



# Multicriterial approach to the determination of buffer zones for the Moravian Karst protected landscape area in the Czech Republic

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**Abstract** Allogenic recharge is an important source of pollution affecting karst protected terrains. In order to prevent the introduction of contaminants and the deterioration of karst phenomena, it is necessary to determine buffer zones that require protection, which is sometimes difficult, especially in densely populated areas. A multicriterial approach for the determination of buffer zones was proposed and verified. The method combines two criteria to identify those watercourses whose catchments lying outside the protected area need to be protected, namely the water quality index and the mass flow of pollutants. The case study was performed in the Moravian Karst (Czech Republic), which is fed by more than 10 small allogenic watercourses. The study proved that not only water quality, but also mass flow of pollutants conditioned by watercourse discharge must be considered. This approach can be adapted for all types of protected landscape areas with water pollution originating in surrounding areas.

**Keywords** Allogenic watercourses · Karst protection · Mass flow of pollutants · Nutrients · Organic pollution · Water quality index

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## Introduction

Karst regions and caves are special places that require special management considerations often extending well beyond the formal boundaries of any protected areas in which the more obvious features occur (Watson et al., 1997). Due to its particular nature, this environment is highly susceptible to destruction and any interference is likely to have irreversible impacts (Ravbar & Šebela, 2015).

The integrity of any karst system is dependent upon the relationship between water, land, vegetation, and soil. There are two main recharge types in karst areas: autogenic recharge, i.e., precipitation falling directly onto the karst landscape and infiltrating through the soil and epikarst, and allogenic recharge, i.e., surface flow originating outside the karst area and sinking into the karst aquifer via swallow holes (Ford & Williams, 2007). In the latter case, the water and potential contaminants are transported over long distances from across the entire watersheds and introduced directly to the phreatic zone. This type of transport of pollutants is extremely fast (Watson et al., 1997; Kosič Ficco & Sasowski, 2018, Knez et al., 2011). The karst area is also highly sensitive to contamination due to high hydraulic conductivity and rapid infiltration, so it is necessary to pay attention to the quality of water flowing into this area (Kovarík et al., 2017; Lucon et al., 2018; Pereira et al., 2019). The maintenance of water quality in karst is becoming increasingly important in areas where the rural populations are well established and increasing rapidly. Wastewater

management in municipalities is, besides land use, one of the most important factors affecting water quality in surface streams (Watson et al., 1997; Hübelová et al., 2020).

Governments around the world regulate behavior toward the landscape surrounding protected areas (PA) differently. Some states, such as Brazil, clearly define these areas in their legal regulations and name them "buffer zones" (3 km around the PA). These are areas where any activity that may affect the biota must be licensed and authorized by the governmental agency responsible for the PA's management (Bellón et al., 2020). India approaches this in a similar way, naming these areas "zones of interaction" (ZOI). The size of a ZOI is decided individually on a case-by-case basis (DeFries et al., 2010). Slovenian protocol for karst source protection zone delimitation unifies two approaches: source vulnerability mapping and travel time criteria. Source protection zones are divided into three levels of protection (Turpaud et al., 2018). The regulations in the USA do not mention surrounding landscapes, nor do they provide any indication as to how those landscapes should be managed. However, some studies from there suggest that landscapes in areas within 10 km of PA systems were more natural, more intact, and more protected than landscapes farther than 10 km from them (Svancara et al., 2009).

In the case of karst areas, the safeguarding of natural processes implies the need to practice careful management of the vegetation and soils of entire water catchment areas, if possible. Land managers should be sensitive to the potential impact of any activities within the catchment, even if they are not located in the karst region itself. Where this is not applicable, there should at least be an extensive buffer zone surrounding the karst land (Watson et al., 1997; Kaçaroglu, 1999). The successful management of karst in urban environments is best achieved by preserving the most vulnerable areas and their drainage basins in their natural state, coupled with minimizing the pollutant loading of the aquifer (Veni, 1999). In densely populated areas where the protection of the whole catchment is not possible, the establishment of scientifically determined and reasonable protection zones is a principal strategy for preventing the degradation of karst groundwater (Hao et al., 2006).

The key problem for the effective management of surface water is identifying the effective radius of any surface water pollution and blocking the pollution

source (Wang & Zhang, 2018). One of the most valuable tools used for assessing overall water quality is the water quality index (WQI). Many WQI methods exist, none of them being universal or best. Their suitability depends on the sources, the parameters measured, the weightage assigned, their classification scale, and their final interpretation (Rana & Ganguly, 2020). A holistic approach, addressing economic, scientific, and cultural factors, can be used for evaluating the karst environmental disturbance index (van Beynen & Townsend, 2005). This index is divided into five categories, each recognizing a distinct part of the natural and human system. However, when using this method, it is sometimes difficult to obtain all the data needed to calculate the index.

Prati et al. (1971) suggested a WQI based on mathematical expressions which transform concentrations of pollutants into a level of pollution. These mathematical expressions are constructed for each polluting factor so that their numerical value is no longer proportional to the concentration but to the "polluting effect" relative to other factors. He classifies the surface water quality as an "implicit index of pollution." Even though this method originated in the 1970s, it is still used alongside other methods and is one that is neither too "soft" nor too "hard" (Zotou et al., 2018).

The aim of the study was to propose a method of identification of allogenic watercourses transporting pollution to the karst protected landscape area (PLA) and determination of watersheds which need to be protected outside the PLA. A multicriterial approach was used to identify surface watercourses posing the greatest risk to the PLA in terms of the pollution they bring to its territory from areas outside. The watercourses were assessed according to 1) the water quality expressed as a WQI and 2) the mass flows of selected pollutants. Allogenic streams jeopardizing the karst ecosystem were identified, and watersheds outside the PLA (i.e., buffer zones) which should be protected were proposed via geographic information system (GIS). The presented approach can also be adapted for other types of PLAs with water pollution originating in surrounding areas.

## Area of interest and methods

### The Moravian Karst PLA and sampling points

The case study was performed for the Moravian Karst region of the Czech Republic (Fig. 1). Typical features of

the Moravian Karst PLA are as follows: small protected area, densely populated area around the PLA, both point and non-point sources of pollution, and more than 10 small surface watercourses entering the PLA from areas beyond its borders. The region was declared a PLA in 1956 to protect its unique environment. It has an area of 92 km<sup>2</sup>, of which nearly half is also included in the Natura 2000 network. The Moravian Karst is the most extensive and most developed karst in the Bohemian Massif and is formed from an approx. 25 km long and 5 km wide area of limestone. It contains more than 1100 caves and karst phenomena, formed mainly in high-purity limestone from the Devonian period (Hromas, 2009).

The PLA is located in a densely populated part of the Czech Republic, with several municipalities located directly in the PLA. The catchment areas adjacent to the PLA differ in land use types. Some are covered mostly by mixed forest, such as the *Říčka*, *Lopač*, *Bílá voda*, and *Luha* river basins. Some include larger areas of arable land and municipalities, such as the *Ochozský*, *Jedovnický*, *Lipovecký*, and *Žďárná* river basins. Some of these disappearing streams show deteriorated hydrochemical status, especially in the case of parameters such as organic substances, nitrates, and total phosphorus. As a result, the bulk of water pollution comes from the non-protected parts of the catchments outside the PLA, which are almost three times larger in area than the PLA itself (Malá et al., 2017). However, due to the dense settlement in the region, the protection of the entire river catchment areas is impossible.

### Sampling points and monitoring

The eleven monitored streams include all of the significant watercourses flowing into the Moravian Karst PLA. In the PLA, they all sink into the underground system. The sampling points (1 sampling point on each watercourse) lie on the border of the PLA (Fig. 1).

Monitoring was performed on a monthly basis from April to November 2019 (a total of 8 sample collections). Water flow measurements were carried out using a hydrometric propeller. The discharge was calculated section by section from the average velocity of the water and the perpendicular cross-sectional area of the specific profile. Dissolved oxygen (DO), pH, and temperature (*T*) were measured in situ using a HQ40D multimeter (Hach Lange

GmbH, Düsseldorf, Germany). The laboratory analyses were performed as follows: chemical oxygen demand (COD)—semi-micro method with potassium dichromate and photometric evaluation using DR3900 spectrophotometer (Hach Lange GmbH, Düsseldorf, Germany), biological oxygen demand (BOD)—standard dilution method, total phosphorus (TP)—mineralization with Oxisolv (Merck & Co., Inc., Kenilworth, New Jersey) and photometric determination of the released orthophosphates by the method with molybdate and ascorbic acid using DR3900 spectrophotometer (Hach Lange GmbH, Düsseldorf, Germany). NO<sub>3</sub>-N was measured via the UV absorption method with an optical Nitratax plus sc Sensor (Hach Lange GmbH, Düsseldorf, Germany).

### Evaluation of the results

The individual WQIs were calculated from the average values (*Y*) listed in Table 1 for each watercourse and indicator. The following equations were used for the calculations (Prati et al., 1971):

$$pH_{(7-9)} = (Y - 7)^2 \tag{1}$$

$$DO_{(50-100)} = 0.08 \cdot (100 - Y) \tag{2}$$

$$BOD = Y/1.5 \tag{3}$$

$$COD = 0.1 \cdot Y \tag{4}$$

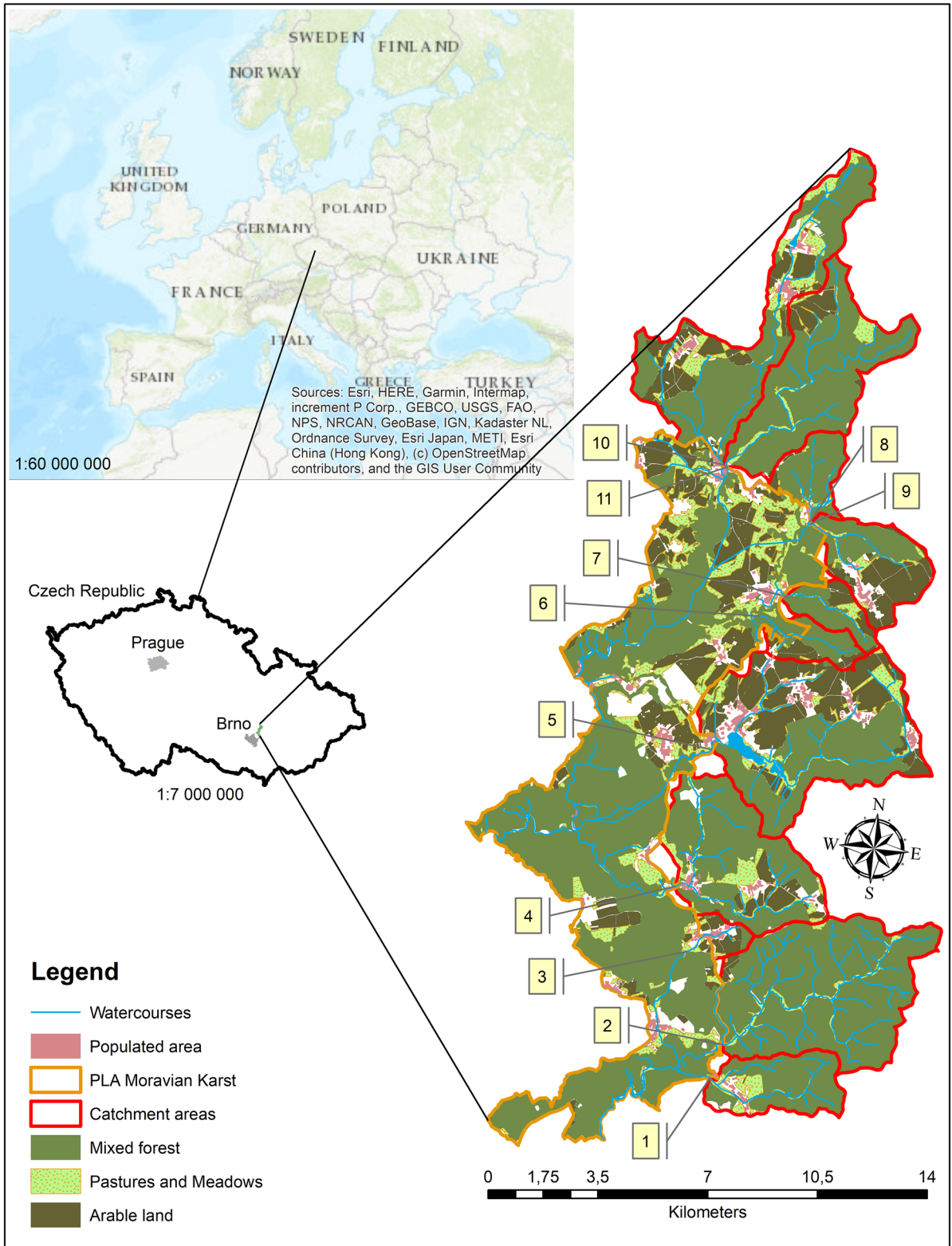
$$NH_4 = 2^{2.1 \cdot \log(10 \cdot Y)} \tag{5}$$

$$NO_3 = 2^{2.1 \cdot \log(Y/4)} \tag{6}$$

In order to evaluate the pollution brought into the PLA by the watercourses, mass flows of COD, BOD, NO<sub>3</sub>-N, NH<sub>4</sub>-N, and TP were calculated for each measurement as a product of water discharge and the mass concentration of the respective indicator.

### GIS mapping of the monitored area

The main purpose of creating a map (Fig. 1) using the GIS tool ArcMap 10.3.1 was to determine the catchment areas of the monitored streams. These areas were defined using underlayers in shp format



◀**Fig. 1** Location of the watercourses flowing into the Moravian Karst PLA and their catchment areas with the land use, and sampling points: 1—*Hostěnický*, 2—*Říčka*, 3—*Ochozský*, 4—*Křtinský*, 5—*Jedovnický*, 6—*Krasovský*, 7—*Lopač*, 8—*Bílá voda*, 9—*Lipovecký*, 10—*Žďárná*, 11—*Luha*

obtained from the DIBAVOD (T. G. Masaryk Water Research institute, public research institution, 2021) and LPIS (The Ministry of Agriculture of the Czech Republic, 2021) databases. The layers of the watersheds and the layers determining the land use (arable land, pastures and meadows, mixed forests, and populated area) were obtained from the same sources. The outline of the Czech Republic and a world map cut-out were obtained from the ArcGIS online database, which is part of the ArcGIS program. The UTM coordinate system was set to S-JSTK Krovak East North.

## Results and discussion

### Risk assessment with regard to the WQI

The average values gained for the measured parameters during the 8-month-long monitoring period (Table 1) correspond with the  $Y$  values in Eqs. (1–4) or were used for their calculation in Eqs. 5 and 6.

Non-problematic indicators included pH and DO. The average pH ranged from 7.5 to 7.9 and showed only small fluctuations (Table 1). The average DO saturation was  $>80\%$  in all streams.  $80\%$  is a value below which DO saturation in "healthy" surface waters should not fall (Horne & Goldman, 1994).

The average concentration of organic matter in the watercourses was rather high and ranged from  $19.4 \text{ mg L}^{-1}$  to  $61.6 \text{ mg L}^{-1}$  for COD and from  $6.1 \text{ mg L}^{-1}$  to  $31.5 \text{ mg L}^{-1}$  for BOD. However, in the case of four streams, the high average value was skewed by a single extreme value. For the *Bílá voda*, *Lipovecký*, and *Luha*, it was the October sample (200, 170, and  $260 \text{ mg L}^{-1}$ , respectively). An even stranger situation was with the *Ochozský*: there was extreme COD in April ( $240 \text{ mg L}^{-1}$ ), and then, there were four months (from July to October) without water due to lack of precipitation. The *Jedovnický* showed the highest average COD ( $>60 \text{ mg L}^{-1}$ ), but high COD was found in most samples. BOD followed a similar pattern as COD in all streams, with the highest average values found for the *Jedovnický* and the *Ochozský*.

Most of the watercourses were rich in  $\text{NH}_4\text{-N}$ . The highest concentrations were found in the *Jedovnický* ( $1.48 \text{ mg L}^{-1}$ ) and *Lipovecký* ( $1.75 \text{ mg L}^{-1}$ ). The *Krasovský* and *Lipovecký* contained high concentrations of  $\text{NO}_3\text{-N}$  ( $7.9 \text{ mg L}^{-1}$  and  $8.8 \text{ mg L}^{-1}$ , respectively) (Table 1).

There were large differences in TP concentrations between the streams. It was below  $0.1 \text{ mg L}^{-1}$  in six of them, but an extremely high average TP concentration ( $0.68 \text{ mg L}^{-1}$ ) was found in the *Lipovecký* (Table 1).

The investigated watercourses were classified from acceptable to polluted according to their WQI (Table 2). None of them received either an excellent or a heavily polluted score. The *Lopač* and the *Žďárná* were rated as acceptable mainly due to their higher average BOD ( $3.71$  and  $4.44$ , respectively) and  $\text{NO}_3$  ( $2.76$  and  $2.64$ , respectively) indices. More than half of the watercourses were evaluated as slightly polluted. From these, the better ranking (close to acceptable) was achieved by the *Hostěnický*, *Říčka*, *Křtinský* and *Bílá voda* in contrast with the *Krasovský*, *Lipovecký* and *Luha* (close to polluted). Two streams were rated as polluted, with the *Jedovnický* being the most serious case mainly due to its high BOD, COD and  $\text{NH}_4$  values ( $16.15$ ,  $6.17$  and  $6.43$ , respectively). The *Ochozský* was classified as polluted mainly due to its high average BOD. In general, it can be stated that the WQIs were most affected by COD and BOD, which suggests the presence of organic pollution. The nitrogen load ( $\text{NH}_4$  and  $\text{NO}_3$ ) moderately affected the WQIs, while pH and DO had the lowest impact.

The validity of Prati's individual WQIs was checked by comparison with the Czech standard for the determination of surface water pollution classes (CSN, 2017). This standard requires a larger number of samples, which is why it could not have been used for hydrochemical evaluation. However, it appears from an approximate comparison that for the evaluated factors (BOD, COD,  $\text{NH}_4^+$  and  $\text{NO}_3^-$ ), Prati's individual WQIs in class I–III (excellent–slightly polluted) are stricter than the standard, while in contrast, his WQIs in classes IV and V (polluted and heavily polluted) are less strict.

As a tool for decision-making regarding the necessity for the protection of watercourse catchment areas, the WQI evaluation system was simplified as follows:

- low risk—WQI  $< 2$  (excellent–acceptable);

**Table 1** Water quality indicators—averages of 8 measurements

	Hostěnický	Řička	Ochozský	Křínský	Jedovnický	Krasovský	Lopač	Bílá voda	Lipovecký	Žďárná	Luha
pH, -	7.5 ±0.2	7.6 ±0.2	7.9 ±0.3	7.7 ±0.1	7.8 ±0.3	7.7 ±0.3	7.7 ±0.2	7.8 ±0.2	7.8 ±0.2	7.8 ±0.3	7.5 ±0.2
DO, %	82.8 ±5.7	86.3 ±7.7	95.2 ±5.3	85.4 ±12.3	81.6 ±15.4	97.6 ±4.2	94.5 ±4.1	97.4 ±4.8	93.1 ±4.9	99.8 ±5.6	95.7 ±3.8
COD, mg L <sup>-1</sup>	26.8 ±14.9	23.5 ±24.6	31.7 ±78.8	23.3 ±18.0	61.6 ±45.9	24.7 ±26.0	19.4 ±12.3	42.6 ±60.2	35.6 ±51.6	19.4 ±20.4	45.3 ±81.9
BOD, mg L <sup>-1</sup>	6.1 ±5.5	9.2 ±13.5	31.5 ±78.9	6.8 ±8.7	24.2 ±32.2	14.1 ±26.6	5.6 ±2.5	8.7 ±12.2	9.1 ±12.1	6.7 ±7.5	16.3 ±33.7
TP, mg L <sup>-1</sup>	0.09 ±0.05	0.01 ±0.01	0.07 ±0.09	0.16 ±0.07	0.22 ±0.15	0.01 ±0.01	0.01 ±0.02	0.13 ±0.03	0.68 ±0.17	0.25 ±0.15	0.00 ±0.00
NO <sub>3</sub> -N, mg L <sup>-1</sup>	2.2 ±0.65	1.3 ±0.87	2.9 ±3.78	3.0 ±0.97	2.8 ±1.51	7.9 ±2.99	4.5 ±3.59	3.7 ±1.79	8.8 ±2.09	4.2 ±1.79	1.8 ±1.07
NH <sub>4</sub> -N, mg L <sup>-1</sup>	0.39 ±0.13	0.30 ±0.13	0.13 ±0.13	0.26 ±0.06	1.48 ±1.15	0.23 ±0.12	0.22 ±0.10	0.28 ±0.14	1.75 ±2.05	0.23 ±0.15	0.16 ±0.06

**Table 2** The individual and average WQIs; classes of average WQI: excellent (0–1); acceptable (1–2); slightly polluted (2–4); polluted (4–8); heavily polluted (>8)

Individual WQI	Hostěnický	Řička	Ochozský	Křínský	Jedovnický	Krasovský	Lopač	Bílá voda	Lipovecký	Žďárná	Luha
pH	0.25	0.36	0.81	0.49	0.64	0.49	0.49	0.64	0.64	0.64	0.25
DO	1.37	1.09	0.38	1.17	1.47	0.19	0.44	0.21	0.55	0.01	0.34
BOD	4.08	6.12	20.99	4.53	16.15	9.41	3.71	5.83	6.07	4.44	10.90
COD	2.68	2.35	3.17	2.33	6.17	2.47	1.94	4.26	3.56	1.94	4.54
NH <sub>4</sub>	2.78	2.37	1.40	2.13	6.43	2.01	1.91	2.25	7.15	2.00	1.58
NO <sub>3</sub>	1.74	1.26	2.09	2.13	2.03	3.95	2.76	2.43	4.21	2.64	1.57
<b>Average WQI</b>	<b>2.1</b>	<b>2.3</b>	<b>4.8</b>	<b>2.1</b>	<b>5.5</b>	<b>3.1</b>	<b>1.9</b>	<b>2.6</b>	<b>3.7</b>	<b>1.9</b>	<b>3.2</b>
<b>Condition</b>	Slightly polluted	Slightly polluted	Polluted	Slightly polluted	Polluted	Slightly polluted	Acceptable	Slightly polluted	Slightly polluted	Acceptable	Slightly polluted

**Table 3** Classification of the watercourses according to their WQIs and mass flows of pollutants

	<i>Hostěnický</i>	<i>Řička</i>	<i>Ochozský</i>	<i>Křtinský</i>	<i>Jedovnický</i>	<i>Krasovský</i>	<i>Lopač</i>	<i>Bílá voda</i>	<i>Lipovecký</i>	<i>Žďárná</i>	<i>Luha</i>
WQI	2.1	2.3	4.8	2.1	5.5	3.1	1.9	2.6	3.7	1.9	3.2
Mass flows											

Legend



- medium risk—WQI 2–5 (slightly polluted);
- high risk—WQI > 5 (polluted–heavily polluted).

According to the simplified system, the *Jedovnický* and *Ochozský* were classified as high risk and the *Lopač* as low risk. The rest of the watercourses showed medium risk (Table 3).

Risk assessment with regard to the mass flows of pollutants

Risk assessment based on WQIs does not take into account the water discharge in watercourses. Although water quality is undoubtedly of great importance, it says little about the amount of pollution that is brought into the PLA and is jeopardizing the karst. Moreover, both the water quality and the discharge varied during the monitoring period (Fig. 2). Some fluctuations were due to the season and weather conditions, while some could have been of anthropogenic origin, which is common in case of small streams (Langhammer et al., 2012). Zero water flow was found during the sampling season at the sampling points of three watercourses (the *Ochozský* from July to October, the *Žďárná* in July, and the *Řička* in August). Consequently, their average concentrations and WQIs were strongly affected by extreme values. That is why the mass flows of COD, BOD, NO<sub>3</sub>-N, NH<sub>4</sub>-N, and TP were also calculated (Fig. 2).

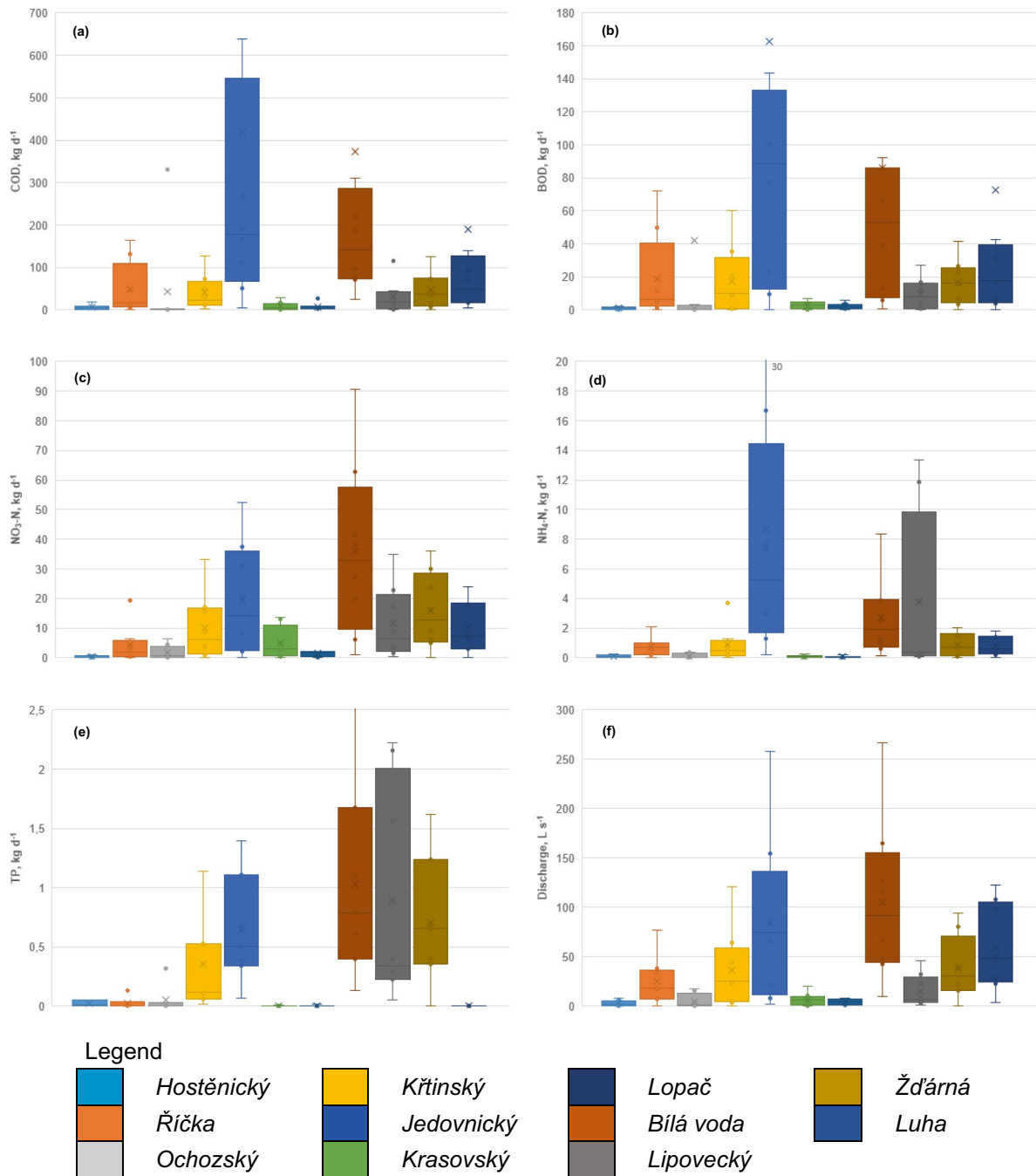
The comparison of watercourses in terms of the mass flows of pollutants provided a slightly different picture than their comparison via WQIs. The mass flow method verified the poor evaluation score of the *Jedovnický* for the indicators COD, BOD, and NH<sub>4</sub>-N, the average mass flows of which were 418 kg d<sup>-1</sup>, 163 kg d<sup>-1</sup>, and 8.7 kg d<sup>-1</sup>, respectively,

and represented the largest share of all evaluated streams (Fig. 2). On the other hand, in the case of the *Ochozský*, the mass flow method did not confirm the high risk of the *Ochozský* derived from its WQI for any of the assessed parameters. It showed—in line with expectations—that due to its low flow and several dry months during the summer, the *Ochozský* ranked among the watercourses with the lowest average mass flows of pollutants (COD and BOD 42 kg d<sup>-1</sup>, NH<sub>4</sub>-N 0.11 kg d<sup>-1</sup>, and NO<sub>3</sub>-N 1.8 kg d<sup>-1</sup>) (Fig. 2). Interestingly, the analysis of mass flows showed that a large proportion of organic pollution was introduced to the PLA by the *Bílá voda* (COD 374 kg d<sup>-1</sup>, BOD 86 kg d<sup>-1</sup>), although its WQI related to COD and BOD indicators displayed similar values as other assessed watercourses (Table 2). The *Bílá voda* was also the largest source of NO<sub>3</sub>-N pollution – 35.9 kg d<sup>-1</sup> in average (Fig. 2c).

Prati’s WQI assessment does not take TP into account, but both N and P should be considered in the eutrophication management of streams (Dodds & Smith, 2016; Prati et al., 1971). The *Bílá voda* and *Lipovecký*, which showed the highest average mass flows of TP (1.03 kg d<sup>-1</sup> and 0.89 kg d<sup>-1</sup>, respectively), dominated this criterion (Fig. 2e). Besides TP, the *Lipovecký* was also the second largest source of NH<sub>4</sub>-N (3.8 kg d<sup>-1</sup> in average) (Fig. 2d).

The risk derived from the mass flows of organic compounds (COD and BOD) and nutrients (NH<sub>4</sub>-N, NO<sub>3</sub>-N, and TP) was assessed according to the following criteria:

- (1) High risk—the watercourse showed high mass flows of both organic pollution and nutrients. The upper quartiles of the mass flows of COD and/or BOD and at the same time at least one of the mass flows of NH<sub>4</sub>-N, NO<sub>3</sub>-N, and TP were among the highest 3 upper quartiles of all assessed streams.



**Fig. 2** Mass flows of contaminants: (a) COD, (b) BOD, (c) NO<sub>3</sub>-N, (d) NH<sub>4</sub>-N, (e) TN, (d) TP, and (e) discharge

(2) Medium risk—the watercourse showed high mass flows of organic pollution or some nutrients. The upper quartile of the mass flow of COD and/or BOD or at least one of the mass flows of NH<sub>4</sub>-N,

NO<sub>3</sub>-N, and TP was among the highest 3 upper quartiles of all assessed streams, but the watercourse was not classified as high risk.



- (3) Low risk—the watercourse did not meet any of the criteria set out in points 1 and 2.

Two watercourses, namely the *Bílá voda* (all parameters) and the *Jedovnický* (all parameters except TP), were categorized as high risk. The following streams fulfilled the criteria for the medium-risk category: the *Luha* (COD), *Řička* (BOD), *Žďárná* (NO<sub>3</sub>-N and TP), and *Lipovecký* (NH<sub>4</sub>-N and TP). The risk connected with pollutant mass flows carried by the *Hostěnický*, *Ochozský*, *Křtinský*, *Krasovský*, and *Lopač* was evaluated as low (Fig. 2, Table 3).

Identification of streams for which the entire catchment area requires protection

The risk assessment based on WQIs and mass flows of pollutants showed similar results for 5 watercourses. Both methods categorized the *Jedovnický* as high risk, the *Řička*, *Lipovecký*, and *Luha* as medium risk, and the *Lopač* as low risk (Table 3).

The reason for the different classification of the other watercourses via the two methods was their discharge. The *Hostěnický*, *Křtinský*, and *Krasovský* had a low average discharge (3.3 L s<sup>-1</sup>, 36.4 L s<sup>-1</sup>, and 6.7 L s<sup>-1</sup>, respectively) and medium water quality compared with the other streams. Therefore, their evaluation according to the mass flows gave more favorable results than the evaluation according to their WQI—all flows were rated as low risk, while their water quality was assessed as slightly polluted, posing medium risk. The *Ochozský* was rated as polluted by the WQI method due to its high average BOD (31.5 mg L<sup>-1</sup>), which was caused by one extreme measurement in April. Its low risk derived from the mass flows of pollutants was due to the low average discharge and the fact that the stream was dry from July till October. In the case of all these streams, the mass flows of pollutants resulted in a lower risk than the WQIs because the supply of pollutants to the PLA was small due to the low discharge.

The opposite situation was with the *Bílá voda*, which was rated as medium risk by WQI and high risk by mass flows of pollutants. The average discharge of the *Bílá voda* was the highest of all the assessed streams (105.3 L s<sup>-1</sup>). Thus, even with its relatively good water quality, this watercourse brought a great quantity of pollution into the PLA.

The above analysis showed that a buffer zone for the Moravian Karst PLA should cover the entire *Jedovnický* catchment area. The reason is both the deteriorated water quality (WQI) of the *Jedovnický* and the high mass flow of pollutants it carries due to its high average flow rate. Attention should also be paid to the *Bílá voda*. Due to its high flow rate, any deterioration in water quality will result in a significant increase in the mass flow of pollutants.

## Conclusion

The Moravian Karst PLA and its surroundings are an example of a densely populated area where the protection of the entire catchments of all surface watercourses entering the PLA is not possible. Nevertheless, it is clear that a large proportion of the pollution entering the PLA arrives via water flowing from areas outside the PLA. In a case study carried out in this location, the simultaneous use of two criteria, namely the water quality index (WQI) and the mass flow of pollutants, proved to be important for the identification of river basins in need of increased protection (buffer zones).

When using this approach elsewhere, water quality can also be assessed by other criteria (e.g., local water quality standards). More indicators may be included in the water quality evaluation, such as phosphorus or specific pollutants occurring in the monitored area. In this manner, watercourses with deteriorated water quality can be identified. However, when assessing the need to delimit buffer zones, the water discharge affecting the mass flows of pollutants should be considered. Protection of the entire catchment is necessary for watercourses with deteriorated water quality and at the same time high water discharge resulting in high mass flows of pollutants. However, attention should also be paid to watercourses with medium water quality and high discharge, for which any deterioration in water quality significantly increases the input of pollutants into the PLA. GIS-based mapping appears to be a very useful tool for determining the catchment areas and buffer zones requiring increased attention to water quality.

Studies such as ours can be an effective decision-making tool for land managers and local stakeholders. They can provide the impetus to make changes to

current land use practices, and support the reduction in future negative human–landscape interactions.

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**Data Availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Competing interests** All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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