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Contamination and Ecological Risk Assessment of Long-Term Polluted Sediments with Heavy Metals in Small Hydropower Cascade

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Abstract The identification of contamination level and ecological risks, associated with heavy metal pollution of sediments in small hydropower cascade was done on the base of index analyses approach. The concentration of As, Cd, Cu, Hg, Pb, Zn, total organic carbon and percentage of fines were determined in sediments of two habitats in cascade sequence – river and dam. Correlation and multivariate analyses suggest that As, Cu, Pb and Zn are associated with similar anthropogenic source. Cadmium and mercury originate from different source and have specific moving. Based on the contamination and background indices the sediments in Middle Iskar cascade are moderate contaminated at least and are subject of intensive hydrological and technological mixing. The potential ecological risk index (PERI) classifies the sediments in dam site with the higher risk level. Suitable indicators for express assessment of metal pollution in "river" sediments are contamination/ enrichment indices which are more sensitive for local concentration increase of less toxic metals. In "dam" sites the process of sedimentation affects strongly the degree of metals accumulation and differences in toxicity are clearly presented – PER/PERI in combination with content of fine sediment fractions and TOC have a potential for rapid identification of sediment-associated risks.

Keywords Small hydropower plant cascade · Sediments · Contamination · Ecological risk assessment · Heavy metals

1 Introduction

Increasing energy demands, depletion of traditional energy sources and concerns about global anthropogenic impact (environmental pollution and climatic change) lead to an expansion of

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the energy generation from renewable sources. Small-scale hydropower plants (SHPP) as environmentally sound alternative of fossil fuels can make a serious contribution to meeting this requirement (ASTAE 2014; Goyal et al. 2015). The hydropower replies for 10–16 % of global electricity production (World Energy Council 2010), more than any other renewable source, and recent drivers to expand renewable energy production, such as European Union legislation requirements for 20 % of energy production from renewable sources by 2020 (Directive 2009/28/EC), have increased interest in hydropower (Anderson et al. 2014). However, a regulatory framework especially in local level is not well defined and the optimal use of hydropower in a sustainable practice still stays a challenge. A cascade of small dams may have detrimental impacts on the environment and on ecosystem services in the absence of proper planning and implementation of mitigation measures (ASTAE 2014; Ferreira and Teegavarapu 2012). The construction of SHPP is based on modification of stream hydraulics and dams compartmentalization of the river channel, which causes changes in the integrity of free-flow conditions and disturbs the hydrological regime of the river and the hydromorphology (Jablonskis et al. 2008; Warner 2012; Zhai et al. 2010; Pasha et al. 2015). Herewith the equilibrium of the ecological features of rivers and their riparian zones, coherent with both transport and retention of suspended sediments, nutrients and pollutants, are also disturbed (Vaikasas and Lamsodis 2011). The strong impacts on aquatic ecology and biology as ecosystem destruction, physical habitat alteration, direct species additions and removals, damage on freshwater habitats and organisms, limitation of biotic migrations are among the most well-known environmental threats of SHPPs (Warner 2012; Malmqvist and Rundle 2002; Hu et al. 2008). Despite this wide range of potential effects, some of the ecological problems have not been studied in great depth. One of the major gaps in knowledge concerns the proper assessment of cumulative impact from SHPP functioning and associated risks of other human-induced impacts as chemical pollutants with high toxicity and difficult biotransformation.

Heavy metals are hazardous substances of considerable environmental interest and the contamination of aquatic systems by heavy metals has been known as one of the most challenging pollution issues. The heavy metals have high risk impacts due to their toxicity, abundance, persistence, and subsequent sediment and bio-accumulation (Barlas et al. 2005; Fu et al. 2014; Zhu et al. 2012; Yi et al. 2011). Depending on hydrodynamics, biogeochemical processes and environmental conditions of rivers, sediments act as an important sink of heavy metals, as well as a potential non-point pollution source for overlying waters (Santos et al. 2003; Wu et al. 2012). The change of hydrological regime in the area of SHPP is the factor with very high risk level for uncontrollable accumulation/deaccumulation of metals and for deterioration of quality and ecological state of this technologically managed ecosystem. The assessment of contamination status of sediments in alternating "river-dam-river" sequence and potential multiplication of ecological risks during the operation of cascade were not well clarified in the previous studies. The aim of this work was to contribute to better understanding and effective solving of this type of ecological problems in future management plans and strategies of modified rivers ecosystems. The identification of contamination level and eco-logical risks, associated with heavy metal pollution of sediments in specific case study of Middle Iskar SHPP cascade, Bulgaria was done on the base of index analyses approach. This well-known approach with simple quantitative interpretation was applied in order to assess the behavior and environmental impact of hazardous pollutants in cascade sequence of two habitats – river and dam. The construction of the technological project with barrages has started since 2000s, but the poor status of historical contaminated bed sediments and degree of

sedimentation in newly dam sites have obtained the crucial importance. Flow regulation and bed modification combined with the strong anthropogenic impacts deepen the environmental and technological problems of the cascade operation. This case study despite its locality can be used as a model for identification of sediment-associated risks from heavy metal pollution in the management of technologically modified ecosystem.

2 Materials and Methods

2.1 Area and Sampling Description

The Middle Iskar cascade covers 33 km river sector in middle part of the Iskar River, NW Bulgaria, Danube River Basin. Iskar is the longest Bulgarian river (368 km) with 8650 km^2 basin area and mean annual runoff of 37.57 m^3/s in the study sector (Todorova et al. 2015). The river seasonal flow is typical for moderate continental climate zone with a low runoff in summer and winter, followed by a high runoff in spring and autumn. In its middle part the river flows through a highly populated and industrialized area and is a long-term receptor of urban and industrial sewage of Sofia area (capital of Bulgaria).

This work was based on long-standing extensive monitoring program applied for assessment of changes in ecosystem caused by construction and functioning of SHPP cascade (Mihailova et al. 2013; Lincheva et al. 2014; Kenderov and Yaneva 2009; Todorova et al. 2015). The emphasis was placed on the assessment of heavy metal contamination and risk status at three sampling sites - critical points in management of risk situations in the cascade. The first site was at the beginning of the river sector – Prokopanik (Prok); the second site was at dam wall of the first constructed plant Lakatnik (Lak) and the third – at the end of river sector Gabrovnitza (Gabr) (Fig. 1). The hydrological regime of river sector is strongly modified from the cascade and the study sites can be subdivided into two different habitats: "river" sites (Prok and Gabr) and "dam" site (Lak). This sampling strategy for habitat division was based on spatial and hydrological heterogeneity (Gao et al. 2015).

The sampling for data collecting for this study was conducted during the summer low flow periods of 2009–2013 years. At each sample site and year, five different samples were obtained using Eckman-Berge dredge with an approximated area of 0.04 m^2 for "impoundment" sediments and by manual dredging for "river" sediments. The stones and
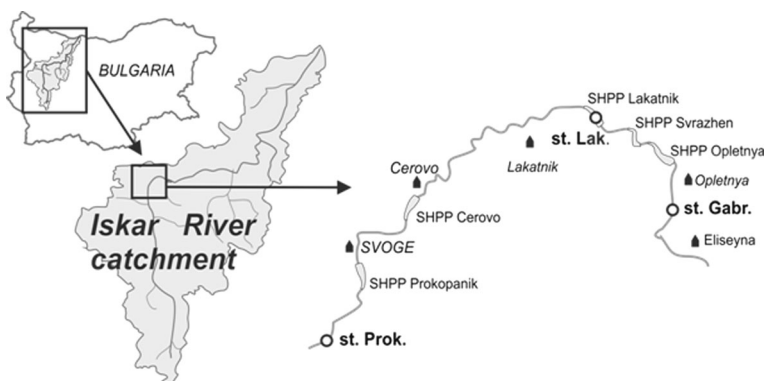

Fig. 1 Location of sampling sites in Middle Iskar SHPP cascade

plant fragments were removed by passing the samples through a 2 mm sieve. Each collected sample consisted of at least 1 kg of sediment and was contained in a separate sealed plastic bag, placed in a cooler at 4 °C, and transported to the laboratory immediately for analysis.

2.2 Analytical Procedures

The basic environmental factors (temperature, oxygen concentration and pH of waters) were analyzed in situ with portable oxymeter Handylab Ox1/set and pH meter Handylab pH 11/set (Schott Instr.). The percentage of fine fractions in sediments (<1 mm) was determined by wet sieving of the samples. The sediment samples were air dried, then powdered and finally passed through a 500 μm sieve (US EPA 2007; Varol 2011). TOC (total organic carbon) analyses of sediment samples were performed on TOC-V analyzer SSM-5000 A, Shimadzu Corporation by combustion catalytic oxidation method. The heavy metals concentrations were determined by atomic absorption spectrophotometry for As, Cd, Cu, Pb and Zn and by cold vapor atomic absorption spectrometry for Hg. The concentrations were presented in mg/kg dry sediments.

2.3 Calculation of Indices for Assessment of Sediment Contamination

For assessment of heavy metals contamination status in sediments of Middle Iskar Cascade, two groups of indices (pollution indicators) were used: (i) contamination and background enrichment indices, which measure the contamination or enrichment levels and (ii) ecological risk indices, which evaluate the potential for observing adverse biological effects (Caeiro et al. 2005). The description and calculation of indices are given in Table 1.

2.4 Data Interpretation and Statistical Analyses

The studied parameters and used indices are 17, and optimization of this large set of data is needed to improve efficiency for real application in good management practice (Gao et al. 2015). The screening of interrelated variables for their underlying dimensions is achieved by multivariate statistical techniques of principal component analysis for identification of pollution source and grouping the samples (Singh et al. 2009). With PCA, a large data matrix is reduced to two smaller ones that consist of principal component (PC) scores and loadings. The PC scores contain information on all of the variables combined into a single number, with the loadings indicating the relative contribution of each variable to that score (Farnham et al. 2003). The geographical detector method proposed by Wang et al. (2010) was adapted for evaluating spatial correlations among ecological factors and testing of some macrodeterminants of the pollution. The GeoDetector is based on the spatial consistency of variables, including a factor detector (to explore the impact of different factors on the research target), an ecological detector (to explore the impacts of different levels of significance on factors) and an interaction detector (to explore the impacts of the combinations of different impact factors) (Wang et al. 2010; Ren et al. 2014). The used tool is Excel version of GeoDetector available on http://www.sssampling.org/excel-geodetector/. Differences between two habitats in SHPP cascade were evaluated additionally through analysis of variance (one-way ANOVA) followed by a post hoc Tukey test; the significance level was set at $P < 0.05$. The statistical analyses were performed using Microsoft Excel 2000/XLSTAT (2014.5.03, Addinsoft, Inc., Brooklyn, NY, USA) and PAST 3.04 (Hammer et al. 2001).

Table 1 Indices used for contamination and risk assessment in sediments

Index	Description	Calculation and interpretation	References
1. Contamination and background enrichment indices			
Contaminant factor (Cf)	The ratio obtained by dividing the concentration of each metal (Ci - the mean content of the substance from superficial sediments at least five samples) by the Cn – pre-industrial reference level	$Cf = Ci/Cn$ $Cf < 1$ indicates low contamination; $1 < Cf < 3$ is moderate contamination; $3 < Cf < 6$ is considerable contamination; and $Cf > 6$ is very high contamination	Hakanson (1980)
Degree of sediment contamination (DC)	The sum of all contaminant factors. In this study, the used background concentrations for some heavy metals in Bulgaria are according to Cholakova (2004).	$DC = \sum Cfi$ $DC < n$ (no. of contaminants): low level of contamination; $n < DC < 2n$: moderate degree of contamination; $2n < DC < 3n$: considerable degree of contamination; $DC > 3n$: very high degree of contamination	Hakanson (1980)
Geo-accumulation index (Igeo)	Compare the contaminants concentrations with different baselines or backgrounds for the specific area. Ci is the concentration of metal examined in sediment samples, and Bn is the geochemical background concentration of the metal (Cholakova 2004). Factor 1.5 is the background matrix correction factor due to lithospheric effects.	$Igeo = \log_2 Ci/1.5Bn$ Class 0 (practically unpolluted): $Igeo \leq 0$; Class 1 (unpolluted to moderately polluted): $0 < Igeo < 1$; Class 2 (moderately polluted): $1 < Igeo < 2$; Class 3 (moderately to heavily polluted): $2 < Igeo < 3$; Class 4 (heavily polluted): $3 < Igeo < 4$; Class 5 (heavily to extremely polluted): $4 < Igeo < 5$; and Class 6 (extremely polluted): $5 > Igeo$.	Muller (1969, 1981)
2. Ecological risk indices and sediment quality guidelines			
Potential Ecological Risk (PER)	An ecological risk factor to quantitatively express the potential ecological risk of a given contaminant. Tri is the toxic-response factor for a given substance, and Cif is the contamination factor.	$PER = Tri \cdot Cif$ $PER < 40$, low potential ecological risk; $40 \leq PER < 80$, moderate potential ecological risk; $80 \leq PER < 160$, considerable potential ecological risk; $160 \leq PER < 320$, high potential ecological risk; and $PERi \geq 320$, very high ecological risk.	Hakanson (1980)
Potential Ecological Risk Index (PERI)	The sum of all PER calculated for each metal inside one area	$PERI = \sum PER$ $PERI < 150$ - low risk; $150 \leq PERI < 300$ - moderate risk; $300 \leq PERI < 600$ - considerable risk; $PERI \geq 600$ is very high risk.	Hakanson (1980) Fiori et al. (2013)

3 Results and Discussion

3.1 Site Characterization

The mean values for study period of basic environmental factors of waters (temperature 19.12÷20.03°, pH 7.53÷7.85 and dissolved oxygen 6.87÷8.8 mg/l) varied with slight spatio-temporal fluctuations at three sampling sites. But the two habitats differed in their sediment characteristics – the range of TOC in Lak site was 6.899 ± 1.076 %; in Prok – 0.125 ± 0.019 %; in Gabr – 0.304 ± 0.246 %. Percentage of fine sediment fractions was 24.39 % in Prok, 32.13 % in Gabr, and very high in Lak sediments – 91.53 %. The Lak samples were characterized by a high percentage of organic matter and fine fractions due to favorable hydrological/sedimentary regime in dams (statistically significant difference, ANOVA, post hoc Tukey test, $p < 0.05$). The presence of organic matter in sediment is directly related to the bioavailability of the heavy metals – the metals bound to biogenic carbonates and organic matter are much more available (Lacerda et al. 1992; Bryan and Langston 1992). The unified criteria for TOC in freshwater sediments are not still established on European or national level but the other recommendations determine the values under 1 % as low and the values above 3 % as indicator of strong anthropogenic impact (Todorova et al. 2015; US EPA 2002).

3.2 Heavy Metals Concentrations in Sediments

The mean concentrations of As, Cd, Cu, Hg, Pb and Zn in Middle Iskar cascade sediments during the study period of 2009–2013 are presented on Fig. 2. The data was interpreted according to local quality standards for soils (Regulation No 3 of 1 August 2008) due to the ongoing procedure for development of the sediment quality standards (Ministry of Environment and Water, Ministry of Health, Ministry of Agriculture and Food, Bulgaria 2008).

The ranges of metals content are: 6–45.5 mg/kg for As, 0.2–5 mg/kg for Cd, 36–235 for Cu, 0.03–1.9 mg/kg for Hg, 27–300 mg/kg for Pb and 158–575 mg/kg for Zn. The higher concentrations of As, Cu, Pb and Zn were detected at the beginning of the cascade (site Prok) in 2009 and the trend for decrease was observed during the study period in this site. These concentrations exceed the maximum admissible concentrations (MAC) for soils by 0.8 to 3 times. In 2010 the low increase in content of these metals was detected too but in the end of cascade (site Gabr). This same trend in spatio-temporal dynamics of As, Cu, Pb and Zn is confirmed by correlation matrix between heavy metals (Table 5).

The highest concentrations of Cd were found at site Lak and measured values exceeded the MAC by 0.1–2.5 times during the whole study period. In 2011, the increase of Hg content was detected in sediments of three sampling sites – the values were 1.2, 1.9 and 1.9 mg/kg for Prok, Lak and Gabr, respectively.

3.3 Indices for Assessment of Sediment Contamination and Ecological Risk

The contamination factor (Cf) and the degree of contamination (DC) are used to determine the contamination status of sediments (Table 2). The highest Cf values were found for mercury in 2011 – the grade of assessment indicated "very high contamination" in sites after first impoundment of the cascade. But the long-term analyses for 5-years period showed high variations of Cf values and very unstable dynamics for this metal. The Cf values for all heavy metals during the first three studied years showed the higher degree of contamination than the
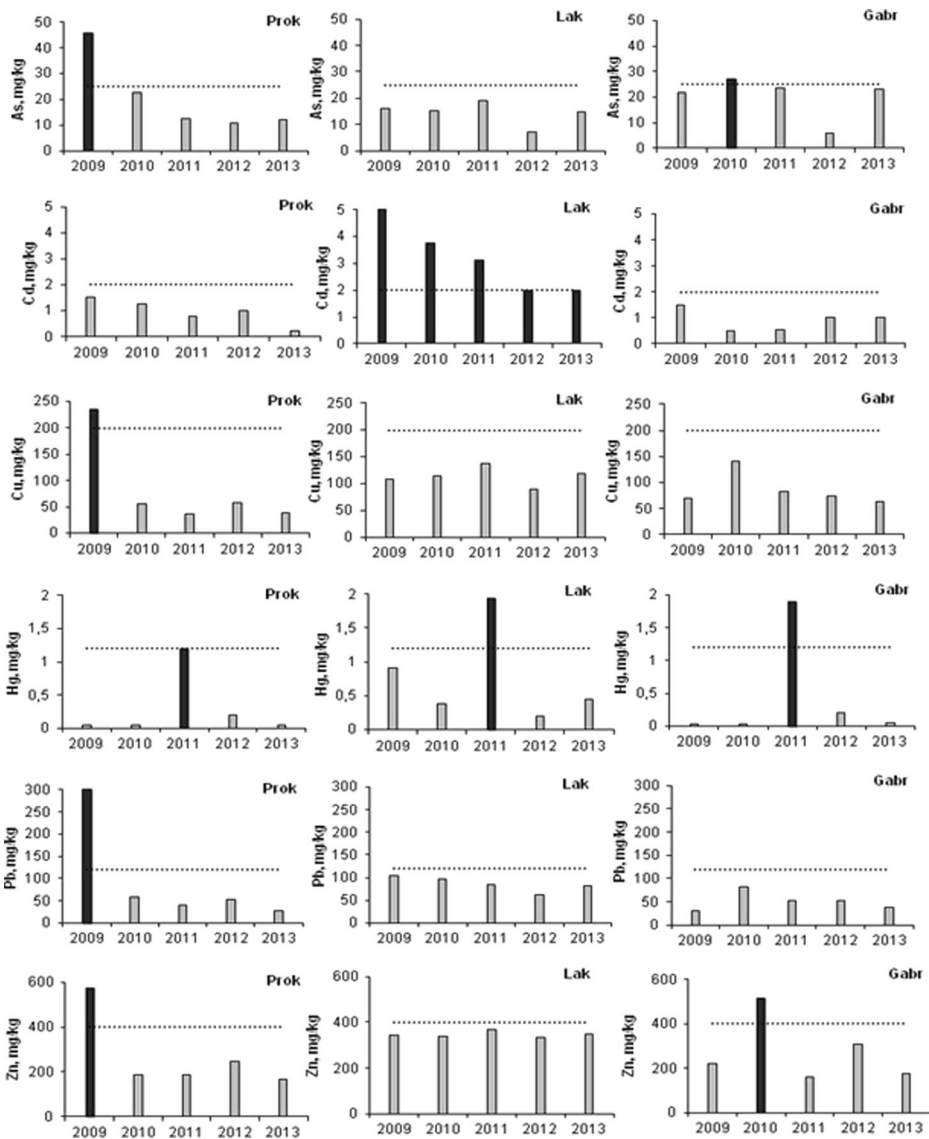
Fig. 2 Mean concentrations of heavy metals (mg/kg) in sediments of Middle Iskar Cascade. *the dot line is MAC for each heavy metal, the black color presents the values over the MAC

degree in 2012 and 2013. The analyses of values for studied metals showed that the sediments in Middle Iskar cascade are moderate contaminated at least and probably are subject of intensive hydrological mixing.

DC values ranked the sample sites in descending order as following: Lak, Prok, Gabr and sampling years: 2011, 2009, 2010, 2012, 2013. The sediments in "impoundment" site Lak had a moderate level of contamination in 2010, 2012 and 2013; considerable level in 2009 and very high in 2011.

A well-known and widely used index to assess the heavy metal pollution in sediments is the geo-accumulation index (Igeo), which was originally defined by Muller (1969). Using the

Table 2 Contamination factors (Cf) and degree of sediment contamination (DC) in Middle Iskar Cascade sediments

		Cf As	Cf Cd	Cf Cu	Cf Hg	Cf Pb	Cf Zn	DC (map overview)
2009	Prok	3.03	1.50	4.70	0.17	4.29	3.29	
	Lak	1.07	5.00	2.16	3.64	1.47	1.97	
	Gabr	1.44	1.50	1.40	0.13	0.44	1.26	
2010	Prok	1.51	1.25	1.10	0.17	0.81	1.07	
	Lak	1.01	3.75	2.30	1.50	1.37	1.94	
	Gabr	1.79	0.50	2.80	0.14	1.15	2.93	
2011	Prok	0.83	0.80	0.72	4.80	0.59	1.06	
	Lak	1.28	3.13	2.76	**7.77**	1.19	2.10	
	Gabr	1.55	0.54	1.65	**7.60**	0.76	0.90	
2012	Prok	0.73	1.00	1.16	0.80	0.76	1.41	
	Lak	0.47	2.00	1.80	0.80	0.89	1.91	
	Gabr	0.40	1.00	1.48	0.80	0.74	1.74	
2013	Prok	0.80	0.20	0.78	0.20	0.39	0.97	
	Lak	1.00	2.00	2.36	1.76	1.16	1.98	
	Gabr	1.53	1.00	1.28	0.20	0.54	1.02	
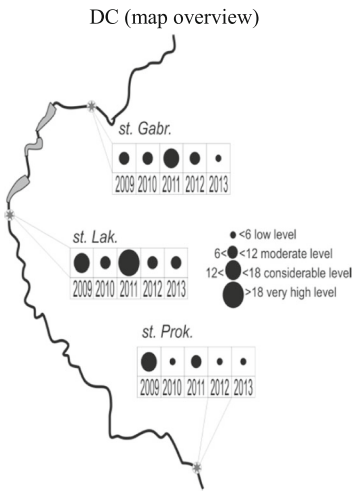
Categories of Cf and grades of assessment (Hakanson 1980): Cf < 1 is low contamination; 1 < Cf < 3 is moderate contamination; 3 < Cf < 6 is considerable contamination; Cf > 6 is very high contamination (bold values)

measured values of heavy metal content in the sediments and the background values of heavy metals according to Cholakova (2004), Igeo for sediments in Middle Iskar Cascade was calculated (Table 3). Among the all studied heavy metals, Hg had the highest Igeo value –

Table 3 Index of geoaccumulation (Igeo) in Middle Iskar Cascade sediments

		Igeo As	Igeo Cd	Igeo Cu	Igeo Hg	Igeo Pb	Igeo Zn
2009	Prok	1.28	0.00	1.80	−2.29	3.00	2.03
	Lak	−0.22	1.74	0.68	2.12	1.46	1.29
	Gabr	0.20	0.00	0.05	−2.67	−0.30	0.64
2010	Prok	0.27	−0.26	−0.30	−2.32	0.60	0.42
	Lak	−0.30	1.32	0.77	0.84	1.35	1.27
	Gabr	0.52	−1.58	1.05	−2.58	1.11	1.86
2011	Prok	−0.58	−0.91	−0.91	2.51	0.13	0.39
	Lak	0.03	1.06	1.03	**3.21**	1.15	1.38
	Gabr	0.31	−1.47	0.29	**3.18**	0.50	0.16
2012	Prok	−0.77	−0.58	−0.22	−0.07	0.50	0.80
	Lak	−1.42	0.42	0.42	−0.07	0.73	1.24
	Gabr	−1.64	−0.58	0.13	−0.07	0.47	1.11
2013	Prok	−0.64	−2.91	−0.79	−2.07	−0.47	0.26
	Lak	−0.32	0.42	0.81	1.07	1.11	1.30
	Gabr	0.29	−0.58	−0.08	−2.07	0.02	0.34

Categories of Igeo and grades of assessment (Muller 1981): Igeo ≤ 0 - unpolluted; 0 < Igeo < 1 - from unpolluted to moderately polluted; 1 < Igeo < 2 - moderately polluted; 2 < Igeo < 3 - from moderately to strongly polluted; 3 < Igeo < 4 - strongly polluted (bold values); 4 < Igeo < 5 - from strongly to extremely polluted; Igeo > 5 - extremely polluted

in 2011 the sites Lak and Gabr were "strongly polluted" but in long-term aspect Pb and Zn had more critical meaning. The Igeo for Pb and Zn had stable values during the studied period and indicated all sites as "moderately" and "from moderately to strongly polluted". As, Cd (only in "river" sites) and Cu were generally around background concentration ranges.

The ecological risk assessment results of heavy metals in study sediments are summarized in Table 4. The risk indices of heavy metals were ranked in the order of Hg > Cd > As ~ Cu > Pb> > Zn. Hg has high potential ecological risk for freshwater ecosystems owing to its high toxic factor values. The average PER for Hg in 2011 was 192.00, 310.88 and 304.00 respectively for Prok, Lak and Gabr sites, corresponded to "high" risk level for benthic biota. In Lak site the PER for Cd indicated the "considerable" risk in period of 2009–2011 – 150.00, 112.50 and 93.90. The sum of PER Hg and PER Cd corresponds to 35–93 % of PERI at each year and site. The lower or higher PERI were obtained according to the weight of Hg and Cd PER. The PERI levels in Lak and Gabr sampling sites in 2011 exceeded 300, which may cause considerable ecological harm according to the evaluation scale. According to values of PER for As, Cu, Pb and Zn the sediments had a "low" potential ecological risk. The potential ecological risk factors are below 40, and the extent of potential ecological hazards is slight for indicated metals at all the sampling sites. The difference between potential ecological risk index and contamination/background enrichment indices is reflected on the results of As, Cu, Pb and Zn pollution. Potential ecological risk index shows that there is a low contamination of these metals while the values of Cf and Igeo indicate a moderate pollution. The main reason is that the Igeo evaluation method focuses on the comparative evaluation of heavy metals contents in sediments, but the potential ecological risk index emphasizes the differences in toxicity of various heavy metal ions and a comparison is made to examine the heavy metal contents (Fu et al. 2014). The significant difference between two habitats in SHPP cascade according the PERI is observed (ANOVA test, post hoc Tukey, $p < 0.05$). The sediments in dam site have the higher risk levels.

Table 4 Potential Ecological Risk (PER) and PER Index (PERI) in sediments of Middle Iskar Cascade

		PER As	PER Cd	PER Cu	PER Hg	PER Pb	PER Zn	PERI (map overview)
2009	Prok	30.33	45.00	23.50	6.88	21.43	3.29	
	Lak	10.73	150.00	10.80	145.60	7.36	1.97	
	Gabr	14.40	45.00	7.00	5.28	2.18	1.26	
2010	Prok	15.07	37.50	5.50	6.72	4.07	1.07	
	Lak	10.13	112.50	11.50	60.00	6.84	1.94	
	Gabr	17.93	15.00	14.00	5.60	5.77	2.93	
2011	Prok	8.33	24.00	3.60	**192.00**	2.93	1.06	
	Lak	12.80	93.90	13.80	**310.88**	5.95	2.10	
	Gabr	15.53	16.20	8.25	**304.00**	3.79	0.90	
2012	Prok	7.33	30.00	5.80	32.00	3.79	1.41	
	Lak	4.67	60.00	9.00	32.00	4.43	1.91	
	Gabr	4.00	30.00	7.40	32.00	3.71	1.74	
2013	Prok	8.00	6.00	3.90	8.00	1.93	0.97	
	Lak	10.00	60.00	11.80	70.40	5.79	1.98	
	Gabr	15.33	30.00	6.40	8.00	2.71	1.02	

Categories of PER and grades of assessment (Hakanson 1980): PER < 40 - low risk; 40 ≤ PER < 80 - moderate risk 80 ≤ PER < 160 - considerable risk; 160 ≤ PER < 320 - high risk (bold values); PER ≥ 320 - very high risk

3.4 Relationships between Pollution Indicators

Principal component analysis (PCA) has been applied to studied pollution indicators and environmental variables to group the parameters based on significant correlations. PCA loading matrix was obtained using correlation matrix of normalized metals concentrations. PCA of the entire data set reveal two PCs with eigenvalues >1 and explained about 77.55 % of the total variance in the heavy metals concentrations data set (Fig. 3). The first PC accounting for 55.93 % of the total variance is correlated with As, Cu, Pb and Zn. It was in accordance with the results of the correlation analysis (Table 5) and spatial dynamics of the variables. The second PC accounting for 21.63 % of total variance is correlated with Cd and Hg (loading >0.75). The results of PCA in order to grouping the samples are shown too. Two sampling sites Prok in 2009 and Gabr in 2010 represent independent isolated cases of heavily pollution. They are definitely separated from other samples and this is due to the enhanced element concentrations of As, Cu, Pb and Zn. The next group comprises samples from the impoundment zone (site Lak). The third group includes the other samples from river habitats and is strongly related to the first axis.

The relationships between all studied variables – metals concentrations, total indices (DC and PERI) and some of environmental variables were evaluated by correlation matrix for each of habitats. A significant positive correlation exists among As, Cu, Pb and Zn (Table 5). Cadmium and mercury show the different pattern from the other heavy metals – no correlation is observed. Probably these two elements originate from different source and have specific moving and behavior in Middle Iskar ecosystem. As, Cu, Pb and Zn have similar spatial patterns and are associated with similar urban and industrial pollution sources. These results confirm the PCA plots for entire data set (Fig. 3). The two total indices DC and PERI correlate each other but the correlation is the stronger for dam sediments. The significantly positive correlation of two indices, %fines and TOC, presented only in dam site show a close relationship between the higher content of fine sediment fractions, organic matter and degree of contamination/ecological risk. A significant positive correlation exists between TOC and Hg and this explains the higher mercury concentrations in Lak sediments - % of TOC in this sampling site is very high.

We use Geographical Detector for additional assessment of the relationships between environmental determinants and comparison of spatial consistency of heavy metal pollution
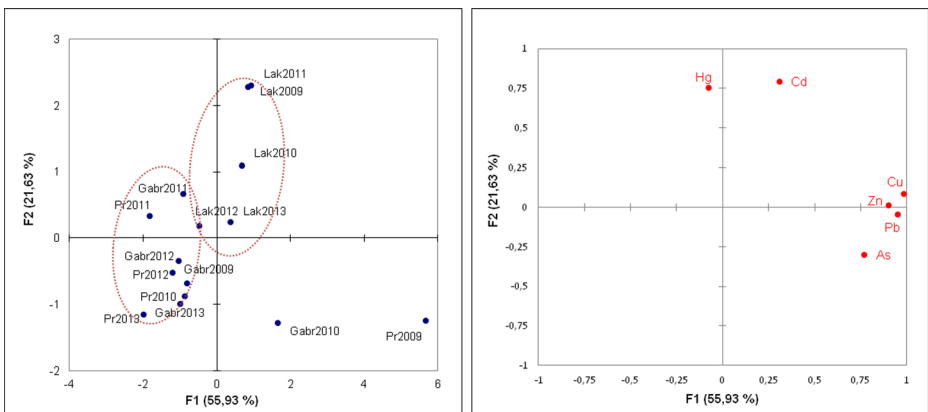

Fig. 3 PCA – variable plot (*left*) and loading plot (PC1 vs. PC2) for samples (*right*)

Table 5 Pearson correlation matrix between variables in sediment samples of Middle Iskar Cascade

	DC	PERI	%fines	TOC	As	Cd	Cu	Hg	Pb	Zn
(a) river habitat										
DC	**1**									
PERI	**0.594**	**1**								
%fines	−0.017	0.092	**1**							
TOC	−0.040	−0.244	**0.509**	**1**						
As	**0.763**	0.109	−0.026	−0.183	**1**					
Cd	0.237	−0.150	−0.052	−0.224	0.405	**1**				
Cu	**0.813**	0.026	0.013	0.195	**0.855**	0.347	**1**			
Hg	0.386	**0.965**	0.113	−0.203	−0.120	−0.347	−0.199	**1**		
Pb	**0.807**	0.060	−0.291	−0.041	**0.815**	0.437	**0.931**	−0.174	**1**	
Zn	**0.611**	−0.194	0.008	0.478	**0.643**	0.238	**0.910**	−0.368	**0.798**	**1**
(b) dam habitat										
DC	**1**									
PERI	**0.993**	**1**								
%fines	**0.587**	**0.589**	**1**							
TOC	**0.559**	**0.666**	**0.881**	**1**						
As	**0.871**	**0.818**	**0.609**	−0.220	**1**					
Cd	**0.606**	**0.550**	0.159	−0.499	0.495	**1**				
Cu	**0.780**	**0.755**	**0.532**	0.482	**0.912**	0.137	**1**			
Hg	**0.929**	**0.959**	**0.614**	**0.522**	**0.753**	0.291	**0.804**	**1**		
Pb	**0.580**	**0.587**	0.266	−0.461	**0.700**	0.365	**0.889**	0.243	**1**	
Zn	**0.860**	**0.879**	**0.657**	−0.457	**0.806**	0.120	**0.914**	0.192	**0.961**	**1**

Values in bold are different from 0 with a significance level < 0.05

risk versus environmental factors. The variables included in test were TOC, %fines, and other suspected determinants as degree of sedimentation, retention of water (as qualitative assessment) and basic water quality parameters. The quantitative data were discredited at first and then classified into different grades (Cao et al. 2013). The factor and risk detectors identify the TOC, %fines, degree of sedimentation, retention of water as environmental factors with large impact on heavy metal pollution; the interaction detector detects that the effect of interaction of each two environmental determinants are combined. This means that their effect will be greater after interaction than their individual. The basic water quality parameters have no distinct influence on heavy metal pollution in sediments.

4 Conclusions

The rapid development of SHP energy conversion systems meets some specific environmental challenges: (i) a trapping of sediments, nutrients and organics is one of well-known environmental impacts, related to SHPP (Warner 2012); (ii) the predication "there is no pollution of the environment from SHP operation" must be viewed in a new light, when hazardous pollutants has been presented historically in the modified river. The cumulative impact of (i) and (ii) may have very high risk level for environment and needs a specific strategy for risk

assessment and early identification of impact levels, related to the hazardous pollutants. Specific ecological situation of Middle Iskar cascade case study can be considered as a model for development of framework for identification of sediment-associated risks from heavy metal pollution in SHPP cascade. Based on the contamination and background indices the sediments in Middle Iskar cascade are moderate contaminated at least and are subject of intensive hydrological and technological mixing. The potential ecological risk index (PERI) classifies the sediments in dam site with the high risk level. The combination of high organic content, small grain size fraction, increased sedimentation and retention of waters and compounds in dams of SHPP cascade have the enhanced effect on heavy metal pollution and increased the environmental risk. Suitable indicators for express assessment of metal pollution in "river" sites sediments are contamination/enrichment indices which compare the contaminants with pre-industrial baselines or backgrounds for the specific area and are more sensitive for local concentration increase of less toxic metals. In "dam" sites the process of sedimentation affects strongly the degree of heavy metals accumulation and differences in toxicity of heavy metals are clearly presented – PER/PERI in combination with content of fine sediment fractions and TOC have a potential for rapid identification of sediment-associated risks.

Compliance with Ethical Standards

Conflict of Interest   The authors declare that they have no conflict of interest.

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