3 analysed watersheds comply with the targets of the Baltic Sea Action Plan (BSAP) and Country Allocated Reduction Targets (CART). The impact of agricultural practices was assessed on the basis of farm questionnaires and calculations of nutrient balances for the examined farms. The nutrient concentrations in the soil and drainage ditches were examined, followed by an assessment of nutrient concentrations in the watercourses at the sampling points located close to the estuaries. The average mineral N fertiliser consumption (109 kg N/ha) in the analysed watersheds was higher than Poland's average. The average N and P surpluses for surveyed farms (96.4 kg/ha and 4.4 kg/ha, respectively) were higher than the EU mean in case of N and markedly lower in case of P. We used Principal Component Analysis which confirmed that there were correlations between nutrient surpluses and nutrient concentrations in streams and/or drainage ditches. The N–NO_3 and P_{min} concentrations were also correlated to precipitation. The average N concentrations in the analysed watercourses were equal to 1.53 mg/L for Gizdepka, 1.88 mg/L for Mrzezino canal and 3.52 mg/L for Błądzikowski Stream. The mean P concentrations observed in the investigated watercourses were markedly higher than 0.1 mg/L. With regard to BSAP objectives, as well as CART set for Poland, the average nutrient concentrations in rivers should be approximately at the level of 2.5 mg N/L and 0.07 mg P/L.

1. Introduction

Eutrophication continues to be one of the most important problems of many coastal marine waters and estuaries (Álvarez et al., 2017; Heisler et al., 2008; Howarth, 2008; Humborg et al., 2006; Nixon, 2009). Anthropogenic input of nutrients causes increased water fertility, leading to enhanced primary production of algal blooms, followed by decomposition of organic matter. This results in oxygen depletion and the formation of dead zones. The eutrophication-related problems are of particular importance to the Baltic Sea, which is one of the world's most eutrophication-susceptible areas (Elofsson, 2001 ; Ning et al., 2018; Voss et al., 2011; Savchuk, 2018). There are two kinds of reasons for the Baltic Sea eutrophication. The first is associated with specific features of the Baltic Sea, which is a semi-closed, shallow inland sea with limited water exchange with the North Sea. The average time of complete water exchange through the Danish straits is estimated as 25–30 years, and for the inland bays, it can be even longer (Fleming-Lehtinen et al., 2015). In addition, there are also the reasons connected to the anthropogenic activities in the Baltic Sea basin. These have substantially intensified in the past decades, resulting in the increased inputs of nitrogen and phosphorus originating from agriculture (Larsson and Granstedt, 2010; Voss et al., 2011

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) and urban lands (Matej-Łukowicz and Wojciechowska, 2017; Wu et al., 2015). The land cover has drastically changed in the past 100 years, when substantial areas covered by wetlands and forests were turned into agricultural lands and the widespread use of fertilisers for stimulating crop productivity. In the Baltic Sea region, the use of mineral N and P from fertilisers increased by 17-fold and 8-fold respectively, in the period 1950–1988, according to Nausch et al. (1999), followed by a decreasing tendency in the next decades. Tillage and irrigation were introduced in agricultural catchments. The stream and river beds were straightened and as a consequence, became shorter, pursuing higher hydraulic slopes and flow velocities, which in turn shortened the water residence time and decreased self-purification potential with regard to organic matter decomposition and denitrification (Reid et al., 2018). As a result, riverine transport of nutrients increased worldwide by 4-fold (Humborg et al., 2006; Pastuszak et al., 2014). In the Baltic Sea basin, the diffuse inputs constitute a major anthropogenic source of waterborne nitrogen (71% in 2000) while the largest loads of phosphorus originate from point sources (56%). Agriculture is definitely the largest N emitter (80% of the total diffuse flux), while the municipalities are the main source of P, constituting 90% of the total point source discharges (HELCOM, 2009; Kowalkowski et al., 2012).

Poland, as the large state of the Baltic Sea basin, with the population and agricultural area constituting 45% and 50% of the region respectively, is one of the major contributors of river-borne loads of nutrients. In the recent 30 years, Poland has made remarkable progress in controlling the point sources of pollution (Pastuszak et al., 2014; Saaltink et al., 2014). After the "fall of the iron curtain" in the early 1990s, the large and ineffective national agricultural farms collapsed, while small private farms were struggling to survive in the market economy. After joining the EU in 2004, the agricultural sector was revived, and large progress was made in the modernisation of agriculture and livestock production, as well as the rationalisation of fertiliser usage (Pietrzak, 2012). The sum of these changes resulted in the decrease of N and P emissions, followed by a permanent decrease in the nutrient load discharge from Poland's territory to the Baltic Sea (Kowalkowski et al., 2012; Kowalkowski and Buszewski, 2006; Pastuszak et al., 2014). Nevertheless, the annual nutrient discharge from Polish territory is equal to 301,565 t of N and 14,845 t and P, constituting 30% and 39% of the total riverine inputs of N and P to the Baltic Sea (Svendsen et al., 2015). The absolute loads are definitely highest in the Baltic Sea basin, while the N and P loads per capita place Poland as fifth in the rank of Baltic states (Svendsen et al., 2015).

To counteract the eutrophication of the Baltic Sea, which is expected to persist in the coming decades (Ning et al., 2018), the Baltic Sea Action Plan (BSAP) was developed by the Helsinki Commission (HELCOM, 2013a, 2017). BSAP sets constraint requirements on nutrient reduction for the Baltic Sea states, assuming the maximum input of N below 600,000 tonnes per year and 21,060 tonnes of P per year. In comparison to a reference period (1997–2013), this means that the fluxes of nutrients should be reduced by 135,000 tonnes of nitrogen per year and 15,250 tonnes of phosphorus per year (HELCOM, 2007). According to Country Allocated Reduction Targets (CART) defined in 2013, Poland is obliged to reduce yearly N and P loads from land and air by 43,610 t and 7480 t respectively (percentage reductions by approx. 30% of TN and 66% of TP) (HELCOM, 2013b; Pastuszak et al., 2018). (HELCOM, 2013b). Compared to the other countries in the Baltic Sea basin, this is a drastic reduction since Poland alone is responsible for almost 49% of N load reduction and 52% of P load reduction. As the diffuse sources play a major role in nutrient emission, reducing the impact of agriculture remains the main target. Fears arise that meeting the stringent requirements of CART would decrease Poland's agricultural productivity, making Polish agriculture sector a loser at a market competition within the EU, since the present concentrations of N and P in Polish major rivers meet the demands of EU Framework Directive. The same authors argue that reduction required by CART may not be feasible since the riverine nutrient concentrations would be on the level characteristic for pre-industrial times, with significantly lower population and agricultural intensity (Pastuszak et al., 2018).

Taking into account all these aspects, it is necessary to revisit the impact of agriculture and agricultural practices in Poland on the status and nutrient loads carried by Polish rivers, as 99,7% of Polish territory belongs to the Baltic Sea basin. In 2014 EU Court of Justice judged that Poland failed to fulfil obligations of the Nitrates Directive ("Nitrates Directive," 1991). The Nitrate Vulnerable Zones (NVZ) were not sufficiently designated, the adequate measures for the protection of nitrates released from agricultural lands were also not undertaken. Thus, in 2017 new legislative regulations (Suligowski and Nawrot, 2018; "The Water Law Act dated 20 July 2017," 2017) were introduced, and measures towards nitrates mitigation were introduced for the whole territory, instead of the 4,46% it formerly concerned. While several studies concentrate on the catchments of major Polish rivers: Vistula and Oder, the small catchments of the Pomerania region are monitored extensively, and fewer studies refer to their input to the Baltic Sea (Dzierzbicka-Glowacka et al., 2019; Wojciechowska et al., 2018). However, flowing through mostly agricultural lands, these catchments do play a role in the nutrient discharge to the Baltic Sea. According to former Polish legislation, those catchments were not defined as NVZ despite the intensively cultivated land and direct outflow to the inner bay of the Baltic Sea.

The objective of our study was to examine loads of N and P released into the Bay of Puck (inner part of the Gulf of Gdansk) from three small first-order agricultural watersheds in northern Poland with regard to BSAP requirements in the view of the implementation of new regulations and measures towards nitrate mitigation. The farm nutrient balance study in the analysed catchments was performed on the basis of questionnaires, giving insight in the structure of agricultural production and fertiliser usage. The direct impact of agricultural farms on the surface waters in draining ditches as well as nutrient concentrations in agricultural soils were monitored. The nutrient concentrations in watercourses were assessed at the sampling points located close to the estuaries. The Principal Component Analysis (PCA) was performed for statistical evaluation of the factors influencing nutrient concentrations in the investigated watercourses.

2. Methods

2.1. Study area

In this study, we focused on the small rivers of the Pomerania region (Puck Municipality) that contribut directly to the Bay of Puck, Baltic Sea (Fig. 1). Three short watercourses: Bladzikowski Stream (BS), Gizdepka river (G) and Mrzezino canal (M) with relatively small agricultural catchments in the Puck Municipality were selected for evaluation (Fig. 2). The selection was based on a prior analysis of their impact on the waters of the bay (Zima, 2019). The length of all the watercourses was an important factor since self-purification processes (important for at least N removal) are not likely to be highly efficient; also, the catchment area is an important factor for scaling nutrient retention. Kyllmar et al. (2014) pointed out that small agricultural watersheds generally have a high proportion of drained arable land to forests and impervious areas, other than larger river catchments. Thus, the stream water quality in those small catchments tends to respond more rapidly to changes in agricultural field management compared to larger rivers. Furthermore, the relatively small size favours greater homogeneity within each of the catchments.

The Puck Municipality is located in northern Poland. The population density is 107 inhabitants per km^2. It occupies an area of 242.6 km^2 while crops, meadows, pastures and forests constitute 107.7, 28.4, 6.6, and 75.8 km^2 respectively. The Gizdepka river and the Bladzikowski Stream have similar catchment sizes - longitudinal

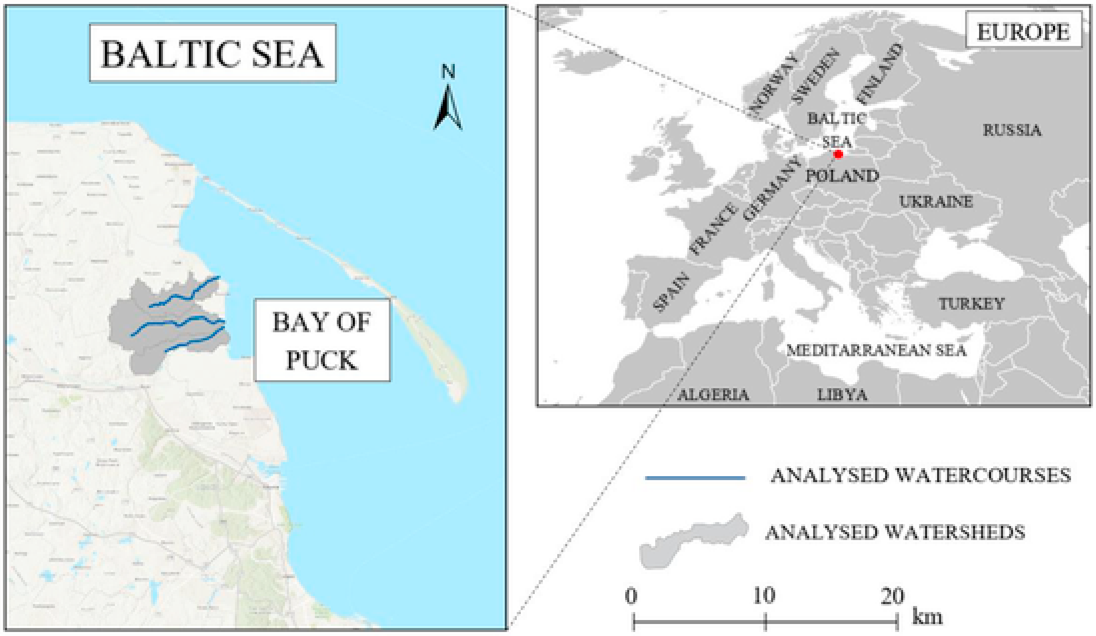

Fig. 1. Map of the study area (source: Google Maps).

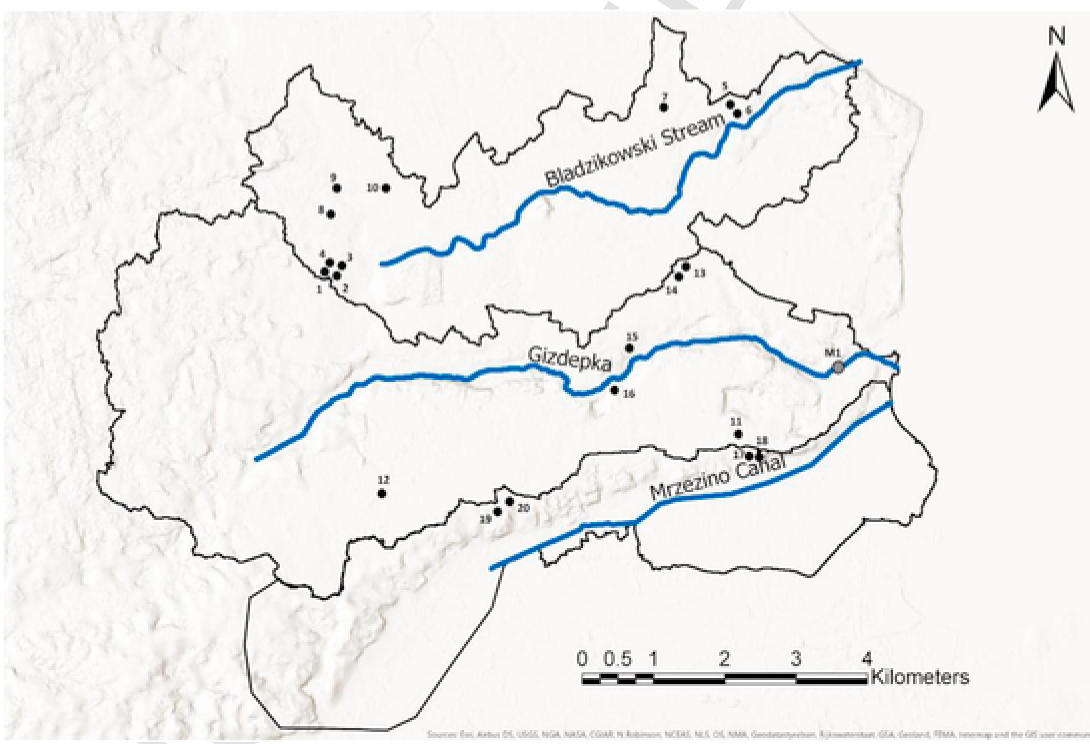

Fig. 2. Location of surveyed farms on the digital elevation model of Puck Municipality.

and condensed in a small range from the watercourse. Both catchments are covered with a dense hydrographic network (drainage ditches, canals) as well as tiles serving regulation of water level for agriculture. Mrzezino canal is an artificially created branch of the Reda river, one of bigger rivers in the area; the canal drains water from peat bogs and agricultural fields irrigation. All the analysed watercourses outflow directly to the Bay of Puck and have artificially shaped and straightened river beds. Catchment boundaries and slopes in the catchments and streams were estimated basing on a digital elevation model with a resolution of 10×10 m. The calculations were made by adopting the Soil and Water Assessment Tool (SWAT) software used as a plug-in for the Q-GIS program (QSWAT) (Kalinowska et al., 2018). The major differences between the analysed watercourses include the land use of the watersheds (agricultural fields, meadows, forests, natural grasslands), population density, and the density of tillage systems developed for the stabilisation of the water table (Table 1). Soil type and land uses were described basing on a soil and agricultural map (Fig. 3).

Table 1
The characteristic of streams and rivers of the 1st catchment.

Stream and catchment characteristics	Bladzikowski Stream (BS)	Gizdepka river (G)	Mrzezino canal (M)
Hydrologic:			
Catchment Area A [km ^{2}]	19.8	31.5	16.5
Stream Length L [km]	8.7	10.4	6.3
Flow rate (specific) Q_s [m ^{3}/s]	0.02	0.25	0.02
Flow rate (min) Q_{min}	0.01	0.18	0.01*
Rainfall min [mm]	11.2 (13 VI 2018)		
Rainfall max [mm]	192.2 (21 IX 2017)		
Rainfall mean [mm]	63		
Slope of the catchment [%]	0.68	0.73	1.02
Slope of the watercourse [%]	0.42	0.3	0.07
Land use:			
Crops [%]	50.2	45	0.3
Pastures/Meadows [%]	39.3	15.4	99.7
Forest [%]	8.7	39.2	0
Urban [%]	1.8	0.4	0
Soils:			
Medium-grained sands [%]	0.3	10.7	37.1
Fine grained sand [%]	4.3	14.6	0
Clay sands [%]	38.6	52.3	48.7
Sandy loam [%]	54.1	15.7	0
Clay [%]	0.3	0.4	9.9
Peat [%]	2.4	6.3	4.3

*Periodically no outflow to the Bay of Puck

2.2. Farm questionnaire method

20 farms in the Puck municipality were selected to complete questionnaires. A representative group of farms was selected via the purposive sampling method. This is a non-stochastic method of selecting a representative sample based on expert knowledge. The selection of farms was based on their specialization (type of cultivation, type of livestock; cows, pigs, mixed), the area of arable land as well as the farmer's willingness to co-operate. The overall assumption was that the percentage share of different sizes of farms in the representative sample should be similar to their equivalent percentage share in several agricultural investigations and surveys already performed in Poland (performed i.e. by GUS – the Main Statistical Office). The method was also explained by Dzierzbicka-Glowacka et al. (2019).

The area of the selected farms constitutes 7.5% of the total agricultural land of the farms in the Puck Municipality. The size-structure of surveyed farms is presented in Fig. 4. The average size of 20 farms in the analysed watersheds was equal to 47.5 ha. Majority of the farms belonged to the most characteristic for the whole Puck Municipality groups of medium-size and large farms. The total area of 20 analysed farms constituted over 949 ha. Arable lands constituted 69% and green areas – 31%. Cereals constituted 61.4% of cultivation, rape – 15.7%, maize – 9.8%, peas – 7.1% and potatoes – 4.5%. Most farms were also breeding milk cows and pigs.

2.3. Farm nutrient balance study

Farm nutrient balance studies were performed for the 20 analysed farms, according to the method described by Ulén et al. (2013) and Dzierzbicka-Glowacka et al. (2019). The area of the selected 20 farms constitutes 7.5% of the total agricultural land of the farms in the Puck Municipality. In brief, the inputs and outputs of N, P and K were calculated for each farm. The components of nutrient fluxes "in" and "out" are presented in Fig. 5. The nutrient balance was calculated as a difference between input and output – if input was higher than output there was a nutrient surplus; otherwise there was a nutrient deficit in the farm.

2.4. Collecting water and soil samples and laboratory analyses

Samples of water from drainage ditches were collected between January and October 2018 using a standard 1 L volume sampler. The water samples were stored in pre-cleaned 1L glass bottles. The numbers of sampled ditches, sampling campaigns and the total number of collected samples for each watershed is presented in Table S1.

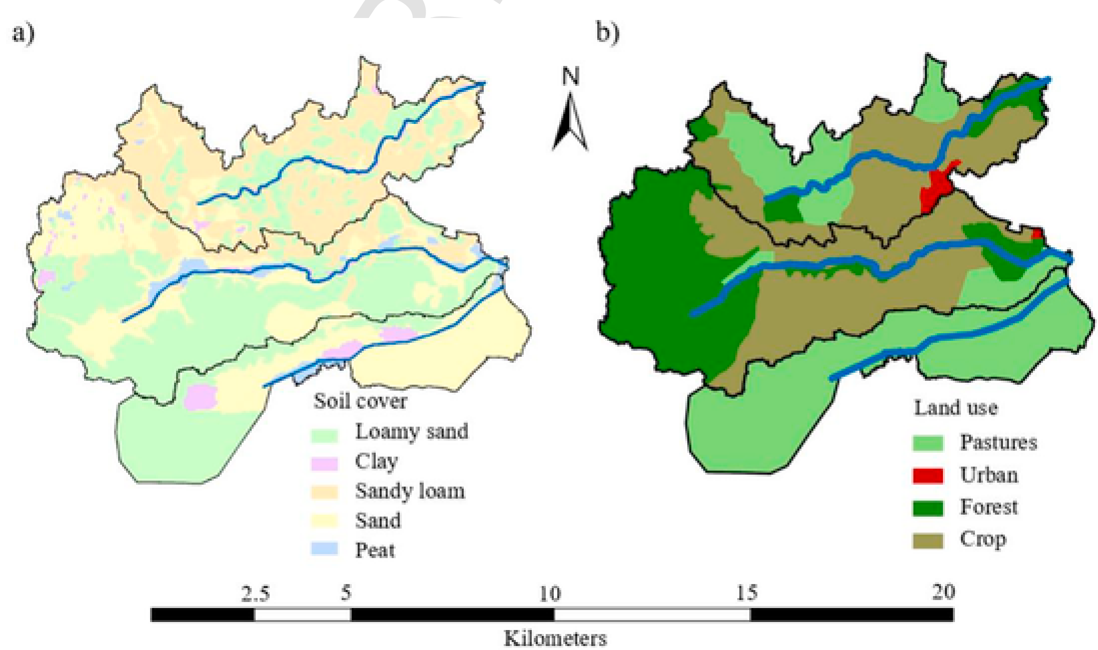

Fig. 3. Soil type map (a) and agricultural map (b) of the analysed area.

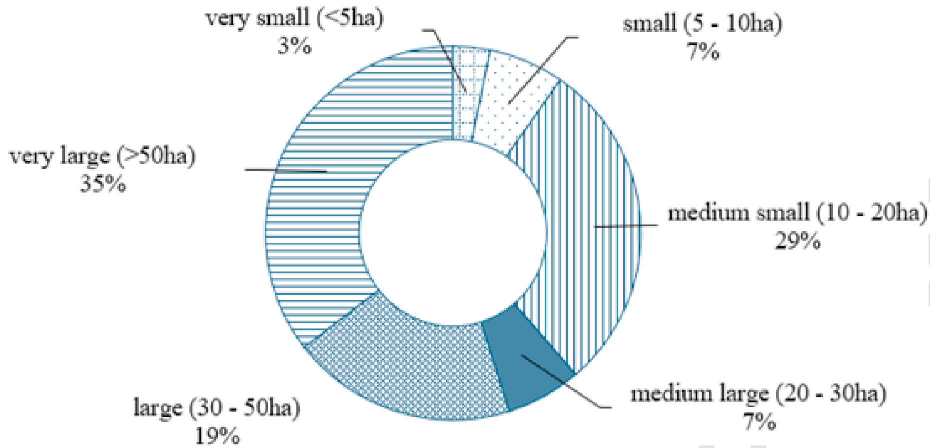

Fig. 4. The structure of investigated farms in Puck Municipality [% of the total arable lands].

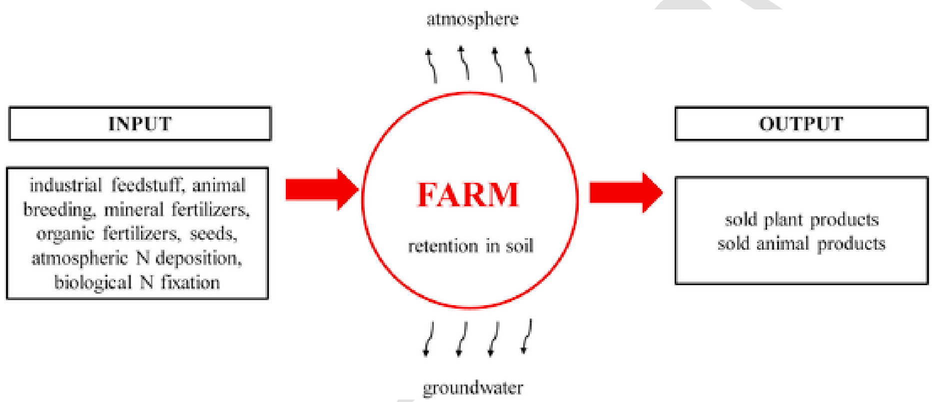

Fig. 5. Components of nutrient balance for a farm.

Stream water samples were collected between July 2017 and January 2019. The sampling campaigns were conducted once every 3–4 weeks. Each time 1 L (L) of water every 5 min during a 30 min period of time was collected. A water sample was taken from the midstream course. The samples were immediately transported to the laboratory in cooling conditions (8 °C).

The determinations of ammonium nitrogen ($N{-}NH_4$), nitrite nitrogen ($N{-}NO_2$), nitrate nitrogen ($N{-}NO_3$), total nitrogen (TN), mineral phosphorus (P_{min}) and total phosphorus (TP) were carried out according to Polish Standards compatible with EU and US-EPA standards. All determinations were carried out in 3 replications.

Soil samples were collected from the surface layer (0–25 cm) separately for each type of cultivation during spring and autumn 2018. The composite samples were formed from at least 20 sub-samples, according to Polish Norm PN-R-04031:1997 (Polish Committee for Standardization, 1997a). Altogether, 81 samples were collected from investigated farms. Determination of available forms of phosphorus in mineral soils was conducted using the Egnera-Riehma method, by means of calcium lactate solution (pH ~ 3.55) in accordance with the Polish norm PN-R-04023:1996 (Polish Committee for Standardization, 1996). In the case of organic soils, the assimilated forms of phosphorus were determined in the eluate of 0.5 mol $HCl{\cdot}dm^{-3}$ according to the PN-R-04024:1997 Standard (Polish Committee for Standardization, 1997b). The content of nitrate nitrogen ($N{-}NO_3$) was determined by means of the Spectrophotometric method according to the Polish norm PN-R-04028: 1997 Standard (Polish Committee for Standardization, 1997c).

2.5. Meteorological and hydrological data acquisition

The daily sums of precipitation were obtained from archival resources of the Institute of Meteorology and Water Management (National Research Institute) from station number 254180040 located in the Zelistrzewo village.

Starting from May 2018, flow discharge for the Gizdepka River was observed in point M1 (Fig. 2) in Smolno Village. The sound probe performed continuous measurements with a frequency of 2 min. Flow rates were determined from the empirical flow curve made on the basis of hydrometric measurements performed in the period 2017–2018. In other channels, the flow velocity measurements were carried out with the use of the FlowMate and OTT portable magnetic flow meters. The distances between hydrometric plumbs and the depths at which the measurements were carried out was dependent of the current water level. The flow rates were determined using the arithmetic method, and earlier the geodetic levelling of cross-sections were carried out at the sampling points.

2.6. Statistical analysis

Statistical analysis of the results was carried out using Statistica® 13.1. Descriptive statistics (mean, standard deviation and relative standard deviation) for nutrients in the water were analysed, followed by principal component analysis (PCA). PCA was undertaken to identify the relationships between nutrients in the water and soils samples and nutrient surpluses. Based on the correlation matrix, the possibility of using PCA was checked. Subsequently, eigenvalues, loads and a scree plot were determined. This enabled the number of new variables to be generated. In the next step the factor coordinates of the cases and variables (factor loadings) were constructed. The result is a graph of variable co-ordinates, which allows the correlation between input variables to be estimated and checked for new matching variables. The significance level used for all tests was set at $p < 0.05$.

Correlation analyses (in the form of matrix correlation) between nutrients (in the form of N_{tot}, $N\text{–}NO_3^-$, P_{tot} and P_{min}), rainfall amount (RD) and flow rate (Q) were performed using monthly data for the analysed watersheds.

3. Results

3.1. Farm survey results

Representative farms were selected for analyses taking into account the total number of farms in the Puck commune, diversification area of agricultural land and the types of production. The number of surveyed farms in each catchment was 10, 6 and 4 for the Bladzikowski Stream, Gizdepka river and Mrzezino canal, respectively.

The location of the surveyed farms is presented in Fig. 6. The structure of land use in the surveyed farms is presented in Fig. 6, reflecting the differences between the analysed watersheds. Arable lands constituted 85% of land in the Bladzikowski Stream catchment, 70% of land in the Gizdepka catchment, and only 25% of land in the Mrzezino canal catchment. On the other hand, the share of meadows was highest in the Mrzezino canal catchment (46%), while in the Gizdepka river and Bladzikowski Stream watersheds, meadows occupied 29% and 9%, respectively. The low share of arable lands and greater area occupied by meadows in Mrzezino canal catchment results from the fact that it borders the Beka Nature Reserve located in the estuary of the Reda River. The differences in the land use in the catchments of Bladzikowski Stream and Gizdepka (with a larger area of arable land in the Bladzikowski Stream catchment vs the Gizdepka catchment) were mainly due to better soil composition (lower share of clay sands and sandy loams) (Table 1).

In Fig. 7, the crops cultivated in the investigated farms, along with the average harvest [dt/ha] are presented. Apart from meadows, the winter wheat, winter triticale, and fodder corn occupied the largest area. The highest harvest of fodder corn (447 dt/ha) and potatoes (339 dt/ha) was reported in the questionnaires.

The vast majority of the surveyed farms (96.8%) used crop rotation. The most common crop rotation was field-corn cereal - in 76.7% of cases. Only 19.4% of the farms used after-crops (a later crop in the same year), equally catch crops and mixed cropping. In the majority of cases, the aftercrops (83.3%) were plowed into green fertiliser. The cultivated area of after-crops constituted between 14.4 and 35.7% of the arable land of the investigated farms. The structure of agricultural and livestock production was discussed by Dzierzbicka-Glowacka et al. (2019).

Usage of mineral fertilisers, expressed as a pure elements (N, P, K), was relatively high, comparing to the average values in Poland and in the Pomerania Region (Fig. 8).

In the Puck Municipality, according to the recently updated regulation of Minister Council of 5th June 2018 (Council of Ministers, 2018), the usage of mineral fertilisers and liquid organic fertilisers (manure) is allowed between 1st March and 31st October on grasslands and long-term cultivated areas, but only between 1st March and 25th October on arable lands. The application period of solid organic fertilisers is somewhat longer – until 31st October for arable lands and until 30th November on other types of lands. In Table 2, the periods of

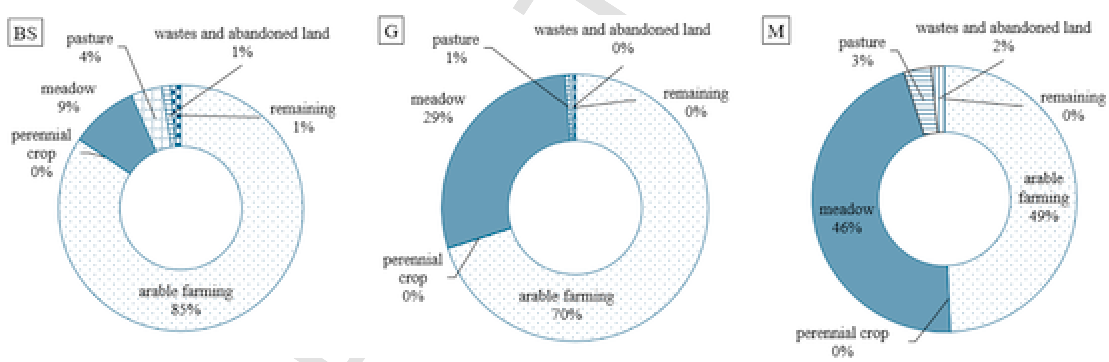

Fig. 6. The land use structure of investigated farms in the watersheds of Bladzikowski Stream (BS), Gizdepka river (G) and Mrzezino canal (M).

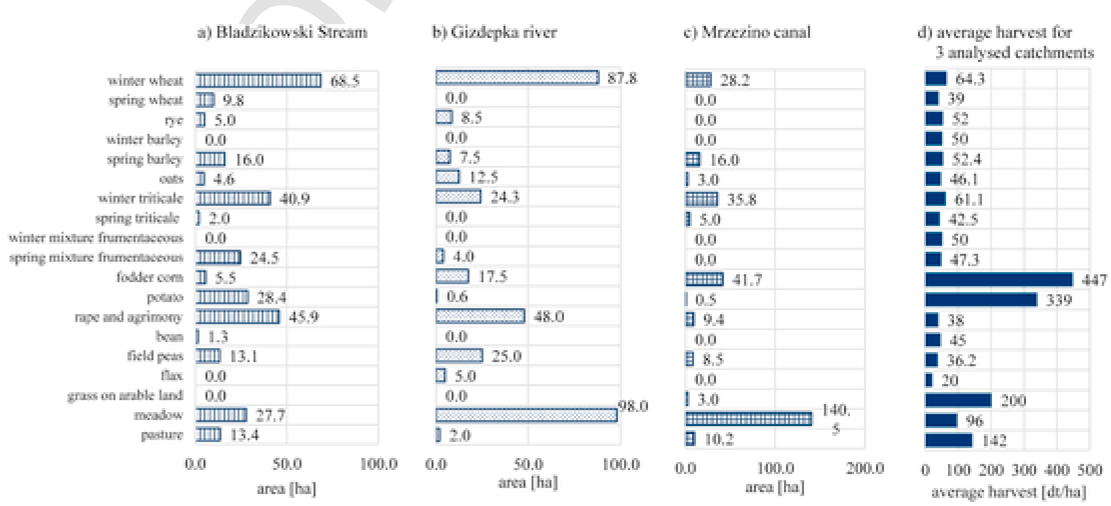

Fig. 7. Type and area of field crops and permanent grasslands in investigated farms for a) Bladzikowski Stream, b) Gizdepka river, and c) Mrzezino canal,d) Average harvest [decitonnesper hectare] of field crops and permanent grasslands in investigated farms for the entire catchment.

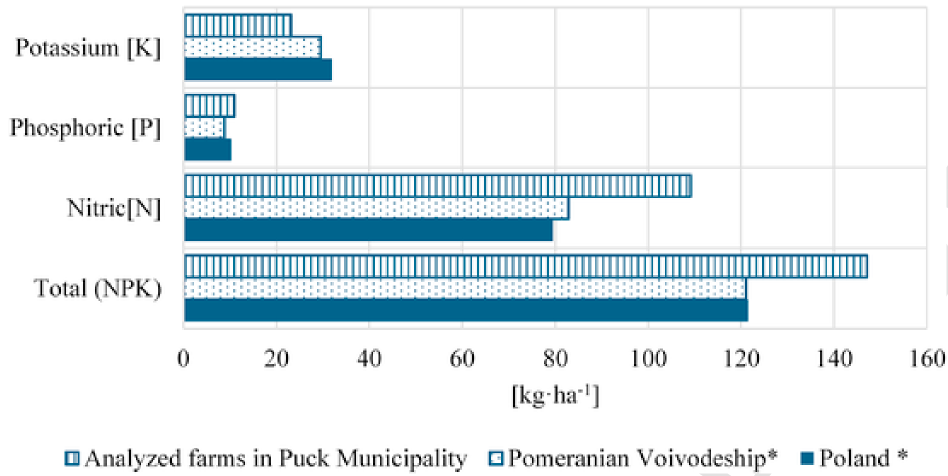

Fig. 8. Consumption of mineral fertilisers (calculated as a pure component) per 1 ha of agricultural land in the 2016/2017 marketing year (Source: Means of production in agriculture in the 2016/2017 marketing year - updated tables (Polish version), 0.21 MB. Website: https://stat.gov.pl/obszary-tematyczne/rolnictwo-lesnictwo/rolnictwo/srodki-produkcji-w-rolnictwie-w-roku-gospodarczym-20162017,6,14.html (access: May 16, 2018).

Table 2
Fertilisation periods in surveyed farms in three analysed watersheds.

Fertilizers	Months during the year											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Bladzikowski Stream												
Natural fertilizers			01.03								30.11	
Organic fertilizers									1.09		30.11	
Mineral nitrogen fertilizers		15.02									05.11	
Gizdepka												
Natural fertilizers			01.03								30.11	
Organic fertilizers												
Mineral nitrogen fertilizers			01.03							15.10		
Mrzezino												
Natural fertilizers			01.03								30.11	
Organic fertilizers												
Mineral nitrogen fertilizers			1.03				01.07					

fertiliser application in investigated farms in three analysed catchments are shown. The beginning and finishing dates were in compliance with obligatory regulations (Council of Ministers, 2018) in the Gizdepka river and Mrzezino canal catchments. In the case of the Bładzikowski Stream catchment, the fertilisation period started on 15th February and the finishing date of mineral fertiliser application also did not match to the obligatory 25th October.

3.2. Farm nutrient balance study results

The farm nutrient balance performed for 20 farms in the analysed watersheds (Table 3) showed a very broad range with max values for N – 233 kg/ha (in Gizdepka catchment) and for P – 24.9 kg/ha (in Bladzikowski Stream catchment). In 3 of the 20 analysed farms, consumption of N in mineral fertilisers exceeded the 170 kg N/ha recommended in the ("Nitrates Directive," 1991). The average N and P surpluses for surveyed farms were equal to 96.4 kg/ha and 4.4 kg/ha, respectively, while the highest mean and median N surplus was found in the Gizdepka river catchment (Table S2).

The N surplus, expressed in [kg/ha], was above the mean value at 5 farms located in the catchment of Bladzikowski Stream, 3 farms in the catchment of Gizdepka river and in 2 farms in the Mrzezino canal catchment. Regarding the P surplus expressed in [kg/ha] – the values above mean occurred at 4 farms in the catchment of Bladzikowski Stream, at 2 farms at Gizepka river catchment and at 2 farms in Mrzezino canal catchment. Please compare Table S2 (in the supplement) showing nutrient consumption and nutrient surplus at each of the analysed 20 farms. Some farms reported both N and P surplus, but in some other farms only one nutrient was above the mean value. In Mrzezino canal catchment only at one farm both surplus N and surplus P occurred; this one farm actually influenced the mean vale for the catchment (please note high SD value for this catchment in Table 3). It is worth noting that the nutrient surpluses for this one farm in the catchment of Mrzezino canal were highest for all 20 farms analysed within our study. In the catchments of Bladzikowski Stream and Gizdepka river there were more farms exhibiting nutrient surplus values above mean (8 out of 10 farms in BS catchment and 4 out of 6 in G catchment).

3.3. Concentrations of nutrients in streams and drainage ditches

In Fig. 9 box-plot charts for nutrient concentrations: N_{tot}, N–NO_3, N–NO_2, N–NH_4, P_{tot}, P_{min} in the Bladzikowski Stream, Gizdepka river and Mrzezino canal are presented. The seasonal changes of nutrients are presented in Figs.S1-2. The box-plot charts for nutrient concentrations in the drainage ditches of the three analysed watersheds are shown in Fig. 10.

Table 3
Characteristic values of farm nutrients balance and surplus of N and P in Bladzikowski Stream, Gizdepka river and Mrzezino canal (Min - minimum value in analysed farms; Max - maximum value in analysed farms; SD – standard deviation).

Catchment		Mineral fertilisation per unit of cultivated area			Surplus			
		N, kg/ha	P, kg/ha	K, kg/ha	Surplus N kg/ha	Surplus N kg	Surplus P kg/ha	Surplus P kg
Bladzikowski Stream	Min	16.3	1.3	4.2	5.8	323	−13.0	−732
	Max	172	24.9	58.4	147	5283	21.6	505
	Mean	111	12.5	29.9	89.5	2337	5.2	13.61
	Median	135	13	30	93.3	1708	4	60.1
	SD	45.1	6.6	15.9	41.9	1682	9.8	322
Gizdepka river	Min	0	0	0	−23.3	−501	−4.2	−179
	Max	233	17.4	32.9	203	26,383	17.8	494
	Mean	113	7.1	13.4	110	8511	3.8	103
	Median	113	7.2	13.5	106	3568	0.0	53
	SD	75.6	6.1	11.6	77.6	9513	7.7	235
Mrzezino canal	Min	55.8	7.3	13.7	−14.3	−1394	−17.1	−445
	Max	161	22.9	46.9	255	30,029	26.6	3136
	Mean	104	13.3	26.0	92.7	9207	3.5	761
	Median	99.2	11.5	21.6	65.2	4097	2.2	177
	SD	38.1	6.2	13.2	105	12,522	16.2	1431

The highest average concentrations of total N and total P were observed in Bladzikowski Stream – 3.52 mg/L and 0.34 mg/L, respectively. Also mean nitrate $N–NO_3$ concentration was highest in BS (2.33 mg/L), as well as $N–NH_4$. The maximum concentrations during the measurement period in BS were as follows: 8.68 mg/L N_{tot}, 7.55 mg/L – $N–NO_3$, 0.58 mg/L $N–NH_4$, 1.89 mg/L P_{tot} and 0.45 mg/L – P_{min}. Since cultivated land was the dominant form of land use in the catchment of the Bladzikowski Stream (85%), the highest nutrient concentrations in this watercourse were expected. Quite surprisingly, the second highest mean N species concentrations were found in Mrzezino canal, with only 49% of cultivated land, not in Gizdepka river (70% of cultivated land). The average N_{tot} concentration in Mrzezino canal was 1.88 mg/L vs 1.53 mg/L in Gizdepka. Also, average concentrations of $N–NO_3$, $N–NO_2$ and $N–NH_4$ were higher in Mrzezino canal than in Gizdepka. Average N species concentrations were lowest in Gizdepka river despite the highest consumption of N fertilizers in the farms located in its catchment, reported in the questionnaires. On the other hand, the mean and median N surpluses in the farms located in Gizdepka catchment were lowest. Relatively high N species concentrations detected in Mrzezino canal can be explained by low flow rate and periodically delayed outflow to the Bay of Puck. As a result, Mrzezino canal was more like a drainage ditch with stagnating water, which can account for elevated nutrient concentration more typical for drainage and tillage systems. Another factor that could have potentially caused elevated concentrations in Mrzezino canal is highest average slope of its catchment, encouraging nutrient loss through leaching. Regarding mean P_{tot} and P_{min} concentrations, the lowest values were found in Mrzezino canal while the highest concentrations were detected in Gizdepka, despite lowest mineral P supply with fertilisers and lowest P surplus in Gizdepka catchment.

Drainage ditches are the direct receivers of the field runoff and underground tiles (Kleinman et al., 2015). Together with small gradients and flow rates, this usually leads to high nutrient concentrations. In addition, the nutrient concentrations in the ditches respond quickly when fertilisation is applied to cultivated land, which is reflected by a high variability range of nutrient concentrations shown in Fig. 10. The observed nutrient concentrations in ditches are generally higher than those in watercourses, with surprisingly high mean concentrations of N_{tot}, P_{min}, and P_{tot} found in the ditches located in Gizdepka watershed (17.4 mg/L, 1.26 mg/L and 1.50 mg/L, respectively), along with $N–NO_3$ mean concentration of only 2.0 mg/L.

3.4. Relationships between the analysed parameters

In Table 4, correlations between flow rates (Q), rainfall amount in the period of 30 days (RD) and 7 days (RD-7) before the sampling took place, and concentrations of nutrients in the three watercourses are presented. Statistically relevant correlations were found between concentrations of $N–NO_3$ and P_{min} and rainfall height (RD and RD-7) as well as flow rates for the Bladzikowski Stream (Q/BS) and Gizdepka (Q/G). No correlations between nutrient concentrations, flow rate (Q/M) and precipitation were found in Mrzezino canal. This seems to be in agreement with the observations regarding water stagnation in the canal along with elevated nutrients concentrations. No relevant correlations were found between concentrations of N_{tot} and P_{tot} and precipitation or flow rate in any of analysed watercourses.

PCA analysis results are presented in Figs. 11–13. PCA showed that correlations exist between the nutrient surpluses and nutrient concentrations in streams and/or drainage ditches: in the Bladzikowski Stream catchment, mean N_{tot} concentration in the watercourse was correlated to N surplus, while consumption of N fertilisers was related to N_{tot} concentration in drainage ditches. Phosphorus surplus affected both concentrations of P_{tot} in drainage ditches and in the Stream. In Gizdepka catchment there were correlations between consumption of N fertilizers (highest among analysed watersheds), N surplus and N_{tot} concentration in the river. Consumption of P fertilisers affected P_{tot} concentration in Gizdepka, while a P surplus was correlated to P_{tot} concentration in drainage ditches. Concentrations of N_{tot} in Mrzezino canal as well as in drainage ditches in its watershed were correlated to N surplus. There was also a correlation between the consumption of P fertilisers, surplus P, and P_{tot} concentration in the Mrzezino canal. Concentrations of $N–NO_3$ and P in the soil (Table S3–S5) did not affect the nutrient concentrations in drainage ditches and in the watercourses.

To summarize, the surplus N was correlated to the N_{tot} concentration in all watercourses. Surplus P was correlated to P_{tot} concentration in drainage ditches (BS, G) and P_{tot} concentration in the watercourse (BS, M). No correlation was found between surplus P and P_{tot} concentration in Gizdepka, however there was a strong correlation between surplus P and P_{tot} concentration in drainage ditches in this

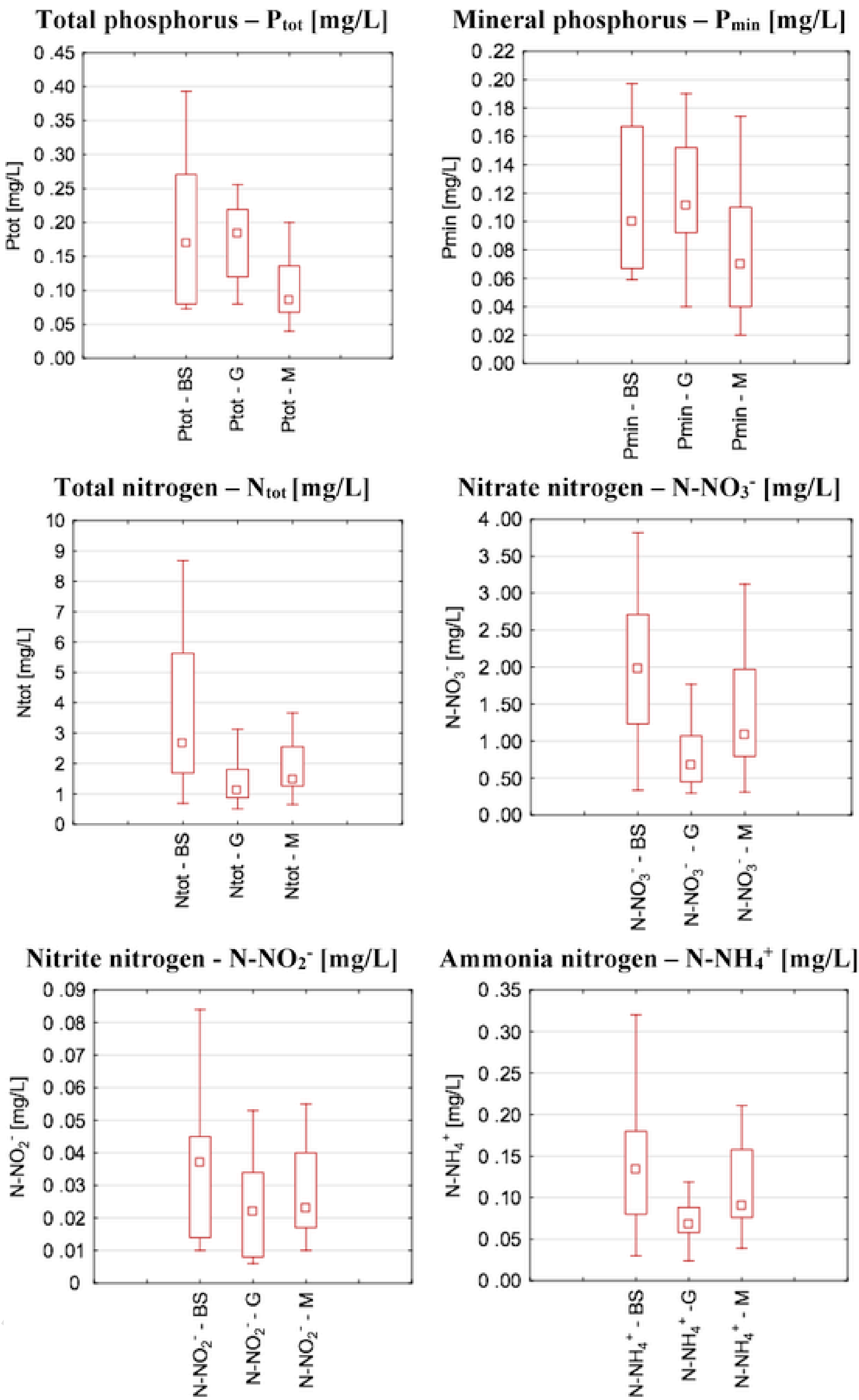

Fig. 9. Box-plot charts presenting nutrient concentrations [mg/L] in Bladzikowski Stream (BS), Gizdepka river (G) and Mrzezino canal (M).

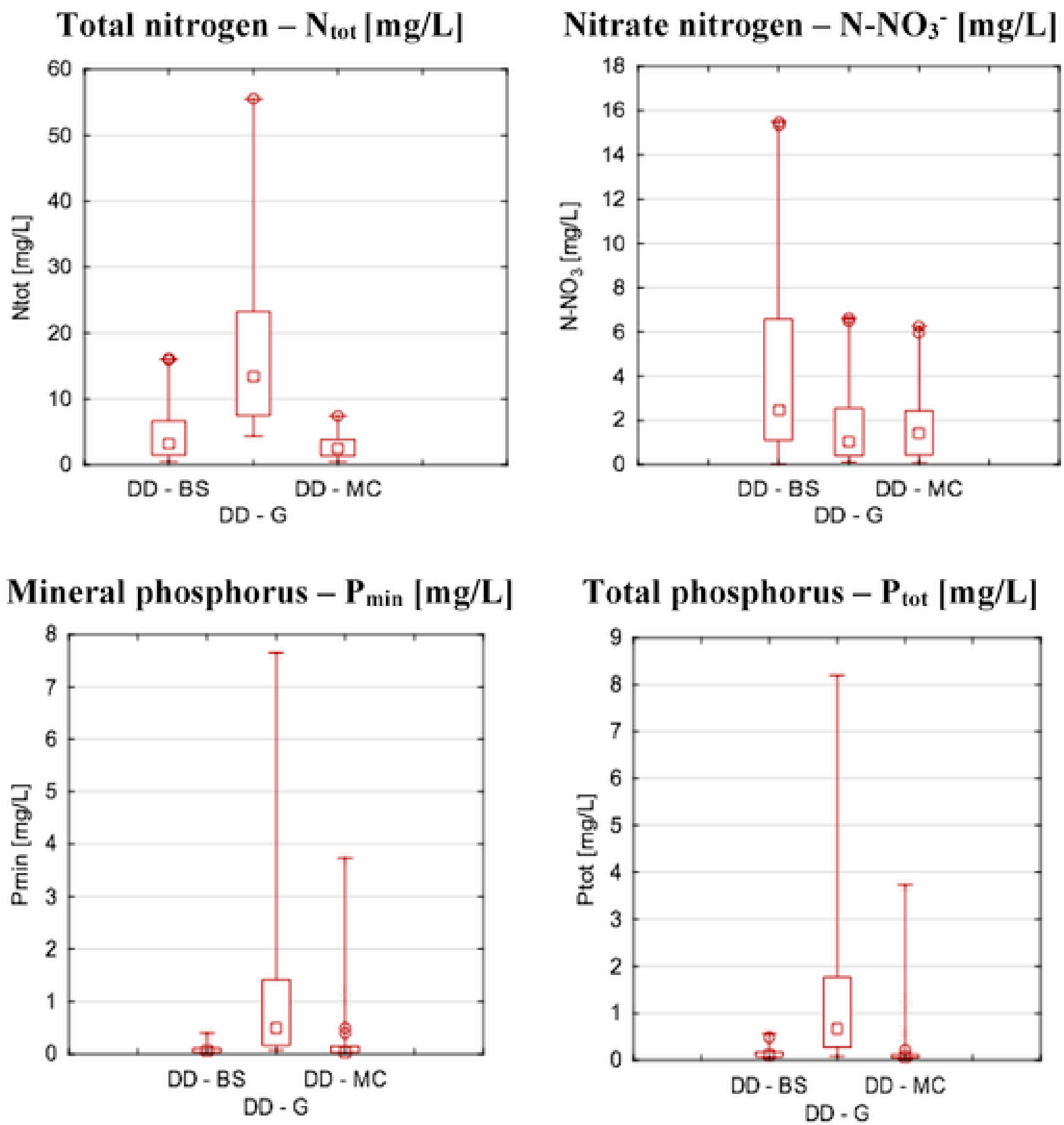

Fig. 10. Box-plot charts presenting nutrient concentrations [mg/L] in drainage ditches located in Bladzikowski Stream (DD-BS), Gizdepka river (DD-G) and Mrzezino canal (DD-M) watersheds.

Table 4
Correlation between nutrients (in the form of N_{tot}, $N–NO_3^-$, P_{tot} and P_{min}) and rainfall amount (RD) and flow rate (Q) in Bladzikowski Stream (BS), Gizdepka (G) and Mrzezino (M).

	Bladzikowski Stream (BS)				Gizdepka (G)				Mrzezino (M)			
	N_{tot}	$N–NO_3^-$	P_{tot}	P_{min}	N_{tot}	$N–NO_3^-$	P_{tot}	P_{min}	N_{tot}	$N–NO_3^-$	P_{tot}	P_{min}
RD	0.25	0.55	0.25	0.61	0.24	0.54	0.05	0.78	−0.09	−0.08	−0.21	0.03
RD-7	0.25	0.55	0.25	0.61	0.25	0.54	0.05	0.78	−0.09	−0.08	−0.21	0.03
Q/BS	0.37	0.64	0.26	0.68								
Q/G					0.37	0.64	−0.11	0.68				
Q/M									−0.13	−0.11	−0.19	0.26

RD - rainfall amount, measured for 30 days preceding rainfall; RD-7 - rainfall amount, measured for 7 days preceding rainfall; Q – flow rate [m^3/s]; Q/BS – flow rate Bladzikowski Stream [m^3/s]; Q/G – flow rate Gizdepka [m^3/s]; Q/M – flow rate Mrzeino canal [m^3/s].

watershed. This may indicate higher retention of P in Gizdepka watershed. Gizdepka is the longest of the analysed streams (10.4 km) and it has the largest watershed (31.5 km^2); it also has a smaller slope than Bladzikowski Stream (Table 1). All these factors can be of significance and may explain higher P retention in this particular watershed.

4. Discussion

4.1. N and P riverine concentrations

The mean N concentrations in the investigated watercourses in the Puck Municipality – Gizdepka river and Mrzezino canal, were lower

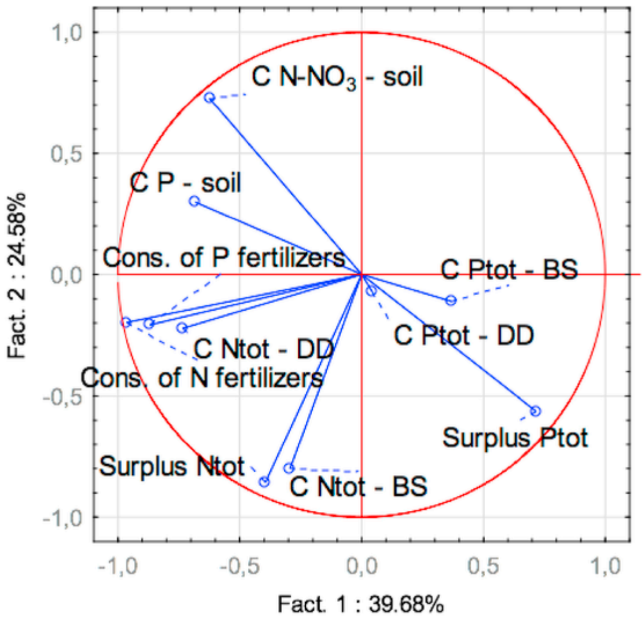

Fig. 11. Correlations between concentrations of nutrients in stream (C Ptot – BS, C Ntot – BS), drainage ditches (C Ptot – DD, C Ntot-DD), soil (C P – soil, C N–NO_3-soil), fertiliser consumption and surplus nutrients in Bladzikowski Stream catchment.

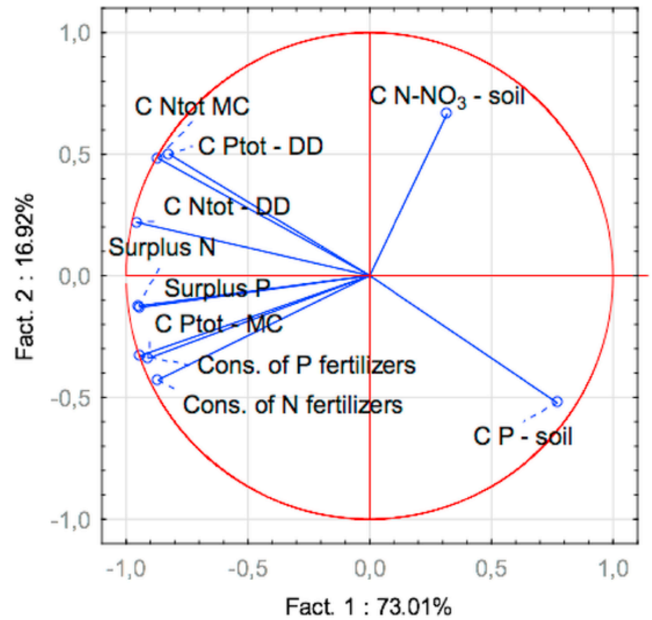

Fig. 13. Correlations between concentrations of nutrients in stream (C Ptot – MC, C Ntot – MC), drainage ditches (C Ptot – DD, C Ntot-DD), soil (C P – soil, C N–NO_3-soil) and fertiliser consumption and surplus nutrients in Mrzezino Canal catchment.

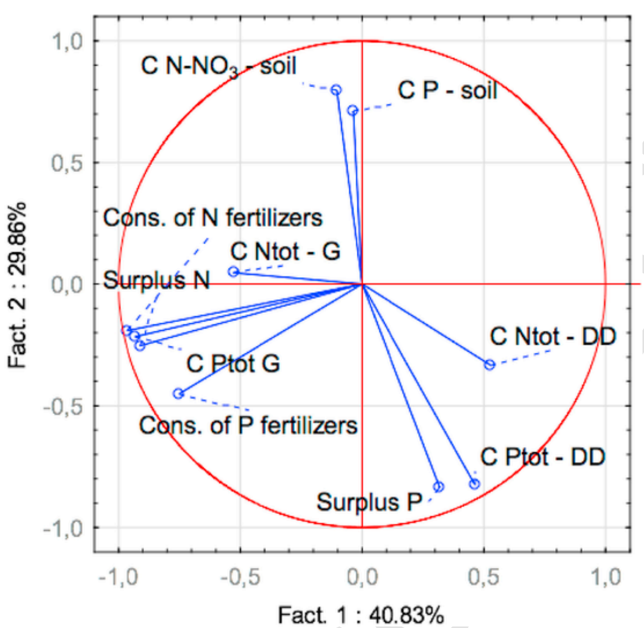

Fig. 12. Correlations between concentrations of nutrients in stream (C Ptot – G, C Ntot – G), drainage ditches (C Ptot – DD, C Ntot-DD), soil (C P – soil, C N–NO_3-soil) and fertiliser consumption and surplus nutrients in Gizdepka catchment.

(G – 1.53 mg/L and M – 1.88 mg/L) than mean concentrations in major Polish rivers Vistula and Oder in 2016 (2.3 mg/L and 3.3 mg/L, respectively) (Chief Inspectorate for Environmental Protection, 2018). However, the average N concentration in the Bladzikowski Stream (3.52 mg/L) was obviously higher. The dominant form of nitrogen was nitrate nitrogen N–NO_3 constituting about 81–82% of N_{tot}, which is typical of streams flowing through agricultural watersheds (Dąbrowska, 2008; Wojciechowska et al., 2018). According to EEA reports, N_{tot} concentration around 3.6 mg/L is found in a high proportion of rivers in several European countries: Germany, Belgium, large parts of France, and Spain. In northwest France, southeast United Kingdom, and northern Spain, with intensive agriculture and high population density within the catchments, the nitrate concentrations over 5.6 mg N/L are quite frequent. On the other hand, in the northern part of Europe – Scandinavia, Scotland, Ireland, and in the mountainous regions (the Pyrenees, the Alps, the Apennines), markedly lower nitrate concentrations of 0.8 mg/L are typical. Taking a closer look at the range of N_{tot} concentrations obtained during our investigations, it can be observed that the lowest measured values (0.051 mg/L in G, 0.065 mg/L in M and 0.069 mg/L in BS) are on similar level as the mean values for Scandinavian rivers (Stålnacke et al., 1999), while the maximum concentrations are similar (Gizdepka river, Mrzezino canal) or even higher (Bladzikowski Stream) than the values reported for intensively cultivated and populated European catchments.

Regarding phosphorus, the EEA again reports relatively low concentrations in freshwater in northern Europe: Scandinavia, Scotland, Wales and Ireland, as well as in other regions of low population density and good status of wastewater collection and treatment. In the report, P_{tot} concentrations higher than 0.1 mg/L are regarded as relatively high. Such concentrations are reported in the regions with high population densities and intensive agriculture: south-eastern UK, Netherlands, Belgium, western Germany, northern France, southern Europe (north-eastern Spain and Italy, mid-Portugal), eastern and south-eastern Europe. The mean P_{tot} concentrations observed in Polish rivers (Ławniczak et al., 2008; Dąbrowska et al., 2017), also in the investigated watercourses in the Puck Municipality, are markedly higher than 0.1 mg/L (ca. 0.15 mg/L for Vistula and 0.2 mg/L for Oder) (Chief Inspectorate for Environmental Protection, 2018). According to Jarvie et al. (2006) natural riverine P concentration is around 0.02–0.03 mg P/L.

A question arises if the obligatory requirements on nutrient concentrations in Poland are adequate in the context of Baltic Sea eutrophication status as well as BSAP goals. According to the Ministry of Environment regulation of 16th July 2016 (Ministry of the Environment, 2016), following the requirements of the Water Framework Directive (WFD), and with respect to the river type (type 21 according to WFD), the concentrations of N_{tot} and P_{tot} below 3.2 mg/L and 0.20 mg/L, respectively, are regarded as the first class of water quality (very good environmental status). The second class, corresponding to good environmental status, requires N_{tot} below 4.9 mg/L and P_{tot} below 0.30 mg/L. If these requirements are not fulfilled, waters are classified as III, IV or V class – in other terms, poor ecological status. It could be of interest to compare Polish regulations to those obligatory in other countries. In the UK, 0.1 mg P/L is generally considered as III class water. The Irish regulations are even more restrictive – waters containing more than 0.07 mg P/L are considered as polluted (Trząski et al., 2010). According to the European Environment Agency (2019) P_{tot} concentrations over 0.1–0.2 mg P/L are sufficiently high to cause freshwater eutrophication. With regard to BSAP objectives as well as CART set for Poland, the average nutrient concentrations in rivers should be approximately on the level of 2.5 mg N/L and 0.07 mg P/L, assuming average riverine outflow of 61.5 km^3 per year from the territory of Poland. In this context, the present first and second class quality concentrations seem rather high. On the other hand, Pastuszak et al. (2018) state that the target riverine P_{tot} concentrations are close to those in pre-industrial times, with substantially lower population and agricultural production and are unrealistic to obtain in a densely populated and agriculturally-oriented country.

4.2. Agricultural practices in the analysed watersheds

Assessment of nutrient concentrations in the analysed rivers results in the conclusion that although the concentrations generally fulfil Polish national regulations as well as WFD, they are too high in the context of meeting BSAP requirements. In the next step, we focused on agricultural practices in the watersheds to find out if they comply with the standards of Nitrates Directive and Codes of Good Agricultural Practice (CGAP). Firstly, we analysed fertiliser usage to see if it is at an appropriate level and how it affects the nutrient surpluses.

Consumption of mineral fertilisers in the three analysed watersheds (109 kg/ha) was higher than Poland's average (80 kg N/ha). For the reference period 2012–15 the average fertiliser consumptions in some other Baltic states were as follows: ca. 75 kg N/ha in Germany; ca 80 kg N/ha in Denmark, over 100 kg N/ha in Norway; around 30 kg N/ha in Sweden and Estonia (European Environment Agency, 2018). It can be stated that Poland's average is on reasonable level among countries in the region, while the fertilisers consumption in the analysed catchments could be lowered. Probably, the value could be affected by high precipitation in summer 2017 which caused washing of fertilisers and forced the farmers to use extra fertilisation doses. We confirmed correlations of N–NO_3 and P_{min} and rainfall amount for Gizdepka and the Bladzikowski Stream that were also reported by Shi et al. (2017). N and P surpluses in agricultural production were strongly related to the emission of nutrients to rivers (Oenema et al., 2005; Castaldelli et al., 2015; Zalidis et al., 2002). In our study, we also confirm such correlations in all analysed catchments. The surplus of nitrogen in EU countries shows a decreasing trend, dropping by 18% from an average 62.2. Kg/ha in the period 2000–2003 to 51.1. Kg/ha in the years 2012–2015 (European Environment Agency, 2018). In Poland the nutrient surpluses in the period 2008–2010 varied in the range 53.8–62.7 kg/ha for N and from 3.6 kg/ha to 7.2 kg/ha for P. In our study, the nutrient surpluses in the analysed farms were highly dispersed, however average and median values were higher than the EU mean in case of N (96.4 kg/ha), and markedly lower in case of P (4.4 kg/ha). Again, this indicates that there might be some potential for decreasing N fertilisation. On the other hand, P loads from Polish territory seem to be the issue of major concern, especially in the view of the BSAP targets. Since P surpluses in the analysed catchments were on rather low level, so further abatement would be a difficult task with potentially high costs for the farmers. Vibart et al. (2015) estimated the costs of several strategies to reduce N and P losses on the scale of a single farm for the region Southland region in New Zealand. Depending on the adopted abatement strategy, the costs for farmers, calculated as loss of income, varied from 10 to 70 NZD (5.80–40.85 EUR) per 1 ha of farm area. The highest costs were shouldered by farms with livestock breeding. According to Helin et al. (2006) the costs of a 50% reduction in N load generated by agriculture in Finland varied between 2752 and 3756 EUR per farm. In a recent study by Marshall et al. (2018) it was shown that a 45% Na and P reduction from agriculture for the catchment Mississippi/Atchafalaya catchment would require subsidies of 5.48 USD (4.89 EUR) per pound of N and 13.5 USD (12 EUR) per pound of P.

Adaptation of Polish national law to full compliance with the Nitrates Directive includes further implementation of CGAP, which sets limits on maximum nutrient input with fertilisers, forbids fertiliser application on steep slopes, frozen or snow covered soil and near the watercourses, limits the periods when nitrogen fertilisers can be applied on land and recommends crop rotation as well as after-crops and winter crops to minimise nutrient losses by leaching in wet seasons. Analysing the agricultural practices in the farms investigated in our study, most of them were following these instructions, though some improvements can be done. Three of the surveyed farms exceeded the maximum recommended N input with fertilisation. In case of the Bladzikowski Stream catchment, fertilisation was started earlier than allowed (15th February instead of 1st March) and lasted until 5th November instead of 25th October. Crop rotation was used in the vast majority of analysed farms. The major disparity regarded after-crops and winter crops, which were used only in 19.4% of farms. In this field, the progress should be made to prevent nutrient losses from soil due to leaching, in the view of the fact that concentrations of P_{min} and N–NO_3 in Gizdepka and Bladzikowski Stream showed relevant correlations with precipitation. Following the recommendations of the CGAP seems even more important in the analysed watersheds due to steep slopes, making leaching of nutrients more likely (Dzierzbicka-Glowacka et al., 2019), in contrast with the majority of Polish territory, since 87% of Poland is flat with terrain slopes below 0.3%. Also, direct impact of the nutrients fluxes from the watercourses on the eutrophication-sensitive Bay of Puck is of significance (Zima, 2019).

4.3. Further potential steps and research needs

According to the HELCOM (2018) the nutrient loads from Poland are characterised by comparatively large proportions from agriculture (45% N and 34% P) and from point-sources (31% N and 42% P). Analysis of agricultural practices in three Pomeranian watersheds shows that they generally comply with CGAP. Some minor corrections could and should be done, although their potential for nutrient mitigation does not seem sufficient to reach the target riverine N_{tot} and P_{tot} concentrations (2.5 mg N/L and 0.07 mg P/L resulting from CART). It seems that present requirements set in CART are unrealistic to be fulfilled without implementing some extra measures to support existing ones. Therefore, there are urgent and important questions that need to be answered as to whether any further reduction of the nutrients inflow from agriculture in Poland is feasible, what abatement measures should be undertaken and what would the economic cost be. Wustenberghs et al. (2008) analysed the cost-effective measures for the abatement of nutrient emission from agriculture in Flanders, concluding that increased dairy cattle efficiency, sowing winter cover crops and reducing nutrient content in pig forage turned out to be most cost-effective measures. Some extensive nutrient abatement cost studies for the Baltic Sea region were published by Gren et al. (1997) and Elofsson (2001). They showed that the most cost-effective measure for P reduction was an improvement in wastewater treatment technology, while in the case of N abatement waste water treatment plants, the restoration of wetlands and measures directed towards the agricultural sector played an almost the equal role. Analysing allocation of costs between countries, both studies concluded that Poland, with its large population and agricultural land use, should bear the highest abatement costs among the Baltic states. Recently, Wulff et al. (2014) estimated that 50% of the HELCOM load reduction cost equal to 4.7 10^9 EUR annually is shouldered by Poland and this causes understandable objections (Pastuszak et al., 2014, 2018).

Further possible abatement strategies include establishing better control and treatment of wastewater in rural areas as many abatement studies indicate the high cost-efficiency of such strategies (Wustenberghs et al., 2008). However, in the light of high share of P emitted from point sources in Poland, careful monitoring of the effluent quality, especially in case of small WWTPs (serving 2000–10,000 person equivalent), followed by introduction of increased nutrient removal at those facilities that do not comply with the effluent standards would be of importance. In the light of the findings of the study performed by Kiedrzyńska et al. (2014) for the catchment of Pillica river, central Poland, wastewater in these small WWTPS is treated insufficiently, because the limits concentration of TP and TN were repeatedly exceeded. Secondly, constructed wetlands should be built for treating farm diffuse runoff (Ballantine and Tanner, 2010). Finally, counteracting soil erosion by fit-for-purpose agro- and phyto-techniques and mitigation of diffuse nutrient fluxes by buffer strips along river beds (Kiedrzyńska et al., 2014; Vymazal and Dvořáková Březinová, 2018) is of high relevance, since soil erosion was identified as the major source of phosphorus, constituting around 30% of P load carried by major Polish rivers (Pastuszak et al., 2014).

5. Conclusions

The analysis of agricultural practices and input of nutrients from 3 small first-order agricultural watersheds in Pomerania region (Poland), into the Bay of Puck was the main purpose of this paper. The goals of the BSAP and CART were taken into account to check the feasible implementation and progress towards agricultural nutrient mitigation. The mean N_{tot} concentrations in the analysed watercourses ranged from 1.53 mg/L for Gizdepka river to 3.52 mg/L for the Błądzikowski Stream. These values were similar to other rivers in central Europe with medium-intensive agricultural land use in the catchments. However, the mean P_{tot} concentrations in the analysed watercourses were markedly higher than 0.1 mg/L. In general, the target riverine concentrations, arising from CART (2.5 mg N/L and 0.07 mg P/L) were not reached; specifically reaching the target P_{tot} concentration seems to be problematic. Especially important for the present agricultural state in Pomerania is that appropriate agricultural practices are used with some minor corrections to be made specifically towards the reduction of N fertilisation and sowing after-crops. To summarize, the statistical analysis (PCA) indicated that fertiliser consumption and nutrient surpluses were directly linked to the mean nutrient concentrations in watercourses draining the catchments with dominant agricultural land use. Average P surpluses were generally lower than the Polish and EU average. Correlations were confirmed between precipitation and concentrations of nutrients in watercourses, pointing out the need for measures counteracting nutrient losses through leaching and erosion. Forward-looking implementations and perspectives that can improve the quality of surface runoff receivers from fields and prevent erosion include all kinds of Green Infrastructure applications such as constructed wetlands and buffer strips along river beds.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.109637.

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