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LIMNOLOGICAL CHARACTERISTICS, WATER REGIME AND WATER QUALITY PROBLEMS OF BORKOVAC RESERVOIR (VOJVODINA, SERBIA)

LIMNOLOŠKE ZNAČILNOSTI, VODNI REŽIM IN PROBLEMI KAKOVOSTI VODE AKUMULACIJSKEGA JEZERA BORKOVAC (VOJVODINA, SRBIJA)

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DRAGAN DOLINAJ

The Borkovac reservoir with Fruška Gora Mountain in the background.
Zajezitev Borkovac s Fruško goro v ozadju.

Limnological characteristics, water regime and water quality problems of Borkovac reservoir (Vojvodina, Serbia)

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ABSTRACT: In this study we present interdisciplinary investigations of the Borkovac reservoir (Vojvodina, Serbia). The limnological characteristics of the reservoir were analysed in the scope of its sustainable use for irrigation, fishing and tourism. This multipurpose water accumulation has been established in 1975 as a part of regional hydrological system of the Fruška Gora mountain region.
The main environmental problems recognized in this study were: water regime, intensive sedimentation in the reservoir, enhanced water eutrophycation and toxic cyanobacterial blooms. Observed environmental problems and proposed solutions in the case of the Borkovac accumulation including construction of the sediment precipitator at the Borkovac stream junction to lake, sediment removal, artificial water mixing and oxygenation, phosphorous inactivitation, different kinds of biomanipulations and biomass removal and introduction of ecoremedation methods could also be applied to other artificial water bodies of the Fruška Gora slopes.

KEY WORDS: geography, hydrology, limnology, artificial lakes, Borkovac reservoir, Vojvodina, Serbia, limnology

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1 Introduction

In spite of their great importance, lack of water resources investigations is common for countries of the Western Balkan region. However, several studies regarded to different water use problems in the region, mostly in Slovenia (Smrekar 2006; Sodnik and Mikoš 2006, Vovk-Korže and Vrhovšek 2006; Frantar 2007; Breg et al. 2007; Polajnar 2008; Sahin 2009; Keesstra et al. 2009; Zorn 2009) were published during the last several years. Due to geographical similarities experiences from current Slovenian hydrological research can be applied also in Serbia.

Research of water accumulations in the region of Srem became more intensive when numerous problems related to water quality in lakes had been realized (Svirčev and Marković 1995; Simeunović et al 2005; Svirčev 2005; Svirčev et al. 2006, 2007; Dolinaj 2006; Dolinaj et al 2007, 2008a, 2008b).

In this study we present interdisciplinary investigation of the Borkovac reservoir limnological characteristics in the scope of its suistanable use for different purposes: irrigation, recreative fising and tourism. The goal of the research was to define present state as well as to gather information on present state of reservoir. Identified hydrological problems and proposed solutions in the case of the Borkovac accumulation are similar to other arteficial water bodies of the Fruška Gora mountain.

2 Methodology

2.1 Geographical settings

The Borkovac reservoir is situated in the central part of the southern slope of Fruška Gora mountain. Central lake point is situated at N 45° 02' 37.44'' and E 19° 49' 08.30''. The reservoir is situated 65 km from Belgrade and 35 km from Novi Sad (Figure 1).

Quaternary sediments in Borkovac reservoir drainage area are characterized by intense facial diversity, commonly with changes on short distances, both vertical and lateral. These characteristics were caused by palaoeclimatic and palaeoenvironment changes, as well as tectonic movements (Nenadić et al. 2001).

Quaternary deposits in Borkovac area are divided in three genetic types:

- deluvial-proluvial sediments on the Fruska Gora slopes as lateral equivalent of former sediments,
- loess-paleosol sequences (LPS) of Srem loess plateau (Marković et al. 2004, 2006, 2008).
- sediments of alluvial plain (Geologic Map SFRY, 1983) (Figure 2).

Deluvial-proluvial sediments were formed as polygenetic belt which covers slopes of Fruska Gora mountain. These deposits are known as »Srem series«, formed in torrent streams fan deltas and complex alluvial fans. Up to 70 m thick, these sediments lithologicaly consist gravels and sands in the base and in the central zone, silty clays and clayey silts of distal zone. They are genetically connected with maximum uplift of mountain ridge – not later than middle part of Middle Pleistocene (Jovanović in progress).

LPS, which covers deluvial-proluvial sediments, were formed mainly by aeolian and in some horizons by deluvial processes. Up to 20 m thick LPS were found in Ruma brickyard (4 km SE from Borkovac lake) and in few others brickyards and boreholes in the area (Jovanović, in progress). LPS in Ruma brickyard consist 5 paleosol and 6 loess units, formed during the last 4 glacial-interglacial cycles (ca. 350000 years) (Marković et al. 2004, 2006). Relatively high clay content in paleosol horizons (23–46%) is in contrast with ca. 10% in loess layers (Marković et al. 2006), represents suitable bottom for artificial lake formation. These soils were formed in fossil dells channels (Jovanović in progress). Thin layers of alluvial sediments are spread in alluvial plain od the Borkovac valley.

Climatological database for the period 1981–2008 were taken from Meteorological yearbook of Republic Hydrometeorological Service Serbia for the meteorological station Sremska Mitrovica. Figure 3. presents mean monthly air temperature and precipitation time series variability.

The dam was built in year 1972 on the southern part of the present lake basin, which was filed by water in following 3 years. Its length is 209 m and its height 11 m. It stretches from east to the west. Its length above water surface is 178 m. The dam itself represents soil levee whose sides are covered with concrete plates. Vertical concrete structure is situated in the central part of soil levee, which makes it stronger. Pouring canal was built in the western part of the dam. Its width is 6 m and its length is 22 m. It takes surplus amount of water when the water level is very high. Drain pipe is placed in the basis of the dam. It regulates lake level. The lake supplies Borkovac brook with water.

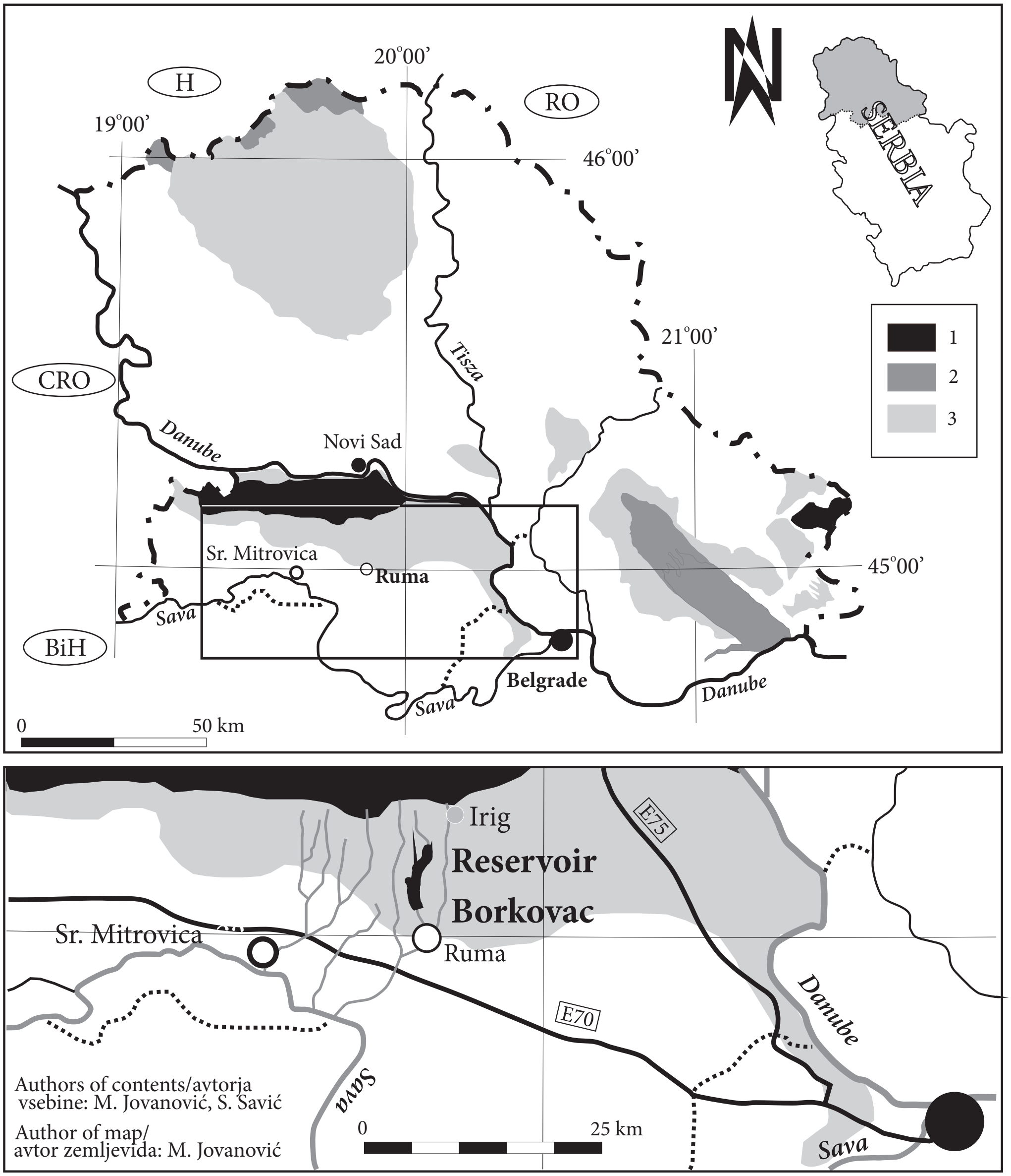
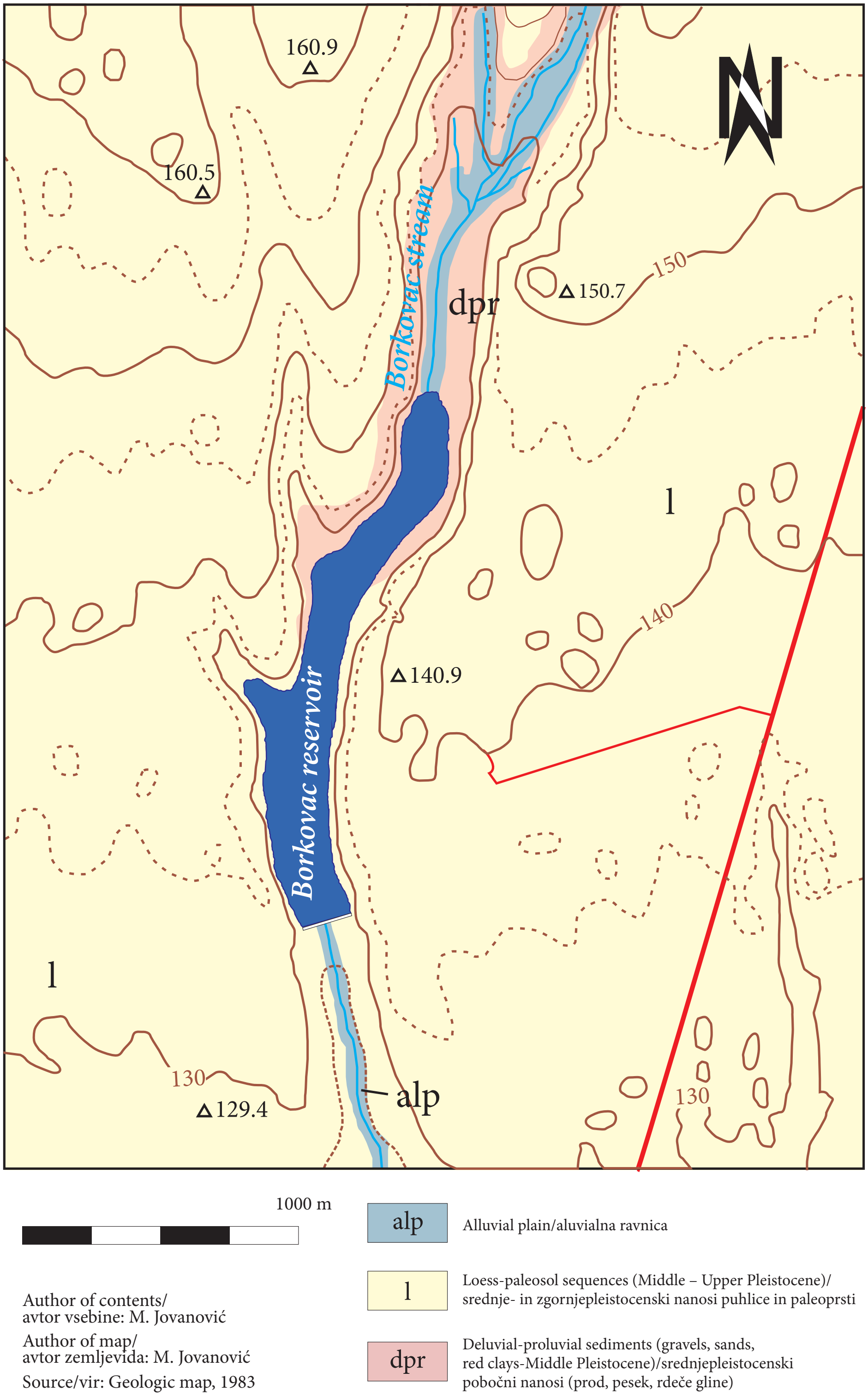


Figure 1: Geographical position of the Borkovac reservoir (1 – mountain; 2 – sandy area; 3 – loess plateau).

2.2 Methods

The research started with field investigation and information gathering. Cartographic basis of topographic section of 1:25000 from 1970 was used for definition of present state of Borkovac brook. Topographic map is digitalized and we obtained digital elevation model (DEM) (Nolan and Brigham-Grette 2007) of brook valley of Borkovac brook in the zone of present accumulation basin before the dam was built (Figure 4).

Figure 2: Topographic and Geological map of the area surrounding the Borkovac reservoir. ➤ p. 70


160.9
160.5
150.7
150
Borkovac stream
dpr
l
140
140.9
Borkovac reservoir
l
130
129.4
alp
130
1000 m
alp
Alluvial plain/aluvialna ravnica
l
Loess-paleosol sequences (Middle – Upper Pleistocene)/
srednje- in zgornjepleistocenski nanosi puhlice in paleoprsti
dpr
Deluvial-proluvial sediments (gravels, sands,
red clays-Middle Pleistocene)/srednjepleistocenski
pobočni nanosi (prod, pesek, rdeče gline)
Author of contents/
avtor vsebine: M. Jovanović
Author of map/
avtor zemljevida: M. Jovanović
Source/vir: Geologic map, 1983

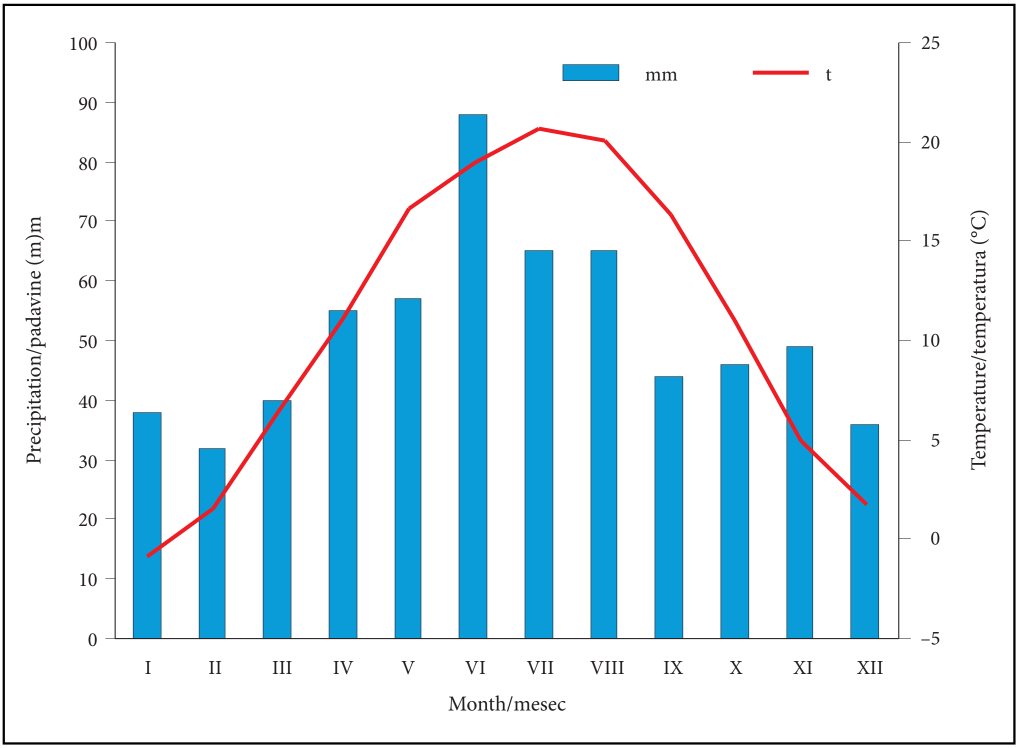


Figure 3: Mean monthly air temperatures (line) and precipitation (columns) variations at the investigated area (Meteorological station Sremska Mitrovica, period 1981–2008).

The process of deposition of fluvial and accumulation sediments started after the dam was built and Borkovac reservoir was formed. Following methods and instruments were used for definition of present state of accumulation and its morphometric characteristics: sonar instrument Humminbird and Garmin was used for depth measurements; cross section of the lake was done by the method of dual analysis, satellite images (Lemoalle 1991; Birkett 1995, 1998; Sarch and Birkett 2000) and field cross section was done with Laica laser measuring device (Brunskill and Ludlam 1969; Olsson at al. 1985). Batigraphic map (Brunskill and Ludlam 1969; Hunter 1970; Olafsson 1979; Vanriel and Johnson 1995; Vollmer at al. 2005) of the Borkovac reservoir was made according to obtained information. Obtained data were analyzed (Hakanson 1977, 1978; Olafsson 1979; Hakanson 1981, 1982; Hakanson and Karlsson 1983). Techniques of drilling were used for the analysis of sediments at the bottom of the lake basin (Hasler 1964), whereas results were presented with two-dimensional model (Qin, 1999). The thickness and spatial disposition of accumulated sediments at the bottom of accumulation were stated, too. Batigraphic map was digitalized and digital depth model of batigraphic map which shows present state at Borkovac accumulation was made (DM BM). Sediment thickness was marked according to number of years starting with the year when dam was built and reservoir start to fill up (1972) until year 2008. when research was completed (36 years). Sediments were sampled at 20 measuring points. It was supposed that deposition at each measuring point was done according to specific constant which defined the annual input of the sediment yield.

$Sx/36 = Qx$

whereas S represents sediment thickness (obtained according to field measurement);
x – index mark for sampled sediment measuring point (1, 2, 3, 4 … 20);
36 number of years from the period when accumulation was made since the end of research (2008);
Q – specific annual deposition constant for each measuring point.

Obtained values were analyzed at each measuring point. Multiplied specific annual deposition constant was added to obtained sediment value, whereas specific value was set for each point. Simple adding of obtained multiplied annual deposition values for each point defined possible future state of accumulation from the aspect of deposition of fluvial and accumulation material in 15 and 25 year period, since the research was finished in 2008.

$Sx + 15\ (25) \cdot Qx = Nx$
where S is sediment thickness
x – index mark for sampled sediment place (1, 2, 3, 4 … 20),
15 (25) – years of deposition
Q – specific annual deposition constant for each measured place;
N – expected future sediment thickness specific for each measuring point.

These values were processed by DDM BM (Figure 6) and digital depth models of possible future batigraphic map in the next 15 (DDM BM15) and 25 years (DDM BM25) were obtained (Figure 6; Figure 7).

Models such as the prediction of a two-dimension model with the scenarios of constant and sequenced deposition have already been noticed in limnology (Qin 1999).

Surface water temperature was measured during four months (January, April, July, October) in the period from 2003 to 2008 with standard termometre once a day, five times during a month. (Table 1).

Table 1 Average surface water temperature (°C) of Borkovac Lake in the period 2003–2008

January	April	July	October	Mean
1,2	11,1	27	12	12,8

3 Results and Discussion

From hydrological point of view loess layers are quite interesting since their porosity ranges from 35% to 45% (Dolinaj et al. 2008a). Filtration coefficient ranges from $K = 10^{-3}$ to 10^{-4} cm/s, whereas in deeper parts, where loess is degraded, it ranges from 10^{-4} to 10^{-6} cm/s (Dolinaj et al. 2008a). These parameters have significant influence on filtration, i.e. on water loss and breaking through lower and older geological series. Similar geological problems were noticed at some accumulations (Dolinaj et al. 2008a; Dolinaj et al. 2008b) in the region.

Morphology of the Borkovac loess valley makes possible significant water accumulation after relative small dam construction. However, other hydro-geomorphological characteristics indicate several important lamentations for sustainable existence of the Borkovac reservoir such as: small catchment and vuernability of LPS to erosion (Svirčev and Marković 1995).

The lake is extended in north-south direction which is conditioned by the shape of the lowest part of the brook valley (Figure 4). Lake Basin is the widest at the central part, at the west bay, whereas the lake narrows in the north. There is also one wider area 1.3 km north of the dam. Both western and eastern slopes of the valley are gentle. Western bank is above lake level only in its southern part (from the dam in the north direction from the wide bay) about 1.5–3 m. The bank of the lake is quite low in other parts and its slopes gently reach the lake basin.

Present morphometric data on the Borkovac reservoir are given according to the mean water level. The length of the lake is 2000 m. It was measured with broken line which connects mouth of Borkovački brook to the furthest western point of the dam. This direction slightly deviates from north-south direction. The greatest width of the lake is 320 m in the middle part of the lake across the wide bay in the western bank. The width of the lake ranges from 200 to 230 m from the dam to this line where the lake is widest. North from the line where the lake is the widest, the lake is 150 m wide, to the second, smaller bay in the western coast where the width of the lake is 230 m. The width of the lake is constant in the north direction, and it ranges from 150 to 160 m. Average width of the lake is 180 m. Western coast is more jagged and its length is 2400 m, i.e. 2000 m when compared to the left bank. Total length of the coastal line is 4400 m. It varies over the year and depends on water level. When water level is high, the lake floods lower

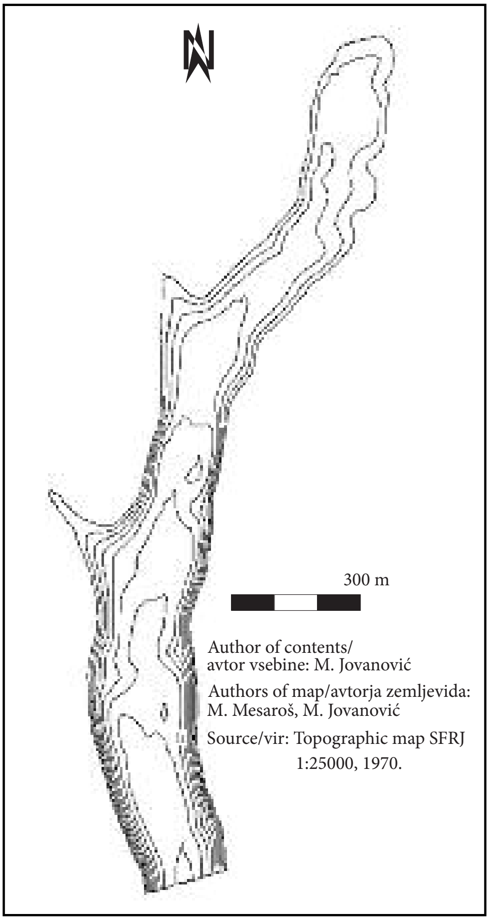


Figure 4: Digital elevation model of lake area before dam construction.

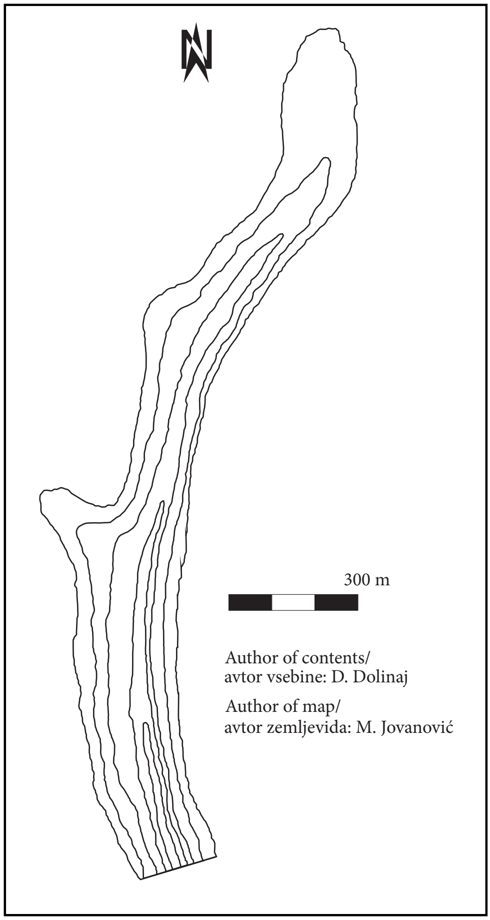


Figure 5: Batigraphic map of the Borkovac reservoir.

parts and its surface is bigger and coastal line is longer for 5–10%. The depth of the lake basin varies, too. Northern part of the lake is the shallowest. Its depth ranges from 0.5 to 1 m. Wide bay in the western coast is also quite shallow. Its depth is up to 1.5 m. The lake becomes deeper in the south direction. Water is deeper closer to the central part of the lake, whereas the slope is more prominent in the eastern coast. The Borkovac reservoir is the deepest in the central part near the dam (maximal measured depth is 5 m). The average depth of the Borkovac lake is 2.5 m. The surface of the lake occupies 360000 m^2, whereas it can change 2% over the year which depends on water level. The volume of the lake basin is 900000 m^3.

The morphometric data obtained by field measurement confirm that projected characteristics of accumulation were not taken into account when the dam was built and the area of future lake basin cleaned and the lake was formed (Table 2).

The main source of the brook is situated 10 km to the north from the lake basin. Borkovac strem discharge range from 1.5 l/sec to 12 l/sec. These data refer to the period from 2003 to 2008. They were taken from the profile situated 400 m north from the northeastern point of the lake basin of Borkovac accumulation.

Two smaller canals which reach lake basin were also digged. They supply lake with relatively large amounts of water at the end of the spring and the beginning of summer when plowed field and nuesery plants near the lake are drained. Precipitations bring certain amount of water to the lake due to direct contact to the surface or to the basin area. The greatest amount of precipitation is in the second half of the autumn, at

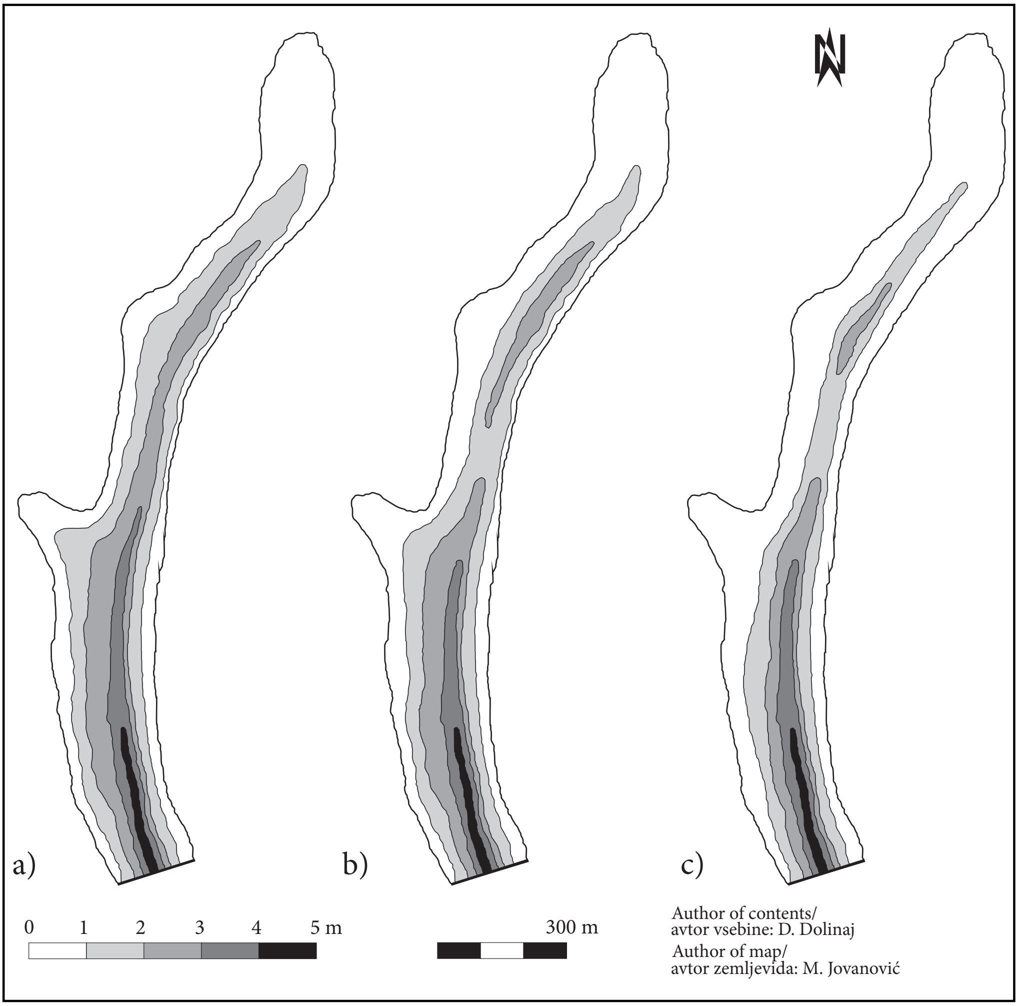


Figure 6: Digital depth model (a), and predicted batigraphic map after 15 years (b) and 25 years of sedimentation (c).

the end of spring and at the beginning of summer. The shallowest groundwater zone was discovered at loess and clay layers contact zone when lake basin was built. These springs have small and changeable water level, so that it is not possible to define their influence on total water regime of Borkovac lake. The lake loses water through drain pipe in the basis of the dam. Water release is controlled during a year and it depends on season and water influx to the lake basin. When water level is high the lake loses water through pouring canal which is situated close to the dam. Lake level varies over the year. Total annual amplitude of lake level is 70 to 130 cm and it varies over period of time. The level of the lake is lowest at September and October. Its maximum depth is 4.6 m over that period of time. Lake water level is the highest in the second half of November and the first half of December, during March and April. During that period maximum depth is 5.9 m.

The authors investigated process of deposition of fluvial sediments. These processes are typical of most lake basins in the region of Srem (Dolinaj at al. 2007; Dolinaj at al. 2008a; Dolinaj at al. 2008b) and Vojvodina (Svirčev at al. 2007). Depth of mud layers at the northern part of the lake in the central part ranges from 60 to 110 cm. Their depth at the sides of lake basin is about 70 cm. Directions as well as the continuity of

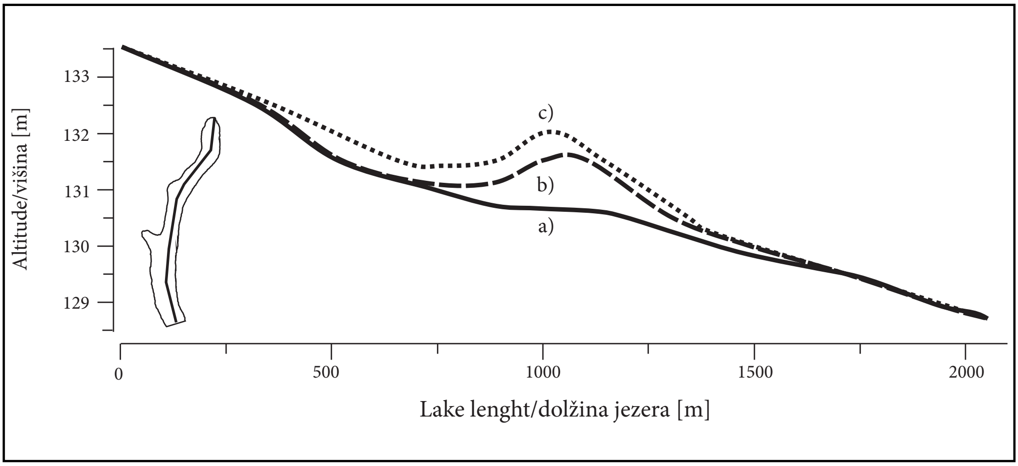


Figure 7: The reservoir cross section, digital depth model (a), and predicted batigraphic map after 15 years (b) and after 25 years of sedimentation (c).

deposit series were defined according to the analysis of strength of deposition of fluvial lake sediments. Figures 6 and 7 presents predicted state of deposits at the lake basin in the next 15 (DDM BM15) and 25 (DDM BM25) years. Greatest amount of deposits in the next 15 years is expected in central, narrowed part of the lake basin (Figure 6; Figure 7). It will be most prominent in central, narrowed part and north from it over that period of time (Figure 6; Figure 7).

Surface water temperature generally follows trends of air temperature. Daily temperature of water exceeds 28 °C in July and August, whereas it is about 1 °C in the coldest period of year (Table 2). Lake was covered with ice 9 to 18 days during winter in the period from 2003 to 2008. Water transparency varies from 40–50 cm (in the spring) to 1.3 m (in the summer).

Table 2: Morphometric characteristics of Borkovac reservoir at the mean water level.

	Projected	Present state	Percent of projected (~%)
Length (m)	2800	2000	71
Width: maximum/mean (m)	–	320/180	–
Length of coastal line (m)	–	4400	–
Coastal line development	–	2.1	–
Depth maximum/mean (m)	8.3/–	5/2.5	60
Surface (m^2)	414000	360000	87
Volume (m^3)	1486900	900000	61

The water quality of the Borkovac reservoir was intensively investigated over the years. The results are presented in several publications (Svirčev and Marković 1995; Svirčev et al. 2008, 2009). According to standard physical, chemical and biological parametres (disolved oxygen, % oxygen saturation, saprobity level, biological oxygen demand, chemical oxygen demand, the most probably number of coliforms, suspended matter, dry metter after filtration, pH, floating materials, clor, odor and some others) Borkovac accumulation can be categorized as mesotrophic lake, with high production of organic matter and organic sediment accumulation at the bottom. Qualitative and quantitative structure of phytoplankton, and phytoperiphyton shows high level of eutrophication (Svirčev et al. 2008). According to saprobiological characteristics of zooplankton and benthic invertebrates *!!*-mezosaprobic level was stated, with occasional occurance of *!!*-mezosaprobic and polysaprobic level, which shows gradual eutrophication of the lake. However, if we consider the blooms of potentially toxic cyanobacteria (blue-green algae) and microalgae, water of Borkovac accumulation can be categorized as polisaprobic and occasionally with human and animal health risks. According to research (1990–2010), characteristic blooms have been noticed at least once a year in the period from May to November (Simeunović et al. 2005; Svirčev et al. 2007). Bloom is characterized with uncontrolled proliferation of microalgae and cyanobacteria (Svirčev 2005) and it regularly occurs in other highly saprobic accumulations in Serbia and worldwide (Graneli and Turner 2006).

Cyanobacterial strains belonging to Phormidium, Microcystis and Aphanisomenon genera have been blooming very often in Borkovac accumulation. Most of them were isolated from blooming water and they represent the part of cyanobacterial culture collection NSCCC which belongs to the Department for Biology and Ecology, Faculty of Sciences in Novi Sad (Simeunović 2005). These strains produce cyanotoxins in laboratory conditions and they are potentially dangerous for people who use water from Borkovac accumulation in recreational, fishing and irrigationg purposes. Beside cyanobacteria, some species belonging to Pyrrophyta, such as Ceratium hirundinella have also been blooming in Borkovac accumulation (Simeunović et al. 2005).

The objective of this study is also to identify the key issues and questions posed in the management of the water resources similar to Borkovac reservoir and to contribute to rationale for selecting the most appropriate approach to the specific problems at similar water bodies in the region.

Through systematic investigations on Borkovac reservoir we identified several serious environmental problems and confirmed the trend of significant water quality deterioration, mostly due to drastic shrinking of the water body, agricultural runoff from surrounded fields and originally high total capacity (Svirčev 2005). The remediation strategies that we suggest include construction of the sediment precipitator at the Borkovac stream junction to lake, sediment removal, artificial water mixing and oxygenation, phosporous inactivitation, different kinds of biomanipulations and biomass removal (Svirčev et al. 2009), as well as to propose application of the ecoremedation methods (ERM) developed by Vovk-Korže and Vrhovšek (2006). ERM techniques in broader sense have been applied for more than 20 years in Slovenia and in the other countries of former Yugoslavia. Already established successful examples of ERM methods as perspective long-term approach are utilizing natural processes and systems in favour of the remediation of degraded ecosystems and environmental protection (Vovk-Korže and Vrhovšek 2006). ERM is still not implemented properly in water ecosystems in the Vojvodina region. However, application of the ERM methods for environmental protection and restoration would have special importance for the Borkovac reservoir: 1) introduction of ERM »in vivo« in northern part of accumulation using autochthonous macrophytes, 2) introduction of wetlands »in vitro« outside of the reservoir, in the basement of dam using alochtonous vegetation and 3) special wetlands in surrounding channels in order to prevent agricultural runoff. Similar methods might be implemented in some other accumulations located at the slopes of the Fruška Gora Mountain, due to their seasonal pollution patterns and overall lack of fresh water resources in the region.

4 Conclusion

The Borkovac reservoir is one of the most investigated water bodies at the Fruška Gora Mountain. Since 1975, when the reservoir has been established, the main observed environmental concerns are:

Smaller than planed water volume; present volume of lake basin is 900000 m^3; it is smaller than originally planed for 586900 m^3 (39%) and it still decrease.

Intensive sedimentation in the lake – thickness of mud layer ranges from 60 cm to 110 cm. At the sides of the lake basin thickness of the layer is 70 cm. Fill up of the central and northern part of the lake basin is expected in the next 15 or 25 years.

Frequent blooms of cyanobacteria belonging to Phormidium, Microcystis and Aphanisomenon genera which produce potent cyanotoxins We proposed possible solutions for identified problems: construction of the sediment precipitator at the Borkovac stream junction to lake, sediment removal, artificial water mixing and oxygenation, phosphorous inactivitation, different kinds of biomanipulations and biomass removal and introduction of ecoremedation methods These methods could also be applied to other similar water reservoirs in order to improve their ecological condition, prevent eutrophication and enable adequate management and sustainable use of them for different purposes such as drinking water use, fishing and recreation.

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Limnološke značilnosti, vodni režim in problemi kakovosti vode akumulacijskega jezera Borkovac (Vojvodina, Srbija)

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IZVLEČEK: V študiji predstavljamo interdisciplinarno raziskavo o akumulacijskem jezeru Borkovac (Vojvodina, Srbija). Analizirali smo limnološke značilnosti jezera v okviru njegove sonaravne rabe za potrebe namakanja, ribolova in turizma. To večnamensko vodno zajetje je bilo narejeno leta 1975 kot del regionalnega hidrološkega sistema na območju Fruške gore.
V študiji smo ugotovili, da predstavljajo glavne okoljske probleme tile dejavniki: vodni režim, intenzivna sedimentacija v akumulacijskem jezeru, povečana vodna evtrofikacija in cvetenje toksičnih cianobakterij. Ugotovljeni okoljski problemi in predlagane rešitve v primeru akumulacijskega jezera Borkovac, kot so izgradnja sedimentnega filtra ob izlivu vodotoka Borkovac v jezero, odstranjevanje sedimentov, umetno mešanje vode in oksigenacija, inaktivacija fosforja, razni načini biomanipulacij in odstranitev biomase ter uvedba ekoremediacijskih metod, bi se lahko nanašali tudi na druga umetna vodna telesa na pobočjih Fruške gore.

KLJUČNE BESEDE: geografija, hidrologija, limnologija, umetna jezera, akumulacijsko jezero Borkovac, Vojvodina, Srbija

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1 Uvod

Čeprav so raziskave o vodnih virih zelo pomembne, je za države zahodnega Balkana značilno njihovo pomanjkanje. V zadnjih nekaj letih pa je bilo vendarle objavljenih več študij o različnih problemih vodne rabe, največ v Sloveniji (Smrekar 2006; Sodnik in Mikoš 2006, Vovk-Korže in Vrhovšek 2006; Frantar 2007; Breg et al. 2007; Polajnar 2008; Sahin 2009; Keesstra et al. 2009; Zorn 2009). Zaradi geografskih podobnosti lahko izkušnje iz novejših slovenskih hidroloških raziskav uporabimo tudi v Srbiji.

Vodne akumulacije na območju Srema so začeli intenzivneje raziskovati šele takrat, ko so ugotovili, da narašča število problemov, povezanih s kakovostjo vode v jezerih (Svirčev in Marković 1995; Simeunović et al 2005; Svirčev 2005; Svirčev et al. 2006, 2007; Dolinaj 2006; Dolinaj et al 2007, 2008a, 2008b).

V študiji predstavljamo interdisciplinarno raziskavo limnoloških značilnosti akumulacijskega jezera Borkovac v okviru njegove sonaravne rabe za potrebe namakanja, rekreacijskega ribolova in turizma. Cilj raziskave je bil opredeliti sedanje stanje in zbrati informacije o sedanjem stanju akumulacijskega jezera. Ugotovljeni hidrološki problemi in predlagane rešitve v primeru akumulacijskega jezera Borkovac so podobni kot pri drugih umetnih vodnih telesih na območju Fruške gore.

2 Metodologija

2.1 Geografski okvir

Akumulacijsko jezero Borkovac se nahaja v osrednjem delu južnega pobočja Fruške gore. Njegova središčna točka leži na 45° 02' 37,44'' s. g. š. in 19° 49' 08,30'' v. g. d. Od Beograda je oddaljeno 65 km in od Novega Sada 35 km (Slika 1).

Slika 1: Lega jezera Borkovac (1 – gore; 2 – peščeno območje; 3 – puhlična planota).
Glej angleški del prispevka.

Značilna za kvartarne sedimente v prispevnem območju akumulacijska jezera Borkovac je intenzivna raznolikost plasti; običajno se te spremembe kažejo na kratke razdalje, tako vertikalno kot horizontalno. Te značilnosti so nastale zaradi paleoklimatskih in paleo-okoljskih sprememb, pa tudi zaradi tektonskih premikov (Nenadić et al. 2001).

Po nastanku se kvartarni nanosi na območju Borkovca delijo na tri tipe:

- deluvialno-proluvialni sedimenti na pobočjih Fruške gore kot stranski ekvivalent nekdanjih sedimentov,
- zaporedja puhlica–paleoprst (LPS) na planoti Srem (Marković et. al. 2004, 2006, 2008).
- sedimenti aluvialne ravnice (Geološka karta SFRJ, 1983) (Slika 2).

Deluvialno-proluvialni sedimenti so nastali v obliki poligenskega pasu, ki pokriva pobočja Fruške gore. Ti nanosi, ki so znani pod imenom sremska serija, so nastali v hudourniških vršajih in kompleksnih aluvialnih vršajih. Litološka sestava teh do 70 m globokih sedimentov je: prod in pesek v osnovi in v osrednjem delu ter meljaste-gline in glineneni-melj v robnih predelih. Po nastanku so povezani z najvišjim tektonskim dvigom gorskega hrbta, ki se ni zgodil kasneje kot v srednjem delu Srednjega Pleistocena (Jovanović, v pripravi).

Slika 2: Topografska in geološka karta okolice akumulacijskega jezera Borkovac.
Glej angleški del prispevka.

LPS, ki pokrivajo deluvialno-proluvialne sedimente, so nastala pretežno z eolskimi procesi, le v nekaterih horizontih pa z deluvialnimi procesi, t. j. disperznim spiranjem. Do 20 m globoke LPS so odkrili v opekarni v Rumi (4 km JV od jezera Borkovac) in nekaterih drugih opekarnah in vrtinah na tem območju (Jovanović, v pripravi). LPS v rumski opekarni sestojijo iz 5 con paleoprsti in 6 con puhlice, nastalih med zadnjimi štirimi glacialno-interglacialnimi ciklusi (pribl. 350.000 let) (Marković et al. 2004, 2006). Za razliko od puhličnih plasti, kjer je gline pribl. 10%, predstavljajo horizonti paleoprsti z relativno visoko vsebnostjo gline (23–46%) (Marković et al. 2006) primerno dno za nastanek umetnega jezera. Te prsti so nastale v fosilnih strugah sotesk (Jovanović, v pripravi). Plitve plasti aluvialnih sedimentov se raztezajo v aluvialni ravnici doline Borkovac.

Slika 3: Srednje mesečne temperature zraka (linija) in nihanja padavin (stolpci) na raziskovanem območju (Meteorološka postaja Sremska Mitrovica, obdobje 1981–2008).
Glej angleški del prispevka.

Klimatološke podatke za obdobje 1981–2008 za meteorološko postajo Sremska Mitrovica smo vzeli iz Meteorološkega letopisa republiške hidrometeorološke službe Srbije. Slika 3 kaže srednje mesečne temperature zraka in nihanje padavin v tem obdobju.

Leta 1972 so na južnem delu sedanje jezerske kotanje, ki se je v naslednjih treh letih napolnila z vodo, zgradili jez dolžine 209 m in višine 11 m. Razteza se v smeri od vzhoda na zahod, nad vodno gladino sega v dolžini 178 m. Sam jez predstavlja nasip, katerega stranici sta pokriti z betonskimi ploščami. V osrednjem delu nasipa stoji navpična betonska struktura, ki daje nasipu večjo trdnost. Na zahodnem delu jeza je bil zgrajen prelivni kanal širine 6 m in dolžine 22 m, ki odvaja odvečno vodo, kadar je gladina previsoka. Odtočna cev je nameščena v bazi jezu in regulira gladino jezera. Jezeru dovaja vodo potok Borkovac.

2.2 Metode

Raziskovanje se je začelo z raziskavami na terenu in zbiranjem podatkov. Kot kartografsko osnovo za opredelitev sedanjega stanja potoka Borkovac smo uporabili topografsko sekcijo v merilu 1:25.000 iz leta 1970. Z digitaliziranjem topografske karte smo dobili digitalni model reliefa (DEM) (Nola and Brigham-Grette 2007) sedanjega območja akumulacijske kotanje v dolini potoka Borkovac, kakršno je bilo, preden je bil zgrajen jez (Slika 4). Proces odlaganja rečnih in akumulacijskih sedimentov se je začel po tem, ko je bil zgrajen jez in se je izoblikovalo akumulacijsko jezero Borkovac. Za opredelitev sedanjega stanja jezera in morfometričnih značilnosti smo uporabili sledeče metode in instrumente: za merjenje globin sonar (tip Humminbird in Garmin); prečni prerez jezera smo naredili z dvojno analizo: 1) s pomočjo satelitskih posnetkov (Lemoalle 1991; Birkett 1995, 1998; Sarch and Birkett 2000) in 2) s terenskim merjenjem z lasersko merilno napravo Laica (Brunskill and Ludlam 1969; Olsson et al. 1985). Batimetrično karto (Brunskill and Ludlam 1969; Hunter 1970; Olafsson 1979; Vanriel and Johnson 1995; Vollmer et al. 2005) akumulacijskega jezera Borkovac smo naredili na osnovi dobljenih podatkov. Pridobljene podatke smo nato analizirali (Hakanson 1977, 1978; Olafsson 1979; Hakanson 1981, 1982; Hakanson and Karlsson 1983). Z raznimi tehnikami vrtanja smo prišli do podatkov, ki smo jih uporabili za analizo sedimentov na dnu jezerske kotline (Hasler 1964), rezultate pa smo predstavili z dvo-dimenzionalim modelom (Qin, 1999). Navedeni sta tudi debelina in prostorska razporeditev akumulacijskih sedimentov na dnu kotanje. Batimetrično karto smo digitalizirali in naredili digitalni batimetrični model, ki kaže sedanje stanje akumulacijskega jezera Borkovac (DDM BM). Globino sedimentov smo označili po številu let, začenši z letom, ko je bil jez zgrajen in se je kotanja začela polniti (1972), pa do leta 2008, ko je bila raziskava končana (36 let). Vzorce sedimentov smo vzeli na 20 merilnih točkah. Predpostavka je bila, da se je na vsaki merilni točki sedimentacija odvijala v skladu s specifično konstanto, ki je opredeljevala letni vnos celotnega sedimenta.

$$Sx / 36 = Qx$$

kjer so:
S – debelina sedimenta (dobljena z merjenjem na terenu)
x – indeksna oznaka za merilno točko, kjer je bil vzet sedimentni vzorec (1, 2, 3, 4 … 20)
36 – število akumulacijskih let – od izgradnje jezu do zaključka raziskovanja (2008)
Q – konstanta specifičnega letnega nanosa za vsako merilno točko

Dobljene vrednosti smo analizirali za vsako merilno točko posebej. Pomnožena konstanta specifičnega letnega nanosa je bila dodana dobljeni vrednosti sedimenta, in specifična vrednost je bila določena za vsako točko. Z enostavnim seštevanjem dobljenih pomnoženih letnih vrednosti nanosov za vsako točko smo opredelili potencialno prihodnje stanje akumulacije glede na nanose rečnega in akumulacijskega materiala v 15 oz. 25 letih, saj smo raziskavo leta 2008 končali.

$Sx + 15\ (25) \cdot Qx = Nx$
kjer so:
S – debelina sedimenta
x – indeksna oznaka za mesto, kjer je bil vzet sedimentni vzorec (1, 2, 3, 4 … 20),
15 (25) – leta nanašanja
Q – konstanta specifičnega letnega nanosa za vsako merjeno mesto
N – pričakovana prihodnja debelina sedimenta za vsako merilno točko

Te vrednosti so bile obdelane z DDM BM (Slika 6) in dobili smo digitalne batimetrične modele potencialnih prihodnjih batimetričnih kart za naslednjih 15 (DDM BM15) in 25 let (DDM BM25) (Slika 6; Slika 7).

Modeli za napovedovanje dvo-dimenzionalnega modela s predvidevanji za konstantno in zaporedno nanašanje so bili v limnologiji že narejeni (Qin 1999)

Temperaturo površinske vode smo merili s standardnim termometrom v štirih mesecih (januarja, aprila, julija, oktobra), in to enkrat dnevno po pet dni v mesecu, v obdobju od 2003 do 2008 (Preglednica 1).

Preglednica 1: Povprečne površinske temperature vode (°C) v jezeru Borkovac v obdobju 2003–2008

Januar	April	Julij	Oktober	Srednja
1,2	11,1	27	12	12,8

3 Rezultati in razprava

S hidrološkega stališča so plasti puhlice kar precej zanimive, saj je njihova poroznost od 35 % do 45 % (Dolinaj et al. 2008a). Filtracijski koeficient znaša od $K = 10^{-3}$ do 10^{-4} cm/s, medtem ko znaša v globljih delih, kjer je puhlica degradirana, od 10^{-4} do 10^{-6} cm/s (Dolinaj et al. 2008a). Ti parametri imajo močan vpliv na filtriranje, t. j. na izgubo vode in njeno prodiranje skozi nižje in starejše geološke plasti. Podobni geološki problemi so bili ugotovljeni tudi pri nekaterih drugih akumulacijskih zajetjih (Dolinaj et al. 2008a; Dolinaj et al. 2008b) v regiji.

Morfologija puhlične doline Borkovac omogoča znatno vodno akumulacijo že ob izgradnji relativno majhnega jezu. Vendar pa druge hidro-geomorfološke značilnosti opozarjajo na upravičeno bojazen glede sonaravnosti obstoja akumulacijskega jezera Borkovac, in sicer zaradi majhnega prispevnega območja in erozijske ranljivosti LPS (Svirčev and Marković 1995).

Jezero se razteza v smeri sever–jug, kar je pogojeno z obliko najnižje ležečega dela potočne doline (Slika 4). Jezerska kotanja je najširša v osrednjem delu ob zahodnem zalivu, na severu pa se jezero zoži. Še eno širše območje se nahaja tudi 1,3 km severno od jezu. Dolinska pobočja so položna na obeh straneh, zahodni in vzhodni. Zahodni breg se dviga nad jezersko gladino zgolj na južnem delu (od jezu v smeri proti severu do širokega zaliva) za okrog 1,5–3 m. Na drugih delih je jezerski breg čisto nizek in pobočja se blago spuščajo prav do jezerske kotline.

Slika 4: DEM jezerskega območja pred izgradnjo jezu.
Glej angleški del prispevka.

Slika 5: Batimetrična karta akumulacijskega jezera Borkovac.
Glej angleški del prispevka.

Morfometrični podatki akumulacijskega jezera Borkovac so podani za srednjo vodno gladino. Dolžina jezera je 2000 m in je bila izmerjena z lomljeno linijo, ki povezuje ustje potoka Borkovac z najbolj oddaljeno zahodno točko jeza. Ta smer rahlo odstopa od smeri sever–jug. Jezero je najširše, t. j. 320 m, v osrednjem delu čez širokegi zaliv na zahodnem bregu. Od jezu do te linije, kjer je jezero najširše, je širina jezera od 200 do 230 m, severno od te linije je jezero široko 150 m, in to do drugega manjšega zaliva na zahodni obali, kjer je širina jezera 230 m. Od tu na sever je širina jezera konstantna in znaša od 150 do 160 m. Povprečna širina jezera je 180 m. Zahodna obala je bolj razčlenjena, dolga je 2400 m za razliko od vzhodnega brega, ki je dolg le 2000 m. Skupna dolžina obalne linije je 4400 m, a se preko leta spreminja, saj je odvisna od vodne gladine. Ko je gladina visoka, jezero poplavi nižje dele in s tem se njegova površina poveča, obalna linija pa podaljša za 5–10%. Tudi globina jezera ni enakomerna. Najplitvejši je njegov severni del, od 0,5 do 1 m. Precej plitev, do 1,5 m, je široki zaliv na zahodni obali. Proti jugu je jezero vse globlje in je najgloblje v osrednjemu delu, ob tem, da se vzhodna stran jezerske kotanje bolj strmo spušča proti dnu. Akumulacijsko jezero Borkovac doseže največjo globino v osrednjem delu v bližini jezu (največja izmerjena globina je 5 m). Povprečna globina jezera je 2,5 m, njegova površina znaša 360.000 m^2, med letom pa se lahko spremeni do 2%, kar je odvisno od vodne gladine. Prostornina jezerske kotanje je 9000.000 m^3.

Morfometrični podatki, pridobljeni s terenskim merjenjem, kažejo, da predvidene lastnosti akumulacijskega jezera niso bile upoštevane, ko so gradili jez in čistili območje bodoče jezerske kotanje, da je nastalo jezero (Preglednica 2).

Preglednica 2: Morfometrične značilnosti akumulacijskega jezera Borkovac ob srednji vodni gladini.

	Načrtovano	Sedanje stanje	Delež načrtovanega (~%)
Dolžina (m)	2800	2000	71
Širina: največja/srednja (m)	–	320/180	–
Dolžina obalne linije (m)	–	4400	–
Razvoj obalne linije	–	2,1	–
Globina: največja/srednja (m)	8.3/–	5/2,5	60
Površina (m^2)	414.000	360.000	87
Prostornina (m^3)	1.486.900	900.000	61

Glavni izvir potoka Borkovac leži 10 km severno od jezerske kotanje. Njegov pretok se giblje od 1,5 l/sec do 12 l/sec, podatki pa se nanašajo na obdobje od 2003 do 2008. Pridobljeni so bili na profilu, ki leži 400 m severno od skrajno severovzhodne točke jezerske kotanje akumulacijskega jezera Borkovac.

Izkopana sta bila tudi dva manjša kanala do kotanje. Tadva napajata jezero z relativno velikimi količinami vode konec pomladi in v začetku poletja, ko se odvaja voda z zoranega polja in drevesnice v bližini jezera. Določeno količino vode zagotavljajo jezeru padavine, ki padejo neposredno na površino jezera in v prispevno območje. Količina padavin je največja v drugi polovici jeseni, konec pomladi in v začetku poletja. Ob izgradnji jezerske kotanje je na stiku puhlične plasti z glinenim slojem privrela na dan talnica iz najplitvejšega vodonosnika. Količina vode v teh izvirih je majhna in spremenljiva in zato ni možno ugotoviti kakšen vpliv imajo na vodni režim jezera Borkovac. Voda odteka iz jezera skozi odtočno cev v bazi jezu. Vodno odtekanje nadzirajo vse leto in je odvisno od letnega časa in dotoka vode v jezersko kotanjo. Ko je vodna gladina visoka, voda odteka iz jezera skozi prelivni kanal, ki se nahaja tik ob jezu. Gladina jezera se skozi leto spreminja. Celoletna amplituda jezerske gladine se giblje med 70 in 130 cm in se z obdobji spreminja. Jezerska gladina je najnižja septembra in oktobra, in v tem obdobju znaša največja globina 4,6 m. Najvišja gladina se pojavi v drugi polovici novembra in prvi polovici decembra ter v marcu in aprilu. V tem času znaša največja globina 5.9 m.

Avtorji so raziskali proces nanašanja rečnih sedimentov. Ti procesi so značilni za večino jezerskih kotanj na območju Srema (Dolinaj et al. 2007; Dolinaj et al. 2008a; Dolinaj et al. 2008b) in Vojvodine (Svirčev et al. 2007). Plasti blata so v severnem delu jezera na sredini debele od 60 do 110 cm, na robovih jezerske kotanje pa okrog 70 cm. Smeri in kontinuiteto sedimentnih slojev smo določili s pomočjo analize moči odlaganja rečnih jezerskih sedimentov. Sliki 6 in 7 kažeta predvideno stanje sedimentov v jezerski kotlini v naslednjih 15 (DDM BM15) in 25 (DDM BM25) letih. Največja količina sedimentov v naslednjih 15 letih se pričakuje v osrednjem, zožanem delu jezerske kotanje (slika 6; slika 7). V tem času bo nanašanje najbolj izrazito v osrednjem, zožanem delu in severno od njega (slika 6; slika 7).

Slika 6: Digitalni model globin v sedanjih razmerah (a) ter po ocenjeni petnajstletni (b) oziroma petindvajsetletni sedimentaciji (c).
Glej angleški del prispevka.

Slika 7: Prečni prerez akumulacijskega jezera, digitalni model globin v sedanjih razmerah (a) ter po ocenjeni petnajstletni (b) oziroma petindvajsetletni sedimentaciji (c).
Glej angleški del prispevka.

Temperatura vode na površini v splošnem sledi spremembam temperature zraka. Julija in avgusta je dnevna temperatura vode višja od 28 °C, v najhladnejšem obdobju leta pa je le okrog 1 °C (tabela 2). V obdobju 2003–2008 je bilo jezero pozimi prekrito z ledom od 9 do 18 dni. Prosojnost vode se giblje med 40–50 cm (spomladi) in 1,3 m (poleti).

Kakovost vode v akumulacijskem jezeru Borkovac so intenzivno raziskovali več let. Rezultati so objavljeni v več strokovnih publikacijah (Svirčev and Marković 1995; Svirčev et al. 2008, 2009). Po standardnih fizikalnih, kemičnih in bioloških parametrih (razvezani kisik, % zasičenosti s kisikom, raven saprobnosti, biološka potreba po kisiku, kemična potreba po kisiku, najbolj verjetno število koliform, suspenzijski material, suha snov po filtriranju, pH, plavajoči delci, klor, vonj in nekateri drugi) bi akumulacijsko jezero Borkovac lahko uvrstili med mezotrofna jezera z visoko proizvodnjo organskih snovi in akumulacijo organskih sedimentov na dnu. Kakovostna in količinska struktura fitoplanktona in fito-perifitona kaže visoko raven evtrofikacije (Svirčev et al. 2008). Glede na saprobiološke lastnosti zooplanktona in bentičnih nevretenčarjev je bila ugotovljena mezosaprobna raven z občasnim pojavljanjem ?mezosaprobne in polisaprobne ravni, kar kaže na postopno evtrofikacijo jezera. Če pa upoštevamo cvetenje potencialno toksičnih cianobakterij (modro-zelene alge) in mikroalg, lahko vodo akumulacijskega jezera Borkovac opredelimo kot polisaprobno in občasno nevarno za zdravje ljudi in živali. Raziskava v letih 1990–2010 je razkrila, da je bilo značilno cvetenje opaziti vsaj enkrat letno v času od maja do novembra (Simeunović et al. 2005; Svirčev et al. 2007). Značilno za cvetenje je nekontrolirano razmnoževanje mikroalg in cianobakterij (Svirčev 2005), kar se redno pojavlja tudi v drugih močno saprobnih akumulacijskih jezerih v Srbiji in drugod po svetu (Graneli and Turner 2006).

Vrste cianobakterij iz rodov Phormidium, Microcystis in Aphanisomenon zelo pogosto cvetijo v akumulacijskem jezeru Borkovac. Večino so jih izolirali iz cvetoče vode in zdaj so del zbirke cianobakterijskih kultur NSCCC, ki jo imajo na Oddelku za biologijo in ekologijo Fakultete za naravoslovne in matema - tičn vede v Novem Sadu (Simeunović 2005). Te vrste v laboratorijskih razmerah proizvajajo cianotoksine in so potencialno nevarne za ljudi, ki uporabljajo vodo iz akumulacijskega jezera Borkovac za rekreacijo, ribolov in namakanje. Poleg cianobakterij so v akumulacijskem jezeru Borkovac cvetele tudi nekatere vrste Pyrrophyta, npr. Ceratium hirundinella (Simeunović et al. 2005).

Namen te študije je bil tudi opredeliti ključne probleme in vprašanja, kakršni se kažejo pri upravljanju vodnih virov, ki so podobni akumulacijskemu jezeru Borkovac, ter prispevati k osnovnim smernicam, kaj izbrati kot naustreznejši pristop k določenim problemom pri podobnih vodnih telesih v regiji.

S sistematično raziskavo akumulacijskega jezera Borkovac nam je uspelo opredeliti več hujših okoljskih problemov in potrditi vse občutnejše upadanje kakovosti vode, v glavnem zaradi korenitega krčenja vodnega telesa, kmetijskega površinskega odtoka z okoliških polj in izvorno velike prostornine jezerske kotanje (Svirčev 2005). K predlaganim remediacijskim strategijam spadajo: izgradnja sedimentnega filtra ob ustju pritoka Borkovac, odstranitev sedimenta, umetno mešanje vode in oksigenacija, inaktivacija fosfor - ja, različne vrste biomanipulacij in odstranitev biomase (Svirčev et al. 2009), predlagamo pa tudi, da se uporabijo ekoremediacijske metode (ERM), ki sta jih razvila Vovk-Korže in Vrhovšek (2006). Tehnike ERM v širšem smislu se že več kot 20 let uporabljajo v Sloveniji in drugih državah nekdanje Jugoslavije. Že uve - ljavljene uspešne metode ERM se kot perspektiven dolgoročen pristop v korist remediacije degradiranih ekosistemov in okoljske zaščite poslužujejo naravnih procesov in sistemov (Vovk-Korže and Vrhovšek 2006). V vojvodinski regiji ERM še vedno niso ustrezno izvajane v vodnih ekosistemih. Na vsak način bi bila uporaba metod ERM za varstvo in obnovo okolja še prav posebnega pomena pri akumulacijskem jezeru Borkovac, in sicer: 1.) z vpeljavo ERM in vivo v severnem delu akumulacijskega jezera z uporabo avtohtonih makro - fitov; 2.) z uvedbo mokrišč in vitro zunaj akumulacijskega jezera, ob bazi jezu z uporabo alohtonega rastlinja; in 3.) s posebnimi mokrišči v okoliških strugah, da bi preprečili kmetijski površinski odtok. Podobne metode bi lahko uporabili tudi pri drugih vodnih akumulacijah na pobočjih Fruške gore zaradi njihove redne sezonske onesnaženosti in vsesplošnega pomanjkanja virov pitne vode v regiji.

4 Sklep

Akumulacijsko jezero Borkovac je eno najbolje raziskanih vodnih teles na območju Fruške gore. Od leta 1975, ko je bilo akumulacijsko jezero dokončno formirano, so bili ugotovljeni kot glavni okoljski problemi tile:

- Manjša vodna prostornina od načrtovane; sedanja prostornina jezerske kotanje je 900.000 m^3 in je od prvotno načrtovane manjša za 586.900 m^3 (39 %) in še upada.

- Intenzivna sedimentacija v jezeru – debelina plasti blata se giblje od 60 cm do 110 cm. Ob straneh jezerske kotanje je debelina te plasti 70 cm. Zapolnitev osrednjega in severnega dela kotanje se pričakuje v naslednjih 15 do 25 letih.
- Pogosto cvetenje cianobakterij iz rodov Phormidium, Microcystis in Aphanisomenon, ki proizvajajo močne cianotoksine.

Za ugotovljene probleme smo predlagali sledeče možne rešitve: izgradnjo sedimentnega filtra na kraju, kjer se v jezero izliva vodotok Borkovac, odstranitev sedimenta, umetno mešanje vode in oksigenacijo, inaktivacijo fosforja, različne vrste biomanipulacije in odstranitev biomase ter uvedbo metod za ekoremediacijo. Te metode bi lahko uporabili tudi pri drugih podobnih akumulacijskih jezerih, da bi izboljšali njihovo ekološko stanje, preprečili evtrofikacijo in s tem omogočili ustrezeno upravljanje z njimi ter njihovo sonaravno rabo za različne namene, kot so npr. uporaba za pitno vodo, ribištvo in rekreacija.

5 Zahvala

Delo je bilo delno podprto s Projektom št. 176020 Srbskega ministrstva za znanost in varstvo okolja. Zahvaljujemo se dvema neimenovanima recenzentoma za njune dragocene pripombe, ki so znatno prispevale h kakovosti tega članka.

6 Literatura

Glej angleški del prispevka.