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Estimated Contribution of Selected Non-point Pollution Sources to the Phosphorus and Nitrogen Loads in Water Bodies of the Vltava River Basin

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Abstract

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Eutrophication of inland waters by phosphorus as well as loads of coastal and marine waters by nitrogen is a major problem that impedes water bodies to meet the status defined by the Water Framework Directive. In order to reduce the nutrient load on the aquatic environment, first the significance of various pollution types should be thoroughly analyzed. The analysis of phosphorus runoff from agricultural land under normal rainfall-runoff conditions, and of nitrogen runoff associated with the application of manure on farmland shows their different impact on water body status in the Vltava river basin. The assessment of phosphorus indicates that annual specific phosphorus runoff ranges from 0.1 to 9.98 kg/km^2 and in the sub-basins of the Upper Vltava, Berounka, and Lower Vltava, the average values from all water bodies reach 4.08, 2.92, and 4.02 kg/km^2, respectively. Compared with the allowable capacity of water bodies for achieving a good status, the average rate of phosphorus input on the load of water bodies comes within 20%, with a maximum value slightly exceeding 50%. This phosphorus input will not be a significant source of eutrophication of inland waters and measures will have to focus rather on other eutrophication sources. Estimating the significance of the impact of manure application on the nitrogen load of water bodies provides a completely opposite picture. The analyses showed that the load of water bodies ranges from very low values in areas without livestock to high loads in tens of kg/ha per year (max. 31.5 kg/ha/year). In the sub-basins of the Upper Vltava, Berounka, and Lower Vltava the annual specific runoff of nitrogen reaches average values for all water bodies (4.8, 3.9, and 5.7 kg/ha, respectively). The assessment of the proportion of nitrogen input on the load of water bodies showed that 25% of cases in the area of the water body may represent a critical load leading to an adverse assessment of ecological status. In many other water bodies it can, however, taking into account the load of mineral fertilizers, lead to exceeding the allowable capacity of water bodies and the risk of not achieving a good status. Nitrogen input after application of manure in soils represents an important source that threatens the good status of waters. Attention should thus be paid to all types of measures that will reduce the load of this source or restrict its transport from soil to waters.

Keywords: eutrophication; nutrients; Water Framework Directive; water quality

Controlling eutrophication associated with input of phosphorus and nitrogen from anthropogenic sources is one of the main objectives of the Water Framework Directive (2000) (hereinafter WFD). Before WFD came into force, Member States were obliged to adopt the principle of two directives, which should have significantly controlled the flow of nutrients into water – the Urban Wastewater Treatment Directive (1991) and the Nitrate Directive (1991). Although these directives were adopted nearly 25 years ago, the measures taken so far in many areas of Europe were not able to stop the eutrophication of waters.

Eutrophication has a major impact on the aquatic community. While increased amounts of phosphorus

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lead to changes in the ecosystem of inland waters (Mason 1991), high nitrogen input mainly causes changes in the marine and coastal ecosystems (e.g. Tamminen & Andersen 2007).

Phosphorus load in surface waters, associated with massive eutrophication, has been documented since the 1950s. At first it was mainly associated with the discharge of sewage from towns and villages (e.g. Chapra & Robertson 1977), and later, after the introduction of effective ways to treat municipal sources, other sources were focused: the input from agricultural land and erosion (e.g Ekholm & Lehtoranta 2012). Despite the fact that many countries significantly reduced the waterload from point sources, the corresponding phytoplankton decline in water bodies did not follow (e.g. Bowes *et al.* 2012). The reason are the persisting high levels of phosphorus, which continue to allow phytoplankton to unlimitedly multipy (Reynolds & Davies 2001). Even in the Czech Republic, despite the considerable efforts that have been made to reduce phosphorus input into waters, the adverse conditions persist. In most water bodies the phosphorus concentrations are moderate or of worse status.

Significant nitrogen loads from anthropogenic sources in Europe and elsewhere in the world are reflected in the contamination of groundwater and surface waters; later this pollution contributes significantly to the eutrophication of transitional and marine waters (Howarth & Marino 2006). Many studies have documented that a decisive factor of nitrogen water pollution is intensive farming, which increases the concentrations of nitrates (e.g. Andersen *et al.* 2014). Despite a series of measures included in the Action Programme under the Nitrates Directive (1991), due to their mobility as well as a relatively high resistance to degradation the improvement in the state of waters in agricultural areas is very slow (Fraters *et al.* 2011).

The aim of the present study was to estimate the share of selected non-point sources of phosphorus and nitrogen in the total load of water bodies and to determine whether a good status of water bodies can be achieved by controlling nutrient inputs from these sources.

MATERIAL AND METHODS

Assessed areas and water bodies. The study area is situated in the south-western part of the Czech Republic and includes the Vltava river basin to its confluence with the River Elbe. From the perspective of the WFD, the area is divided into three river basins – the Berounka sub-basin, the Upper Vltava sub-basin, and the Lower Vltava sub-basin (Figure 1). The total area covers 27 869 km^2. The study area is managed by Povodí Vltavy, state enterprise, and is part of the International District of the Elbe river basin. Through the Elbe River, the Vltava river basin contributes to pollution of the North Sea. In the Vltava river basin, a total of 336 surface water bodies were identified, of which 309 belong to the category of river and 27 to the category of lake. All the bodies in the lake category are dams or ponds and can be considered as heavily modified water bodies. Seen from this perspective, the Upper Vltava sub-basin is specific, having a total of 11 units of the pond type. A more detailed information on the number of water bodies and their overall characteristics is listed in Table 1.

Types of assessed non-point pollution sources and nutrient input data. For the assessment the continuous input of phosphorus and nitrogen from agricultural land into waters was selected. The phosphorus input chosen was that which runs under normal rainfall-runoff situations and does not include episodic phosphorus inputs associated with erosion events. Phosphorus input data were derived from a Czech agricultural watershed monitoring conducted by the T.G. Masaryk Water Research Institute (Fiala & Rosendorf 2010; Fiala *et al.* 2013). The reason for using this procedure was that the phosphorus balance in Czech agricultural soils is very low, in some areas even zero. The concentration of total phosphorus expressed as the median value found for Czech soil types was 0.046 mg/l for 162 exclusively agricultural watersheds and 0.043 mg/l for twenty watersheds

Figure 1. Location of the Vltava river basin and the Upper Vltava, Berounka, and Lower Vltava sub-basins in the Czech Republic

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monitored monthly in 2007–2009 (Fiala *et al.* 2013). Rough estimates of yearly specific phosphorus runoff from the twenty watersheds ranged from 0.77 to 22.4 kg/km^2. Based on the above results, a table of characteristic phosphorus concentrations in runoff with respect to individual soil types was prepared (Krása *et al.* 2013). The characteristic values were also used herein to calculate the phosphorus runoff from agricultural soils in the Vltava river basin.

For nitrogen, the pollution input was selected (manure application into soils, their losses and runoff into groundwater and surface waters). The data on nitrogen produced by livestock collected for Czech cadastral units served as the data source (Klír *et al.* unpublished). The data used characterize the situation in 2009. The amount of nitrogen produced in the excreta was derived from the number of animals and the nitrogen production was related to a large livestock unit.

Procedure for quantifying nutrient inputs from non-point sources in the catchment area of water bodies. To quantify the runoff of total phosphorus, firstly all data on the agricultural land in the water bodies were selected from land use data of ZABAGED® (Pressová 2014). Based on the digital soil map (Němeček *et al.* 1996) each soil type in the study areas was assigned the characteristic concentration of total phosphorus (Krása *et al.* 2013). The annual input of phosphorus in the water body was calculated as a weighted concentration of phosphorus in agricultural soils and the average annual values of specific runoff in the water body derived from Horský *et al.* (1970). Because for the calculation of the phosphorus input characteristic concentrations from monitoring were used, it was necessary to reduce the value by the amount corresponding to the natural input. The natural input was calculated as the weighted concentration corresponding to natural conditions and the average annual value of specific runoff in the water body. Half of the limits for a very good status were used as characteristic concentrations of total phosphorus in natural conditions (Rosendorf *et al.* 2011).

To quantify the runoff of total nitrogen, firstly all data on the agricultural land in the water bodies were selected from land use data of ZABAGED® (Pressová 2014). Two agricultural land categories were defined: (*i*) intensively used agricultural land (arable land, hop fields, vineyards, orchards, and gardens), and (*ii*) other agricultural land (grassland). The inputs of manure from livestock were recalculated as follows: production of nitrogen from pigs was related to the area of intensively used land, production of nitrogen from cattle was related to the total land area in both categories, and production from goats and sheep was related to the area of other agricultural soils. According to total nitrogen balance and the nitrogen surpluses in the last 10–15 years (Klír *et al.* 2007), the overall reduction of the amount available for leaching on intensively used agricultural land was set at 30% and on the other agricultural land (meadows and pastures) it was set at 10%. Changes in nitrogen leaching into water are also influenced by the presence of subsurface drainage (e.g. Withers & Lord 2002). In soils with a subsurface drainage a rapid mineralization of fertilizers occurs and significantly enhances the nitrogen runoff which contributes to water pollution. The same fertilizers application rate on drained and undrained land leads to lower utilization of nutrients in drained soils and the risk of water pollution by nitrogen is higher (Procházka *et al.* 2009).

For this reason, an analysis of the presence of drainage (data AWMA 2009) was carried out and in the area of drained agricultural soils the reductions of nitrogen available for leaching were adjusted as follows: on intensively used agricultural land to 50% and on the other agriculturally used land to 25%. The resulting nitrogen runoff was derived, using spatial analysis, as a sum of inputs from agricultural soils in sub-basin water body after the afore-mentioned reductions.

Table 1. Descriptive characteristics of sub-basins and overall characteristics of water bodies in the Vltava river basin

River basin district	Catchment area (km^2)	Land use (%)					Water body category		Area of water body sub-basin (km^2)	
		woodland	arable	grassland	urban	water	river	lake	mean/median	maximum/minimum
Berounka	8 817	41.5	38.3	15.7	3.7	1.1	86	5	97/83	291/5.5
Upper Vltava	10 988	42.5	29.5	22.4	2.7	3.8	144	18	69/60	288/2.8
Lower Vltava	7 267	30.3	48.1	13.6	6.3	1.7	79	4	87/70	445/5.9

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Method of evaluating the significance of non-point pollution on loads of water bodies with nutrients. The significance of non-point pollution was assessed with respect to allowable phosphorus and nitrogen runoff in the sub-basin water bodies. The permitted capacity was determined by multiplying the allowable concentrations of phosphorus and nitrogen to achieve a right status and the annual runoff in the catchment area of a water body (Horský *et al*. 1970). Target values for the boundary between the good and moderate status of water bodies used in the second River sub-basin Management Plans (Table 2) were used as permitted concentrations. For the evaluation of the total nitrogen the sum of limits for nitrate and ammonium nitrogen was used.

The quantity of phosphorus and nitrogen for both types of non-point pollution in the sub-basin of the water body was compared with the allowable substance runoff and the result was classified according to load ratios as follows: (*i*) very significant – if the input of the substance amounted to more than 100% of the permissible substance runoff, (*ii*) significant – if the input of the substance amounted to more than 20% and less than 100% of the permissible substance runoff, (*iii*) not significant – if the input of the substance was less than 20% of permissible runoff. The results obtained were collectively assessed for each sub-basin of the Berounka, Upper Vltava, and Lower Vltava and statistically analyzed using the SPSS software (Version 10, 2000).

RESULTS

Phosphorus runoff from agricultural land. The values detected in all water bodies are in the range from 0.1 to 9.98 kg/km^2/year. When evaluating runoff in the three monitored sub-basins of the Upper Vltava, Berounka, and Lower Vltava, certain differences are apparent. On average, the least contaminated is the Berounka sub-basin, where the specific runoff ranges from 0.10 to 6.82 kg/km^2/year and the average value of runoff from all the water bodies is 2.92 kg/km^2/year. In the Upper and Lower Vltava, the average values of specific runoff do not differ significantly (4.08 and 4.03 kg/km^2/year, respectively). Also the identified ranges of values are very similar with a slightly higher maximum values in the Upper Vltava sub-basin (Figure 2). Figure 2 shows an obvious size distribution of specific phosphorus runoff in water bodies of the three sub-basins. While in the Upper Vltava sub-basin the graph shows a normal distribution with the highest number of water bodies in the range of 3.5 to 4.5 kg/km^2/year, in the Berounka sub-basin the categories of specific runoff in the range of 1.5 to 2.5 kg/km^2/year significantly prevail. In the intensively cultivated Lower Vltava sub-basin the histogram shows frequency waves with peaks in categories between 3.5 to 4.5 kg/km^2/year and lower between 1.5 to 2.5 kg/km^2/year. The areal distribution of phosphorus transported in runoff is shown in Figure 3. The highest values were observed at medium altitudes and in foothill areas that have still been intensively farmed. Due to the higher specific runoff they account for greater transport of total phosphorus. Conversely, the lowest value was found in lowland areas of the Lower Vltava and Berounka, where low value of specific runoff reduces the total phosphorus runoff. Despite some differences in the size of total runoff in the whole area, the total water pollution by phosphorus from agricultural land is low.

Table 2. Target values for the concentration of nutrients (phosphorus and nitrogen) for the selected types of water bodies and the boundary between good and moderate status according to the Water Framework Directive (2000) used for evaluation in the second River Sub-basin Management Plan of the Czech Republic (only types of water bodies assessed in the Vltava river basin are shown)

Indicator (mg/l)	Characteristic value	Water body type – river category (X-A-B-C)*													
		X-1-1-2	X-1-1-3	X-1-2-2	X-1-2-3	X-2-1-1	X-2-1-2	X-2-1-3	X-2-2-1	X-2-2-2	X-2-2-3	X-3-1-1	X-3-1-2	X-3-2-2	X-4-1-2
Total phosphorus	median	0.15	0.15	0.15	0.15	0.10	0.15	0.15	0.10	0.15	0.15	0.07	0.10	0.10	0.05
Nitrate nitrogen	median	4.50	4.50	4.50	4.50	3.80	4.50	4.50	3.80	4.50	4.50	3.40	3.80	3.80	3.40
Ammonia nitrogen	median	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.16	0.16	0.16	0.08

*description of the water body types: X-A-B-C: A – altitude (1: < 200 m, 2: 200–500 m, 3: 500–800 m, 4: > 800 m); B – geology (1: crystalline and volcanic rocks, 2: sandstones, claystones and Quaternary sediments); C – Strahler stream order (1: stream order 1–3, 2: stream order 4–6, 3: stream order 7–9)

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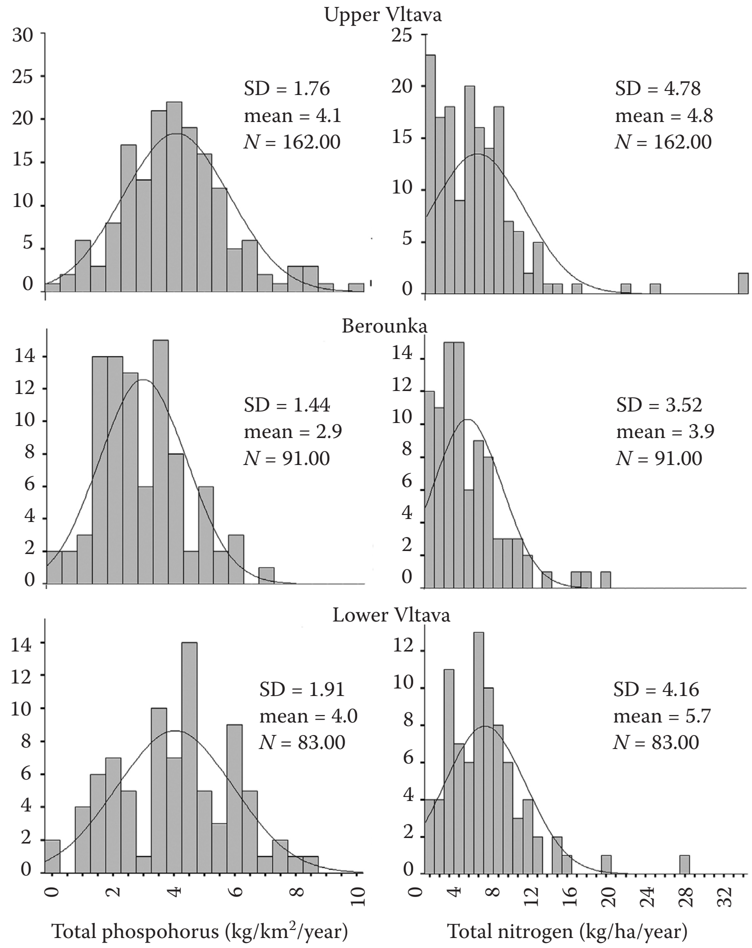

Figure 2. Frequency of distribution of annual specific runoff of total phosphorus (left) and total nitrogen (right) in the sub-basins in the Vltava river basin (SD – standard deviation)

Phosphorus runoff and load rate of water bodies. The obtained results of total phosphorus runoff in all water bodies were compared with an allowable capacity of water bodies. The results show that for the entire study area 258 water bodies reach less than 20% of allowable runoff capacity from a water body (Figure 4.) This represents some 70% of the assessed bodies. It was also found that in none of

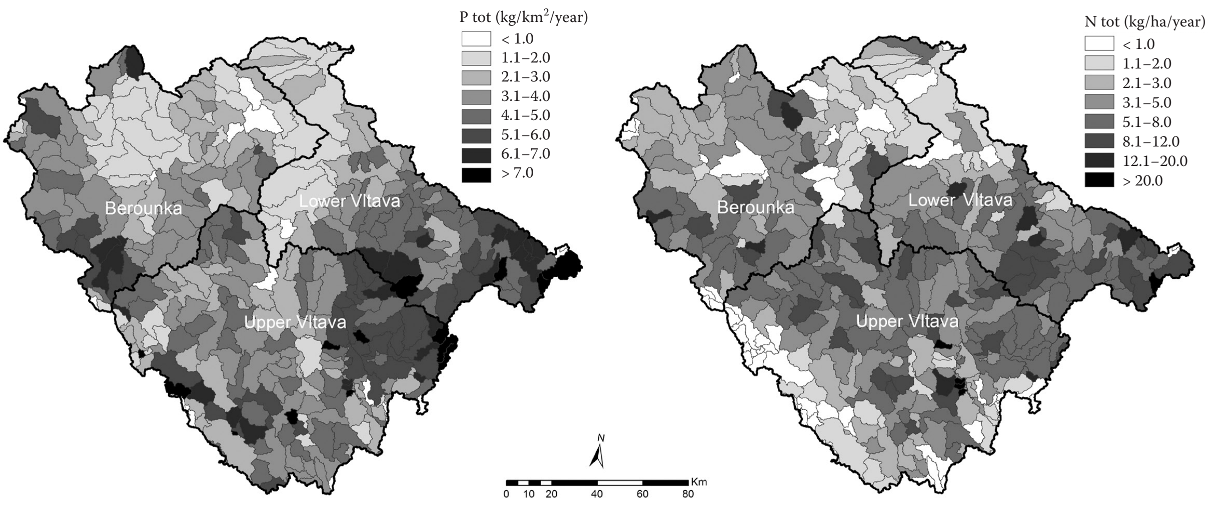

Figure 3. Annual specific runoff of total phosphorus (left) and total nitrogen (right) in the sub-basins of the Vltava river basin

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the evaluated water bodies the total phosphorus runoff reached the limit of 100% and therefore this type of pollution does not constitute a significant problem for achieving a good ecological status of the water bodies. The highest ratio (50.1%) of the runoff to the capacity of the water body was found in a water body in the pond area of the Upper Vltava sub-basin with frequent alluvial soils. A comparison of the three sub-basin areas assessed indicates that the lowest average ratio of body capacity was found in the Berounka sub-basin (15.3%) and the highest in the Lower Vltava sub-basin (17.8%).

Nitrogen runoff from agricultural land with manure application. Values of the specific total nitrogen runoff in the whole study area range from 0.0 to 31.5 kg/ha/year. When comparing runoff in the three monitored sub-basins, differences are obvious. On average, the least contaminated is the Berounka sub-basin, where the specific runoff ranged from 0.0 to 17.5 kg/ha per year and the average runoff value from all the water bodies is 3.9 kg/km^2/year. Although the largest range of specific runoff (0.0 to 31.5 kg/km^2/year) was detected in the Upper Vltava sub-basin, the average value of all water bodies was lower (4.8 kg/km^2/year) than in the Lower Vltava sub-basin (5.7 kg/km^2/year). The reason consists mainly in a higher non-point load of water bodies on the Lower Vltava with manure production, compared with the presence of a larger number of natural formations with low anthropogenic load in the Upper Vltava sub-basin. This fact is well documented by histograms in Figure 2. The distribution of the amount of nitrogen transported from agricultural land (Figure 3) shows that the greatest load can be expected at medium altitudes, where intensive agricultural land cultivating along with intensive livestock farming prevail. Typical areas include the Bohemian-Moravian Highlands, covering a larger part of the Sázava river basin (Lower Vltava), the area of the Lužnice right-hand tributaries (eastern part of the Upper Vltava), and the foothills of the Šumava Mts. in the Upper Vltava and Berounka sub-basins. A relatively low load of water bodies in the northern half of the Berounka basin corresponds to the prevailing livestock grazing in this area.

Nitrogen runoff and load rate of water bodies. The results of total nitrogen runoff in all the water bodies were compared with an allowable capacity of water bodies, which corresponds to the boundary between good and medium ecological status. The results show that only 64 water bodies reach less than 20% of the allowable capacity of the runoff from a water body (Figure 4) which represents 19% of all assessed water bodies. The most frequent is the category in which the load ranges from 20 to 100% of the allowable capacity for a good ecological status. These are 189 (56.3%) water bodies in the whole area. 83 water bodies represent the critical category in which the nitrogen runoff exceeds the allowable capacity of the water body for a good condition. It is thus apparent that in at least 25% of cases the nitrogen supply from manure in the area of formation alone represents the critical load, which will cause adverse ecological assessment. The individual evaluation of the sub-basins shows that the highest average nitrogen load is in the Lower Vltava (87%) and the lowest in the Upper Vltava (73%). This assessment shows that a number of water bodies, where the nitrogen load ranges from 20 to 100% of the allowable capacity, in concurrence with other anthropogenic inputs of nitrogen, exceed the allowable capacity and reach medium or worse status. The

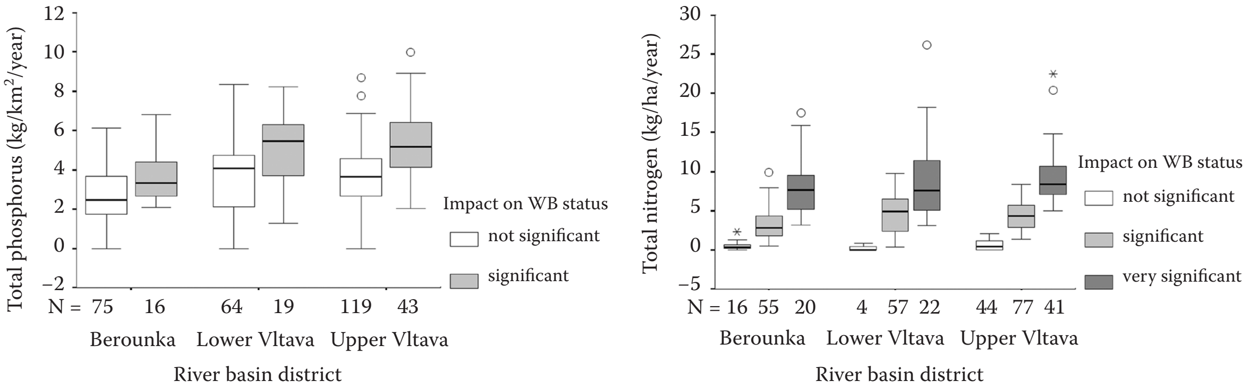

Figure 4. Evaluation of the impact of total phosphorus (left) and total nitrogen runoff (right) from assessed agricultural sources on the status of water bodies in the Vltava river basin (WB – water body)

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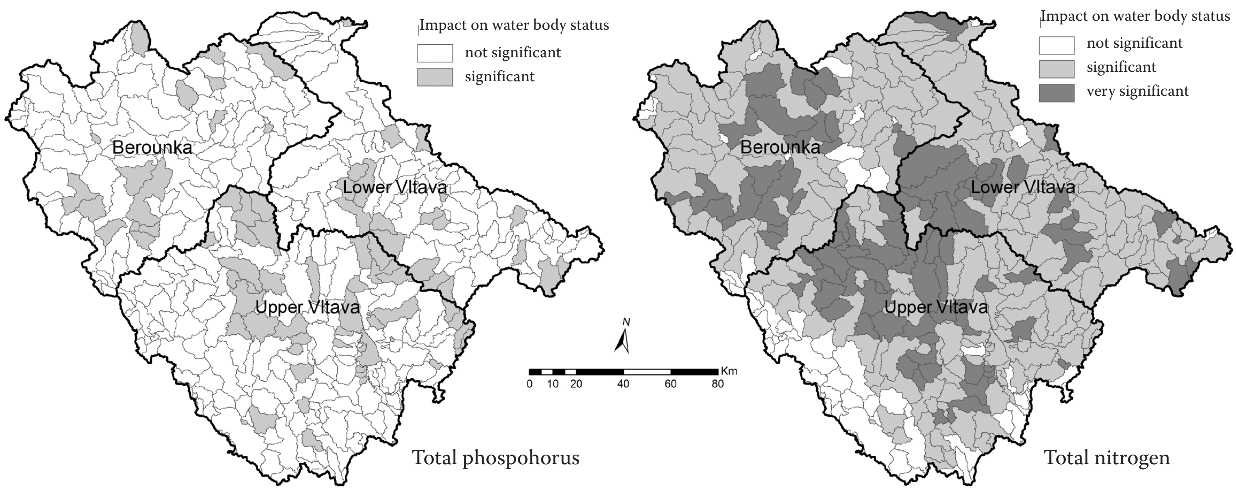

Figure 5. The level of impact of total phosphorus (left) and total nitrogen runoff (right) from assessed agricultural sources on the status of water bodies in the Vltava river basin

distribution of categories of impact on water body status is summarized in Figure 5. It clearly shows that the majority of the study area has a medium or high risk of increased nitrogen runoff into surface waters. Except the regions of the Šumava Mts. in the south of the Czech Republic and smaller areas in the central part of the country, the application of manure fertilizers and nitrogen runoff significantly impede achieving a good ecological status of surface waters.

DISCUSSION

The results obtained by estimating phosphorus runoff from agricultural land under normal rainfall-runoff conditions and nitrogen connected with the application of manure on agricultural land show a very different nature of both types of pollution. Phosphorus runoff is characterized by very low values, which range in the units of kg/km^2. Such load is comparable with natural runoff of phosphorus in anthropogenically-unaffected areas (Topcu *et al.* 2011). Similar results were also detected in an independent study by Fučík *et al.* (2010). Kyllmar *et al.* (2006) documented the phosphorus discharge in 27 Swedish agricultural catchments in the range of 10–90 kg/km^2. Only the lowest annual loads from this study are in a good correlation with our results. The average annual losses of phosphorus in Nordic and Baltic countries were documented in an extensive study of Vagstad *et al.* (2001). The values ranged from 10 to 47 kg/km^2 and were characterized by a large interannual and within-country variation. The high values were typical for catchments where soil erosion is a dominant pattern of phosphorus export. It is important to say that most of phosphorus runoff values reported in the current studies from agricultural catchments do not reflect reduction belonging to natural background phosphorus runoff. Therefore, the results can be compared to our study overestimated. Higher runoffs and thus a higher load of water bodies was in our study found only in water bodies with a higher occurrence of alluvial soils, where there may be a higher remobilization of phosphorus as concluded by Novotny (1995). Given that the Czech Republic permanently decreases the fertilization-induced supply of phosphorus into soils (Klement & Sušil 2012), the probability of the risk of phosphorus runoff from agricultural land in the following years is low. Results of our study are consistent with the hypothesis by Withers *et al.* (2014) that phosphorus inputs from agriculture are overestimated in a number of studies and their influence on the eutrophication is relatively small. Therefore, currently in the Czech Republic there is no need to apply any measures to reduce phosphorus runoff from agricultural land except for erosion runoff, and it is advisable to focus on the more significant input, mainly from municipal point sources.

Nitrogen runoff from agricultural areas associated with the application of manure is in most water bodies characterized by high values, which often significantly exceed the allowable capacity of water bodies. The risk associated with the application of manure is pointed out in Balík *et al.* (2012). Based on field experiment results they conclude that nitrogen from manure, in comparison with mineral fertilizers, is

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worse uptaken by plants and its surpluses are prone to leaching into groundwater and surface waters. The results documenting the high importance of this source of water pollution are supported by the designation of vulnerable zones in the Czech Republic (Hrabánková *et al.* 2012). Areas at risk identified in this study as very important are at the same time largely included in vulnerable zones. Despite the considerable uncertainty associated with the quantification of nitrogen runoff from agricultural land after application of manure, it is obvious that this source of pollution is a major obstacle to achieving a right status of water bodies in the study area. In order to reach a more considerable decrease of water pollution by nitrogen, it will be necessary to take targeted measures that will reduce the risk of leakage of nitrogen while applying manure, and prevent the transport of nitrogen from the soil into waters.

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