UNIVERZA V LJUBLJANI
BIOTEHNIŠKA FAKULTETA

Vesna PETKOVSKA

VPLIV HIDROMORFOLOŠKIH LASTNOSTI VODOTOKOV SLOVENIJE NA ZDRUŽBE BENTOŠKIH NEVRETENČARJEV

DOKTORSKA DISERTACIJA

Ljubljana, 2015

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DOKTORSKA DISERTACIJA

THE INFLUENCE OF HYDROMORPHOLOGICAL CHARACTERISTICS OF SLOVENIAN RIVERS ON BENTHIC INVERTEBRATE ASSEMBLAGES

DOCTORAL DISSERTATION

Ljubljana, 2015

"A river cuts through rock,
not because of its power
but its persistence."

(Jim Watkins)

"No man steps in the same river twice
for it's not the same river
and he's not the same man."

(Heraclitus)

Doktorska disertacija je zaključek univerzitetnega podiplomskega študija Varstvo okolja na Univerzi v Ljubljani. Pripravljena je bila na Inštitutu za vode Republike Slovenije v Ljubljani.

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Komisija za oceno in zagovor:

Predsednik: prof. dr. Mihael J. TOMAN
Univerza v Ljubljani, Biotehniška fakulteta, Oddelek za biologijo

Član: prof. dr. Mitja BRILLY
Univerza v Ljubljani, Fakulteta za gradbeništvo in geodezijo

Član: prof. dr. Zlatko MIHALJEVIĆ
Univerza v Zagrebu, Prirodoslovno matematički fakultet, Biološki odsjek

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JI sl/en
AI Ugotavljali smo vpliv hidromorfoloških spremenljivk različnih ravni na združbe bentoških nevretenčarjev (BN) v vodotokih Slovenije in ekoregij: Alpe, Dinaridi in Panonska nižina. Uporabili smo podatke o združbah BN s 302 mest vzorčenja, pridobljenih med leti 2005 in 2011. Za vsako mesto vzorčenja smo zbrali podatke o 49 okoljskih spremenljivkah in jih razvrstili v štiri skupine: raba tal, regionalne pokrajinske značilnosti (tipologija), lastnosti kakovosti rečnih habitatov (RHQ) in lastnosti spremenjenosti rečnih habitatov (RHM). Povezave med združbami BN in okoljskimi spremenljivkami smo ugotavljali s kanonično korespondenčno analizo (CCA). S spremenljivkami RHQ smo večinoma pojasnili precej večji delež variabilnosti združb BN kot s spremenljivkami RHM. Ugotovili smo razlike v pomembnosti okoljskih spremenljivk glede na ekoregijo. Porazdelitev pojasnjene variabilnosti združb BN med skupine okoljskih spremenljivk smo ugotavljali s parcialno CCA (pCCA). Dobro smo razlikovali med vplivi tipoloških spremenljivk ter RHQ in RHM spremenljivk. Tipološke spremenljivke do neke mere oblikujejo procese na nižjih ravneh, vendar je velik delež zgradbe združb BN odvisen od lastnosti kakovosti habitata ne glede na tipološke dejavnike. S pCCA med spremenljivkami rabe tal in ostalimi skupinami okoljskih spremenljivk smo največje presečne deleže pojasnjene variabilnosti združb BN ugotovili s tipološkimi spremenljivkami. Dobro smo lahko ločili med vplivi rabe tal ter lastnostmi kakovosti in spremenjenosti rečnih habitatov na združbe BN. Na podlagi ekološko pomembnih morfoloških spremenljivk smo za štiri glavne evropske regije določili vodilno sliko rečnih habitatov, ugotovili značilne razlike med alpsko, nižinsko, mediteransko in kraško regijo ter podali usmeritve za upravljanje z ekosistemi tekočih voda. Preverili smo še povezanost kombinacij že prej analiziranih morfoloških spremenljivk z združbami BN in večinoma z njimi pojasnili večji delež variabilnosti združb BN kot s posameznimi spremenljivkami morfoloških značilnosti.

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AB The influence of hydromorphological variables on benthic invertebrate (BI) assemblages was studied in Slovenian rivers and ecoregions Alps, Dinaric western Balkan and Pannonian Lowland. Data on BI assemblages were obtained from 302 sampling sites between the years 2005 and 2011. For each sampling site data on 49 environmental variables were collected and were assigned to four environmental variable groups: regional natural characteristics (typology), land use, river habitat quality variables (RHQ), and river habitat modification variables (RHM). The relation of environmental variables on BI assemblages was analyzed using canonical correspondence analysis (CCA). In general, RHQ variables explained higher share of BI assemblages' variability than RHM variables. The importance of environmental variables was dependent on ecoregion. The explained variability of BI assemblages was devided among groups of environmental variables using partial CCA. The effects of tipological variables and RHQ or RHM variables were well discerned. Tipological variables constrain the processes on smaller scales, but a considerable part of BI assemblage composition is dependent on habitat quality features irrespective of typological characteristics. pCCA between land use variables and other environmental variable groups showed the highest joint effects of explained variability of BI assemblages with tipological variables. We have well discerned among land use effects and RHQ or RHM variables on BI assemblages. Using ecologically relevant morphological variables the guiding images of river habitats of four major European regions were defined. Significant differences were observed among river habitats of alpine, lowland, mediterranean and karst region, and guidance for river management was presented. The relationship between BI assemblages and different combinations of previously used morphological variables was also analysed and generally more variability of BI assemblages was explained than with individual morphological variables.

KAZALO VSEBINE

KAZALO ZNANSTVENIH DEL

Doktorsko disertacijo sestavljajo trije članki objavljeni v revijah, ki jih indeksira SCI. Zaradi celovitosti dela so v disertacijo vključeni še neobjavljeni rezultati v dodatnem poglavju. Objavljeni članki so avtorski zaščiteni in v disertaciji predstavljeni z dovoljenjem založnika, njihova nadaljnja uporaba je možna le ob dovoljenju založnika.

Članek I:

Petkovska V., Urbanič G. 2015. The links between morphological parameters and benthic invertebrate assemblages, and general implications for hydromorphological river management. Ecohydrology, 8(1): doi: 10.1002/eco.1489: 67-82

Članek II:

Petkovska V., Urbanič G. 2015. The links between river morphological variables and benthic invertebrate assemblages: comparison among three European ecoregions. Aquatic ecology, 49: doi: 10.1007/s10452-015-9513-8: 159-173

Članek III:

Petkovska V., Urbanič G., Mikoš M. 2015. Variety of the guiding image of rivers - defined for ecologically relevant habitat features at the meeting of the alpine, mediterranean, lowland and karst regions. Ecological engineering, 81: doi: 10.1016/j.ecoleng.2015.04.043: 373-386

KAZALO PREGLEDNIC

KAZALO SLIK

KAZALO PRILOG

SLOVARČEK

V slovarčku razlagamo izraze, kot jih pojmujemo v tem besedilu in ponekod zaradi lažjega razumevanja dodajamo angleško ustreznico. V različnih raziskovalnih krogih lahko naletimo na rabo različnih sopomenk in/ali drugačne definicije istih pojmov.

Bentoški nevretenčarji (angl. benthic invertebrates): vodni nevretenčarji, ki pri vzorčenju ostanejo v mreži z odprtinami 0,5 mm x 0,5 mm in živijo na podlagi ali med delci podlage. Taksonomsko so raznolika skupina, katere značilni predstavniki so: vrtinčarji (Turbellaria), polži (Gastropoda), školjke (Bivalvia), maloščetinci (Oligochaeta), pijavke (Hirudinea), raki (Crustacea) in iz skupine žuželk (Insecta): enodnevnice (Ephemeroptera), vrbnice (Plecoptera), kačji pastirji (Odonata), hrošči (Coleoptera), mladoletnice (Trichoptera) in dvokrilci (Diptera).

Dinamika vodnega toka oz. hidrološki režim [1] : izraz uporabljamo za označitev sprememb stanja in lastnosti vodnega toka, ki se redno pojavljajo v času in prostoru in potekajo v fazah, npr. sezonsko.

Disjunktni delež pojasnjene variabilnosti združb: delež variabilnosti združb, ki ga z metodo parcialne kanonične korespondenčne analize (pCCA) pojasnimo s posamezno skupino spremenljivk.

Ekoregija celinskih voda (ekoregija, hidroekoregija): geografsko območje, znotraj katerega so si ekosistemi celinskih voda med seboj relativno bolj podobni v primerjavi z ekosistemi celinskih voda v drugih območjih.

Ekološko stanje (angl. ecological status)[2]: izraz kakovosti zgradbe in delovanja vodnih ekosistemov, povezanih s površinskimi vodami. Ekološko stanje vrednotimo z biološkimi elementi kakovosti in hidromorfološkimi ter fizikalno-kemijskimi elementi kakovosti, ki podpirajo biološke elemente kakovosti. Vodna telesa površinskih voda glede na odstopanje

[1] Opis je povzet po Mikoš in sod. (2002)
[2] Izraz je iz Vodne direktive (Direktiva Evropskega parlamenta ..., 2000).

od referenčnih razmer razvrščamo v pet razredov ekološkega stanja: zelo dobro, dobro, zmerno, slabo in zelo slabo stanje.

Gradient (okoljski gradient): izraz uporabljamo v dveh pomenih: 1. v prostoru in/ali času zvezno spreminjanje okoljskega dejavnika; 2. abstraktna dimenzija ekološkega prostora - relativna pozicija statističnih vzorcev v tem prostoru odraža podobnost okolij in/ali sestave združb organizmov.

Hidromorfološki elementi kakovosti (angl. hydromorphological elements)[3]: elementi kakovosti za razvrščanje vodnih teles površinskih voda v razrede ekološkega stanja, ki podpirajo biološke elemente kakovosti. Hidromorfološki elementi v rekah vključujejo: hidrološki režim (količina in dinamika vodnega toka), povezavo s telesi podzemne vode, vzdolžna povezanost in morfološke razmere (spreminjanje globine in širine reke, strukturo in substrat rečne struge in strukturo obrežnega pasu).

Presečni delež pojasnjene variabilnosti združb: delež variabilnosti združb, ki ga z metodo parcialne kanonične korespondenčne analize (pCCA) hkrati pojasnimo z dvema ali več obravnavanimi skupinami spremenljivk.

Prevladujoč substrat struge[4]: tip substrata, ki na dani popisni točki v strugi prevladuje (presek, pravokotno na breg); tipi substrata struge so razporejeni v dvanajst kategorij glede na metodologijo *SIHM* (npr. veliki kamni, prod, pesek, mulj), ki temeljijo na velikosti.

Prevladujoč (vodni) tok[5]: tip vodnega toka, ki na dani popisni točki prevladuje – se pojavlja v več kot 50 % struge (presek, pravokotno na breg); tipi vodnega toka so razporejene v devet kategorij glede na metodologijo *SIHM*, ki temeljijo na vzorcih vodne površine, hitrosti in usmerjenosti vodnega toka.

Prispevna površina ali prispevno območje: topografsko omejena površina kopnega, s katere voda odteka v strugo *vodotoka*.

[3] Izraz je iz Vodne direktive (Direktiva Evropskega parlamenta ..., 2000).
[4] Opis je povzet po Raven in sod. (2003)
[5] Opis je povzet po Raven in sod. (2003)

Referenčne razmere (angl. reference condition) [6]: biotske in abiotske razmere v ekosistemih, kjer ni opaznega vpliva delovanja človeka ali pa so vplivi človeka na ekosisteme minimalni. Referenčne razmere so izhodišče za vrednotenje ekološkega stanja.

Regionalne pokrajinske značilnosti (fiziografske značilnosti): izraz uporabljamo za naravne regionalne biogeografske in ekološke dejavnike, ki na višji prostorski ravni določajo značilnosti ekosistemov tekočih voda. Regionalne pokrajinske značilnosti smo določili po deskriptorjih *tipologije vodotokov* v Sloveniji.

Slovenski hidromorfološki sistem (SIHM): metoda za vrednotenje ekološkega stanja *vodotokov* na podlagi *hidromorfoloških elementov kakovosti*. Metoda vključuje vrednotenje elementa morfološke razmere ter elementa vzdolžna povezanost. Za vrednotenje elementa morfološke razmere metoda vključuje 33 lastnosti, 22 za vrednotenje kakovosti habitata ter 11 za vrednotenje spremenjenosti habitata – podrobneje opisane v Raven in sod. (2003).

Tipologija vodotokov: kategorizacija ekosistemov tekočih voda v ekološke tipe na podlagi njihovih naravnih abiotskih in biotskih značilnosti, ki jih opredelimo s kombinacijo biogeografskih in ekoloških dejavnikov. Dejavniki tipologije vodotokov v Sloveniji so pripadnost *ekoregiji celinskih voda,* geološka podlaga, nadmorska višina, *velikostni razred vodotoka*, vpliv kraškega izvira, presihanje, meandriranje ter nekateri drugi naravni deskriptorji, pomembni za *združbe bentoških nevretenčarjev*. Izraz tipologija uporabljamo tudi za skupino spremenljivk, ki odražajo *regionalne pokrajinske značilnosti*.

Variabilnost združb: raznolikost sestave in številčnosti taksonov v *združbah.*

Velikostni razred vodotoka: deskriptor pri *tipologiji vodotokov* v Sloveniji, določen na podlagi velikosti *prispevne površine* ter srednjega letnega pretoka (sQs); 0 - <10 km^2 prispevne površine (potok), 1 - 10-100 km^2 prispevne površine (majhna reka), 2 - >100-1000 km^2 prispevne površine (srednje velika reka), 3 - >1000-2500 km^2 prispevne površine in sQs <50 m^3/s (srednje velika do velika reka), 4 - >2500 km^2 prispevne površine ali sQs >50 m^3/s (velika reka).

[6] Izraz je iz Vodne direktive (Direktiva Evropskega parlamenta ..., 2000).

Vodilna slika (ang. guiding image)[7]: opis za tip značilnih razmer ekosistemov tekočih voda kot današnje potencialno naravno stanje brez rab vode, vseh reverzibilnih obremenitev in socio-ekonomskih omejitev. Vodilno sliko uporabljamo za opis hidromorfoloških značilnosti rečnih habitatov.

Vodotoki (tekoče vode): izraz uporabljamo za vse tekoče celinske vode, tako reke z *velikostnim razredom vodotoka* 1-4, torej velikostjo *prispevne površine* vsaj 10 km^2, kot tudi potoke z velikostjo *prispevne površine* manj od 10 km^2. Izraz »reke« ohranjamo v primeru citiranja slovenskih virov, ki uporablja izrazoslovje »reke«.

Združba organizmov: populacije organizmov, ki sobivajo v prostoru in času (npr. združba bentoških nevretenčarjev).

[7] Opis je povzet po Gellert in sod. (2014).

Slika 1. Motiv z mesta vzorčenja Radovna, Vintgar

Figure 1. A theme from sampling site Radovna, Vintgar

1 PREDSTAVITEV PROBLEMATIKE IN HIPOTEZE

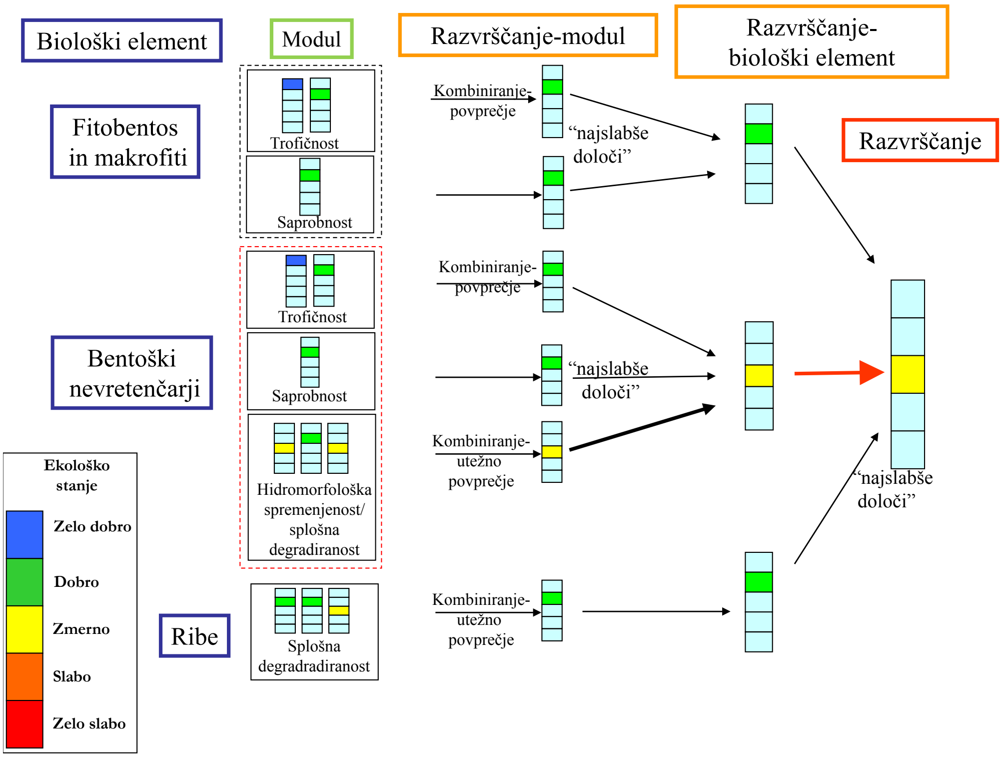
1.1 UPRAVLJANJE Z VODAMI PO UVEDBI DOLOČIL VODNE DIREKTIVE

Evropska unija je s sprejemom Vodne direktive (Direktiva Evropskega parlamenta ..., 2000) vpeljala skupni celostni pristop k reševanju politike upravljanja z vodami držav članic. Z vodno direktivo so bila v upravljanje z vodami uvedena nekatera načela, ki z osnovnim ciljem doseganja dobrega stanja voda omogočajo trajnostno upravljanje z vodnimi ekosistemi. Osnovne upravljavske enote predstavljajo vodna telesa, ki ne zajemajo le samega vodotoka, jezera, obalnega morja ali somornice, ampak tudi prispevno območje, iz katerega se napajajo. V Načrtu upravljanja povodij oz. porečij (ang. River Basin Management Plan), s katerim je na strateški ravni zagotovljeno izvajanje vodne direktive, so zajete analiza obremenitev, analiza stanja voda ter program stroškovno učinkovitih ukrepov, v okviru katerega naj bi se zagotovilo doseganje dobrega stanja voda ob vseh vplivih človekovih dejavnosti na vodni ekosistem. V vrednotenje stanja voda je z vodno direktivo vpeljan ekosistemski pristop, kjer na podlagi prisotnosti združb organizmov (bioloških elementov kakovosti) ovrednotimo kakovost vodnega okolja (ekološko stanje). Izhodišče za vrednotenje stanja voda predstavljajo referenčne razmere, značilne za posamezen tip voda, s čimer se zmanjša možnost subjektivnega vrednotenja vpliva človekovih dejavnosti (Hawkins in sod., 2010).

Z vodno direktivo je v evropski pravni red prvič vnesena zahteva za vključitev hidromorfoloških elementov kakovosti (hidrološki režim, vzdolžna povezanost, morfološke razmere) v vrednotenje stanja voda (Boon in sod., 2010). Spremembe hidromorfoloških (fizičnih) (Raven in sod., 2002) značilnosti vodnih habitatov so v zadnjih desetletjih prepoznane kot eden pomembnejših človekovih vplivov na vodne ekosisteme (European waters …, 2012; Schinegger in sod., 2012). Za doseganje ciljev Vodne direktive je zato pomembno ovrednotiti stanje hidromorfoloških elementov, vendar na takšen način, da bo možna vzročna povezava z oceno ekološkega stanja vodnega telesa na podlagi bioloških elementov kakovosti ter posledično določitev ukrepov za izboljšanje hidromorfoloških razmer vodnega telesa. Kljub številnim raziskavam na področjih hidromorfologije in združb vodnih organizmov je ravno ta povezava še vedno premalo poznana (Vaughan in Ormerod, 2010).

1.1.1 Vrednotenje ekološkega stanja tekočih voda

Vrednotenje stanja tekočih voda temelji na bioloških elementih kakovosti (BEK), ki vključujejo fitoplankton, fitobentos in makrofite, bentoške nevretenčarje ter ribe, in jih podpirajo fizikalno-kemijski in hidromorfološki elementi kakovosti (Direktiva Evropskega parlamenta ..., 2000). V Sloveniji vrednotimo ekološko stanje rek po modularnem sistemu, kjer ovrednotimo vpliv posamezne skupine obremenitev (Slika 2). Z modulom saprobnost ovrednotimo vpliv obremenitve z organskimi snovmi in drugega onesnaženja, z modulom trofičnost vpliv evtrofikacije ter rabe zemljišč, z modulom hidromorfološka spremenjenost oz. splošna degradiranost pa vpliv sprememb hidromorfoloških značilnosti vodotokov, rabe zemljišč, pregrad ter drugega onesnaženja. Metodologije vrednotenja ekološkega stanja rek so določene z Uredbo o stanju površinskih voda (Uredba o stanju …, 2009). S fitobentosom in makrofiti ovrednotimo modul saprobnost (Kosi in sod., 2006) ter trofičnost (Kosi in sod., 2006; Germ in sod., 2007; Kuhar in sod., 2011; Urbanič in Germ, 2012). Z bentoškimi nevretenčarji ovrednotimo tri module: saprobnost (Urbanič in sod., 2006), trofičnost (Pavlin Urbanič in Urbanič, 2012) ter hidromorfološka spremenjenost oz. splošna degradiranost (Urbanič in Tavzes, 2006; Urbanič, 2009; Urbanič in Petkovska, 2007, 2012a, 2012b, 2013a). Z ribami pa ovrednotimo modul splošna degradiranost (Podgornik in Urbanič, 2011, 2012). Glede na vrednost ekološkega stanja vodno telo uvrstimo v enega od pet razredov stanja, ki si glede na odstopanje vodnega ekosistema od referenčnih razmer sledijo od najboljšega k najslabšemu - zelo dobro, dobro, zmerno, slabo in zelo slabo (Slika 2). Najprej ovrednotimo ekološko stanje rek na podlagi vseh relevantnih BEK, nato pa upoštevamo pravilo, da BEK z najslabšo oceno določi stanje (Slika 2).



Slika 2. Predlog razvrščanja rek v razrede ekološkega stanja v Sloveniji na podlagi bioloških elementov kakovosti (Urbanič in sod., 2013a: 28).

Figure 2. The proposal of biological quality elements-based ecological status classification of rivers in Slovenia (Urbanič in sod., 2013a: 28).

1.1.2 Referenčne razmere in vodilna slika tekočih voda

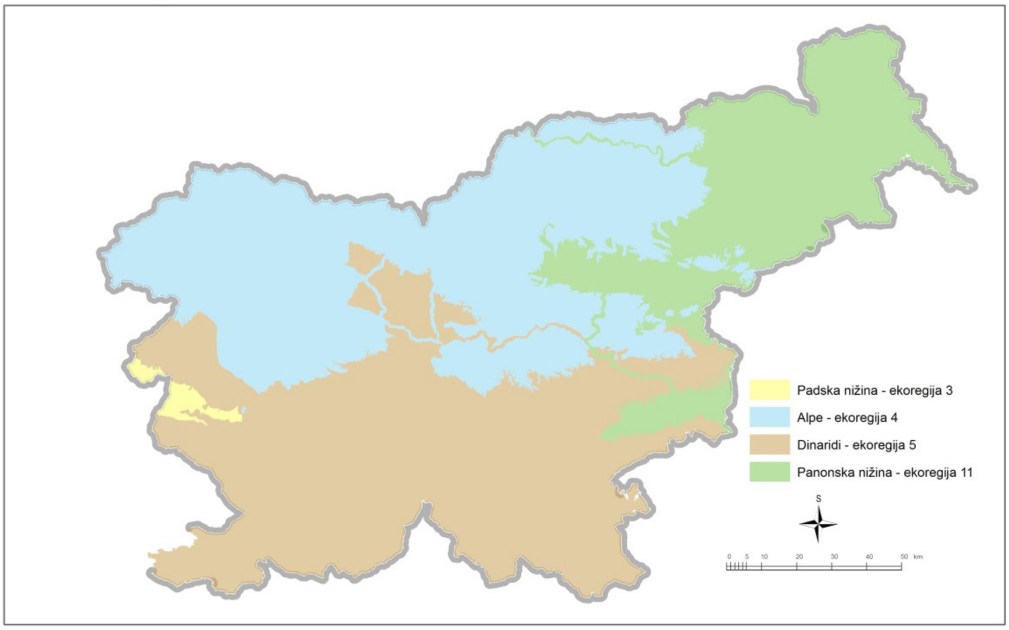
Vodna direktiva (Direktiva Evropskega parlamenta ..., 2000) opredeljuje referenčne razmere za biološke elemente kakovosti ter za tip značilne vrednosti za fizikalno-kemijske in hidromorfološke elemente kakovosti pri zelo dobrem ekološkem stanju. Na referenčnih mestih so lahko prisotne manjše spremembe fizikalno-kemijskih ali hidromorfoloških lastnosti zaradi vpliva človekovega delovanja, če imajo na delovanje ekosistema zanemarljiv vpliv (Wallin in sod., 2003). Trenutno stanje ekosistemov tekočih voda je posledica sovplivanja naravnih dejavnikov in človekovega delovanja (Allan, 2004). Zaradi dolgotrajnega človekovega delovanja na ekosisteme tekočih voda so odseki z izvornim stanjem ekosistemov tekočih voda že v svetovnem merilu precej omejeni na manj dostopna območja (Marsh, 1864; Allan in Castillo, 2007), podobno velja tudi za vodotoke v Evropi, kjer se taki odseki pogosteje pojavljajo le v severni Evropi (npr. arktični vodotoki) ali manjši vodotoki npr. v Italiji in na Balkanu (Tockner in sod., 2009). Določitev referenčnih razmer za potrebe upravljanja voda v Evropski Skupnosti tako še vedno ni dorečena (Nijboer in sod., 2004; Pardo in sod., 2012; Feio in sod., 2013). Obstaja več metod za določitev referenčnih razmer (Raven in sod., 2002; Rinaldi in sod., 2013): v primeru obstoja mest brez ali z zanemarljivim vplivom človekovega delovanja se lahko uporabi prostorski pristop, sicer pa se referenčne razmere lahko določi z uporabo zgodovinskih podatkov, modeliranja ali na podlagi strokovnega mnenja.

Kot zahtevna se je izkazala uskladitev stališč o za tip značilnih (referenčnih) razmerah na podlagi hidromorfoloških elementov kakovosti (Rinaldi in sod., 2013). Zaradi pomanjkanja mest z za tip značilnimi razmerami se je v nekaterih državah uporabil koncept vodilne slike, nem. Leitbild (Kern, 1992, 1994) ali ang. guiding image (Palmer in sod., 2005), v okviru katerega so za tip značilne razmere določene kot današnje potencialno naravno stanje brez rab vode, vseh reverzibilnih obremenitev in socio-ekonomskih omejitev (Gellert in sod., 2014). V Sloveniji je še vedno precej odsekov vodotokov, kjer so hidromorfološke razmere zelo podobne naravnim razmeram oz. razmeram brez vpliva človeka (Mikoš in Urbanič, 2002; Urbanič in Peterlin, 2007; Urbanič in sod., 2014), zato se je pri tipih vodotokov z zadostnim številom referenčnih mest pri določitvi za tip značilnih razmer uporabil prostorski pristop (Urbanič in Tavzes, 2006; Urbanič in sod., 2007; Urbanič in Petkovska, 2008; 2012b; 2013b).

1.1.3 Tipologija tekočih voda

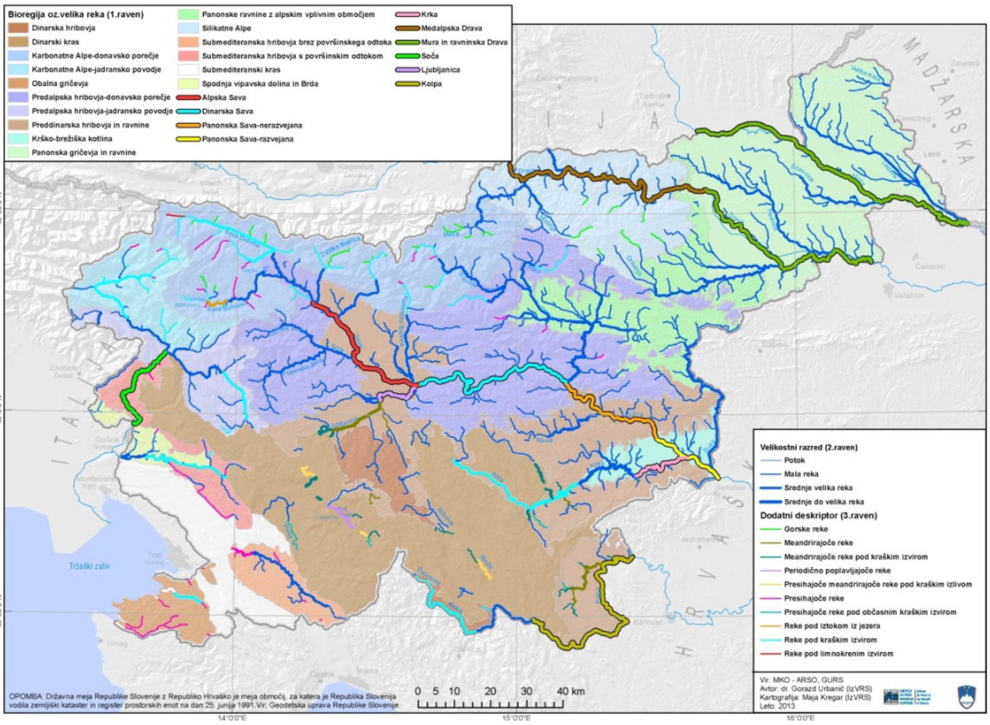
Za preučitev ter razumevanje procesov v tekočih vodah je bilo po svetu razvitih več sistemov razvrščanja rek v skupine glede na abiotske značilnosti, kot npr. geomorfološke značilnosti doline in prispevnega območja, značilnosti hidrološkega režima, obliko struge ali značilnosti vegetacije (Repnik Mah in sod., 2010). V namene upravljanja z vodami so bile na podlagi podobnih podnebnih razmer, kamninske podlage in drugih abiotskih dejavnikov, pomembnih za razširjenost vodnih združb, določene ekoregije celinskih voda v Ameriki (Omernik, 1987) in v Evropi (Illies, 1978). Ekoregije celinskih voda so eden od možnih deskriptorjev za opis tipov rek pri vrednotenju ekološkega stanja voda (Direktiva Evropskega parlamenta ..., 2000).

Na ozemlju Slovenije sta po Illiesu (1978) določeni dve ekoregiji (Alpe – ekoregija 4, Dinarski zahodni Balkan – ekoregija 5), v razdelitvi katerih pa niso bili upoštevani vsi lokalni dejavniki (Urbanič 2008a). Urbanič (2008a) je s podrobnejšo analizo abiotskih značilnosti in vzorca razširjenosti združb bentoških nevretenčarjev pripravil razdelitev ozemlja Slovenije na štiri ekoregije: Alpe, Dinaridi, Panonska nižina in Padska nižina (Slika 3). Na podlagi vzorca razširjenosti vodnih organizmov, ki se po naravni poti ne morejo razširjati med porečji (npr. ribe), se na ozemlju Slovenije ekoregiji Alpe in Dinaridi delita na dve subekoregiji glede na pripadnost Donavskemu porečju ali Jadranskemu povodju (Urbanič, 2008b). Upoštevajoč abiotske deskriptorje (nadmorska višina, geološka podlaga) in vzorec razširjenosti združb bentoških nevretenčarjev so ekoregije in subekoregije v Sloveniji razdeljene na 16 bioregij ter posebno kategorijo »velike reke« (Urbanič, 2008b). Ekološki tipi vodotokov v Sloveniji so opredeljeni na podlagi pripadnosti bioregiji in velikosti prispevne površine ter kombinacije dodatnih deskriptorjev, pomembnih za razporeditev vodnih organizmov v Sloveniji: vpliv kraškega izvira, vpliv občasnega kraškega izvira, vpliv limnokrenega izvira, vpliv iztoka iz jezera, presihanje, periodično poplavljanje, meandriranje, nadmorska višina $\geq$ 700 m (Urbanič, 2011). V Sloveniji je tako določenih 74 ekoloških tipov vodotokov (Slika 4).



Slika 3. Ekoregije celinskih voda v Sloveniji (Urbanič, 2008a: 23).

Figure 3. The inland water ecoregions of Slovenia (Urbanič, 2008a: 23).



Slika 4. Bioregije in ekološki tipi vodotokov v Sloveniji (Urbanič in sod., 2013b: 5).

Figure 4. Bioregions and the ecological river types in Slovenia (Urbanič in sod., 2013b: 5).

1.2 POVEZANOST HIDROMORFOLOŠKIH ZNAČILNOSTI TEKOČIH VODA Z ZDRUŽBAMI VODNIH ORGANIZMOV

Hidromorfološke (HM) značilnosti tekočih voda (vodotokov) predstavljajo lastnosti fizičnega okolja, ki pogojujejo zgradbo in delovanje združb vodnih organizmov (Elosegi in sod., 2010). V mnogih raziskavah so naravne HM značilnosti vodotokov in njihove spremembe povezali s spremembo združb bentoških nevretenčarjev (Lammert in Allan, 1999; Sandin in Johnson, 2004; Erba in sod., 2006; Feld in Hering, 2007; Larsen in Ormerod, 2010; Urbanič, 2014), rib (Smiley in Dibble, 2008; Wyzga in sod., 2009), makrofitov in fitobentosa (O'Hare in sod., 2006; Johnson in Hering, 2009; Lorenz in sod., 2012) ter tudi združb kopenskih organizmov, ki so vezani na vodno in obvodno okolje (Bonn in sod., 2002; Manenti in sod., 2009; Greenwood in McIntosh, 2010; Eskew in sod., 2012). Med združbami vodnih organizmov imajo najdaljšo tradicijo v vrednotenju stanja voda bentoški nevretenčarji zaradi njihove razširjenosti, relativne omejenosti na raven habitatov ter dovolj dolge življenjske dobe, da se odzovejo na spreminjajoče se razmere (Kolkwitz and Marsson, 1909; Sladeček, 1973). Združba bentoških nevretenčarjev zajema vodne nevretenčarje, ki pri vzorčenju ostanejo v mreži z odprtinami 0,5 mm x 0,5 mm (Urbanič in Toman, 2003). Taksonomsko so bentoški nevretenčarji raznolika skupina organizmov, katere najpogostejši pripadniki so ličinke žuželk (enodnevnic, vrbnic, mladoletnic, kačjih pastirjev, raznokrilcev, hroščev, mrežekrilcev in dvokrilcev), raki, maloščetinci, mehkužci, pijavke in vrtinčarji (Knoben, 1995).

1.2.1 Naravne hidromorfološke značilnosti tekočih voda

1.2.1.1 Dimenzije delovanja ekosistemov tekočih voda

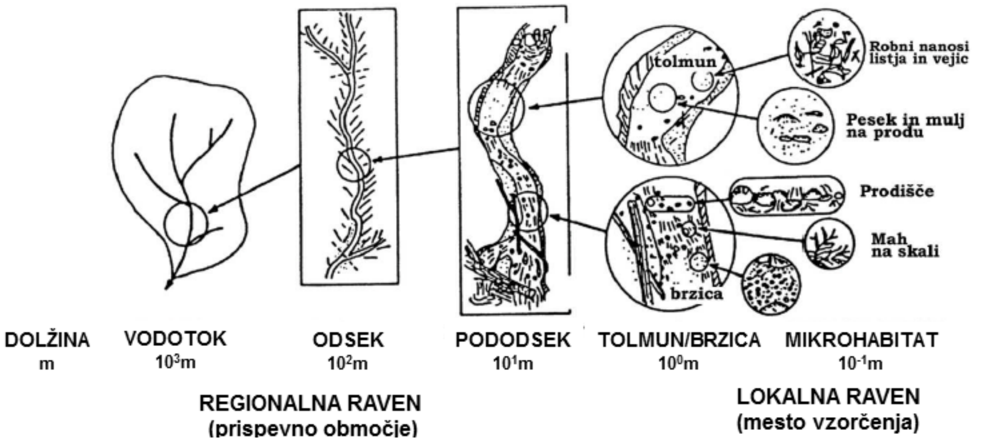
Tekoče vode predstavljajo dinamične ekosisteme, ki so posledica delovanja procesov v treh prostorskih dimenzijah: vzdolžni (longitudinalni), prečni (lateralni), navpični (vertikalni) in v časovni dimenziji (Ward, 1989). Ekosistemi tekočih voda so tako določeni z vsemi prisotnimi fizikalnimi in kemijskimi procesi ter združbami organizmov (Allan in Castillo, 2007).

Zaradi usmerjenosti vodnega toka od izvira proti izlivu (vzdolžna dimenzija) vse razmere v gorvodno ležečih območjih vplivajo na razmere dolvodno. Vzdolž toka se prenašajo plavine, organske snovi in hranila, prav tako pa tudi vodni organizmi. Glede na spreminjanje združb vodnih organizmov po toku navzdol so bile narejene različne razdelitve rečnih sistemov (Huet, 1959; Illies in Botosaneanu, 1963). Koncept rečnega kontinuuma (angl. River Continuum Concept, RCC) opisuje kontinuirane spremembe značilnosti v ekosistemih tekočih voda in temelji na spreminjanju zgradbe in delovanja združbe bentoških nevretenčarjev vzdolž vodnega toka (Vannote in sod., 1980). RCC zajema spremembe hidromorfoloških značilnosti od izvira do izliva kot posledica velikosti vodotoka, kot so naraščanje širine struge, zmanjševanje vpliva obrežne vegetacije (senčenje, vnos organskih delcev), zmanjševanje temperaturnih sprememb ter s tem povezane spremembe v kroženju snovi, pretoku energije in združbah vodnih organizmov (Vannote in sod., 1980). Vendar RCC ne upošteva vseh ostalih dimenzij rečnega sistema ter lokalnih in regionalnih posebnosti (npr. vpliv kraškega izvira, presihanje), ki so pomembne za razumevanje ekosistemov tekočih voda (Ward, 1989; Begon in sod., 2006).

Ward in Stanford (1995) sta priredila RCC tako, da sta upoštevala tudi prečno povezavo med strugo vodotoka, obrežnim pasom in poplavnimi ravnicami. V srednjih in spodnjih delih rečnih sistemov dinamika vodnega toka oblikuje raznolika okolja ob glavni strugi (mrtvica, stranski rokav, močvirje), ki imajo pomemben vpliv na zgradbo in delovanje ekosistema tekočih voda (Keruzore in sod., 2013). Povezava z obrežnim pasom ter poplavnimi ravnicami omogoča izmenjavo snovi (sediment, hranila, listje in večji lesni deli) ter pretok energije med kopenskim in vodnim okoljem in tako vpliva na razmere v rečnih habitatih (Cummins, 1989; Sandin, 2009).

Struga vodotokov je poleg prečne povezave tudi navpično povezana s hiporeikom in podtalnico, med katerimi voda s kroženjem prenaša snovi, med okolji pa se selijo tudi vodni organizmi (Elosegi in sod., 2010). Ta povezava omogoča obstoj habitatov pod obrežnim pasom in poplavnimi ravnicami, ki imajo s prisotnimi združbami organizmov pomembno vlogo pri zgradbi in delovanju ekosistema tekočih voda (Boulton, 2007). Hiporeik nudi zatočišča vodnim organizmom v času neugodnih hidromorfoloških razmer v strugi (Brunke in Gonser, 1997).

Na vseh prostorskih dimenzijah rečnih sistemov delujejo hidromorfološki procesi, ki se spreminjajo v času predvsem na podlagi dinamike vodnega toka (Poff in sod., 1997; Hohensinner in sod., 2011). Hierarhična organiziranost ekosistemov tekočih voda (Frissell in sod., 1986; Allan in sod., 1997; Giller in Malmqvist, 1998) od ravni prispevnega območja, do ravni odsekov, pododsekov, tolmuna/brzice in mikrohabitata definira tudi časovni okvir za dinamiko hidromorfoloških procesov (Slika 5; od milijonov let do nekaj tednov ali dni).



Slika 5. Hierarhična organiziranost rečnega sistema (Frissel in sod., 1986: 202).

Figure 5. Hierarchical organization of a river system (Frissel in sod., 1986: 202).

1.2.1.2 Hidromorfološki procesi in tvorbe tekočih voda ter njihova povezanost z združbami bentoških nevretenčarjev

Ekosisteme tekočih voda v veliki meri oblikujejo hidromorfološki (HM) procesi in pod njihovim vplivom oblikovane HM tvorbe, ki določajo fizične razmere rečnih habitatov. HM procese lahko v grobem delimo na dinamiko vodnega toka, dinamiko sedimenta (plavin), dinamiko bregov, dinamiko obrežne in vodne vegetacije, dinamiko večjih lesnih ostankov ter vertikalno dinamiko med površinsko in talno vodo (Jalon in sod., 2013). HM procesi so odvisni od dejavnikov različnih ravni (Frissel in sod., 1986) in so regionalno značilni (Splinter in sod. 2010). Dinamika vodnega toka oz. hidrološki režim, ki igra glavno vlogo pri oblikovanju ostalih HM procesov, je odvisen od padca in velikosti prispevnega območja ter klime, geološke podlage in topografije območja (Poff in sod., 1997; Bunn in Arthington, 2002). Geološka podlaga pogojuje tudi presihanje tekočih voda ter prisotnost kraških izvirov (Gams, 2004). Na dinamiko sedimenta poleg hidrološkega režima vpliva tudi geološka podlaga ter naklon bregov, kar vse pogojuje količino in velikost substrata, ki se prenaša dolvodno. Na nižjih ravneh so HM procesi med sabo še bolj prepleteni, saj je npr. stabilnost bregov odvisna od prisotnosti obrežne vegetacije (Langendoen in sod., 2009), ta pa od hidrološkega režima (Tabacchi in sod., 1998; Merritt in sod., 2010).

HM procesi se lokalno odražajo v prisotnosti različnih morfoloških tvorb. Dinamika vodnega toka in sedimenta vpliva na prisotnost brzic in tolmunov, zavojev, prodišč in otokov ter izpodjedenih bregov (Statzner in Higler, 1986; Church 2002). Dinamika vegetacije zajema zaraščanje bregov in obrežnih prodišč ter prisotnost vodne vegetacije, ki hkrati oblikuje vodno okolje z zaustavljanjem sedimenta (Sand-Jensen, 1998). Poleg tega je prisotnost obrežne vegetacije povezana z vnosom lesnega plavja v vodno okolje, ki na mestu zaustavitve omogočajo tvorbo novih habitatov, pomembnih za prisotnost združb bentoških nevretenčarjev (Kail in sod., 2007; Hrodey in sod., 2008). Prisotnost HM tvorb in s tem pestrosti habitatov je regionalno pogojena (Szoszkiewicz in sod., 2006; Harnischmacher, 2007; Repnik Mah in sod., 2010), prav tako pa posledično zgradba in delovanje združb bentoških nevretenčarjev. Združbe bentoških nevretenčarjev se dobro odzivajo na HM značilnosti tekočih voda, predvsem v povezavi s habitatsko pestrostjo. V raziskavah so ugotovili pomembnost velikosti in hrapavosti substrata za zgradbo združb bentoških nevretenčarjev (Lammert in Allan, 1999; Syrovatka in sod., 2009). Na odsekih tekočih voda, kjer prevladuje velik substrat, kot so skale ali veliki kamni, se običajno okoli nakopiči tudi manjši (prodniki, pesek), kar ustvari večjo heterogenost substrata in posledično večjo pestrost združbe (Giller in Malmqvist, 1998). Poleg substrata raziskovalci z zgradbo in delovanjem združb bentoških nevretenčarjev povezujejo različne značilnosti vodnega toka in z njim povezanih značilnosti (Poff in sod., 1997; Sandin, 2003; Sandin in Johnson, 2004) ter senčenje, gostoto in širino lesne obrežne vegetacije (Feld in Hering, 2007; Lorion in Kennedy, 2009; Rios in Bailey, 2006). Prisotnost vegetacije v strugi pa poleg samega naselitvenega prostora bentoškim nevretenčarjem nudi tudi zatočišče pred plenilci (Beauger in sod., 2006).

1.2.2 Spremembe hidromorfoloških značilnosti tekočih voda

1.2.2.1 Neposredne spremembe hidromorfoloških značilnosti tekočih voda ter njihova povezanost z združbami bentoških nevretenčarjev

Spremembe hidromorfoloških (HM) značilnosti tekočih voda oz. vodotokov se nanašajo na spremembo hidrološkega režima, morfoloških razmer ter vzdolžne, prečne in navpične povezanosti in so posledica raznolikih človekovih potreb, npr. zmanjšanje poplavne nevarnosti, pridobivanje električne energije, namakanje (Wohl, 2006). Spremembe HM značilnosti vodotokov vodijo v spremembo HM procesov ter zgradbe in delovanja ekosistema tekočih voda (Jalon in sod., 2013).

Regulacije vodotokov z namenom zmanjšanja poplavne nevarnosti vključujejo spremembo prečnega profila struge, spremembo naravnega poteka struge (izvedba izravnave), poglobitev struge, izgradnjo nasipov ali visokovodnih zidov, utrditev bregov in struge ter odstranitev obrežne vegetacije (Jalon in sod., 2013). Omenjene spremembe zmanjšujejo erozijo bregov in s tem spreminjajo vnos sedimentov, ki tvori substrat na dnu struge, omejitev vodnega toka le na glavno strugo pa spremeni hidrološki režim (zmanjšanje vodnatosti in zmanjšanje zadrževalnega časa vode v strugi, povečanje hitrosti vodnega toka in zmanjšanje heterogenosti toka) ter tako dinamiko substrata in vegetacije. Z regulacijo se velikokrat izgubijo morfološke strukture, npr. brzice in tolmuni, prodišča in otoki ter območja zastajajoče vode (Ricaurte in sod., 2012). Zaradi nasipov in visokovodnih zidov je prekinjena povezava med strugo, obrežnim pasom in poplavnimi ravnicami. Z regulacijami spremenjena habitatska pestrost ter omejeno kroženje snovi in pretok energije vodi v spremembo prisotnih združb bentoških nevretenčarjev. Erba in sod. (2006) so ugotovili negativno povezavo zgradbe združb bentoških nevretenčarjev s spremenljivkami, s katerimi so neposredno ovrednotili spremembo bregov vodotokov in struge. Poleg same habitatske pestrosti pa tudi izguba morfoloških struktur, ki opravljajo vlogo zatočišč vodnim organizmom ob večjih spremembah pretoka, vodi v zmanjšanje pestrosti združb bentoških nevretenčarjev (Negishi in sod., 2002; Dunbar in sod., 2010).

Z namenom pridobivanja električne energije, namakanja, zmanjšanja poplavne nevarnosti ali druge rabe je zgrajenih veliko prečnih objektov (pragovi, drče, pregrade, jezovi; Kondolf, 1997; Dams and development ..., 2000; Poff in Hart, 2002; Repnik Mah in sod., 2013). Ne glede na namen prečnega objekta imajo s prekinitvijo vzdolžne povezanosti rečnega sistema vsi vpliv na hidrološki režim in dinamiko sedimenta (Kondolf, 1997). Večji prečni objekti povzročajo zajezitve gorvodno in s tem v veliki meri spremenijo ekosistem tekočih voda (Renofalt in sod., 2010). Gorvodno od prečnih objektov se vodni tok upočasni, kar vodi v pospešitev usedanja plavin (Stefanidis in Stefanidis, 2012), zmanjša pa se tudi erozija bregov kot posledica delovanja vodnega toka. Dolvodno od jezu s sedimentom osiromašena voda lahko povzroča erozijo struge vodotoka (Kondolf, 1997), medtem ko spremenjena dinamika vodnega toka in poplavnih dogodkov spremeni dinamiko obrežne vegetacije - lahko vodi v zaraščanje struge ali pa tudi v spremembo in odmiranje zaradi znižanja talne vode (Poff in sod., 1997; Nilsson in Berggren, 2000). S spremembami HM razmer zaradi prečnih objektov je povezana zgradba in delovanje združb bentoških nevretenčarjev. Avtorji navajajo spremembe v združbah bentoških nevretenčarjev nad in pod posameznimi pregradami (Takao in sod., 2008; Jones, 2013; Kairo in sod., 2012) ter zaradi več zaporednih manjših prečnih objektov (Santucci in sod., 2005; Müller in sod., 2011). Povezavo potrjujejo tudi raziskave sprememb združb bentoških nevretenčarjev po odstranitvi jezu (Pollard in Reed, 2004; Maloney in sod., 2008).

Zmanjšana količina vode v strugi je povezana tudi z odvzemi vode v različne namene. Odvzemi vode s spremembo hidrološkega režima povzročajo spremembe v premeščanju sedimenta in lesnega plavja ter s tem povezanih oblik morfoloških tvorb ob bregu in v strugi, poleg tega se spremeni tudi dinamika obrežne vegetacije. Sprememba HM razmer ter manj vodnega prostora zaradi zmanjšanja količine vode v strugi ima direkten vpliv na združbe bentoških nevretenčarjev (Poff in sod., 1997; Poff in Zimmerman, 2010).

1.2.2.2 Hkratno delovanje antropogenih dejavnikov

Na ekosisteme tekočih voda velikokrat ne delujejo le spremembe v hidromorfoloških značilnostih, ampak nanje vpliva več antropogenih dejavnikov hkrati, ki spreminjajo tudi fizikalno-kemijske lastnosti habitatov (Schinegger in sod., 2012). Raba tal v prispevnem območju je eden najpogostejših vzrokov za hkratno delovanje več antropogenih dejavnikov (Allan, 2004; Matthaei in sod., 2010).

Sprememba rabe tal v prispevnem območju vodotokov iz gozdnate v kmetijsko ali urbano povzroča spremembe v hidrološkem režimu ter morfoloških značilnostih vodotokov (Lammert in Allan, 1999; Towsend in sod., 2004; Vondracek in sod., 2005). Tako je izpostavljena pomembna vloga rabe tal na različnih prostorskih ravneh: v celotnem prispevnem območju (Allan in sod., 1997; Sandin, 2009; Pavlin in sod., 2011), na poplavnih ravnicah (Kail in sod., 2009) ter v obrežnem pasu (Nerbonne in Vondracek, 2001; Sponseller in sod., 2001; Kail in sod., 2009; Sandin, 2009). Kmetijska raba tal v prispevnem območju vodotoka zaradi zmanjšanja pokritosti tal z gozdom ter pogoste izgradnje melioracijskih kanalov zmanjša zmožnost zadrževanja vode v prispevnem območju ter povečuje hitrost in količino površinskega odtoka vode ter spiranje snovi iz prispevnega območja v vodotok (Sponseller in sod., 2001; Allan, 2004). Urbana raba tal ima večinoma zelo veliko neprepustnih površin ter tako znatno pospeši površinski odtok vode (Poff in sod., 1997). S kmetijstvom in urbanizacijo v celotnem prispevnem območju je velikokrat povezana tudi sprememba rabe tal ožjega obrežnega pasu, kar vodi v izgubo omilitvene vloge obrežne vegetacije med strugo in prispevnim območjem. Odstranjevanje obrežne vegetacije ima tudi neposreden vpliv na hidrološki režim in morfološke značilnosti vodotoka preko manjše količine opada in odmrlega lesa v strugi, manj senčenja ter tudi povečane erozije bregov (Tabacchi in sod., 1998; Allan, 2004; Keesstra in sod., 2005; Hopkinson in Wynn, 2009).

Spremenjena raba tal na rečne habitate ne vpliva le s spremembo hidromorfoloških značilnosti, temveč deluje hkrati s spremembo svetlobnih in temperaturnih razmer (Nelson in Palmer, 2007; Julian in sod., 2008, 2011) ter spremenjenim vnosom hranil in strupenih snovi (Sliva in Williams, 2001; Kuhl in sod., 2010). Spremenjene značilnosti rečnih habitatov zaradi spremenjene rabe tal imajo vpliv na zgradbo in delovanje združb bentoških nevretenčarjev (Hall in sod., 2001; Nerbonne in Vondracek, 2001; Stone in sod., 2005; Maloney in Weller, 2011; Pavlin in sod., 2011; Feld, 2013). Poleg vplivov rabe tal velikokrat na združbe tekočih voda delujejo hkrati še drugi antropogeni dejavniki (npr. kanaliziranje, odvzemi vode, pregrade). Med vplivi posameznih antropogenih dejavnikov na združbe tekočih voda so velikokrat prisotne sinergistične ali antagonistične interakcije, zato so vplivi hkratnega delovanja antropogenih dejavnikov težko napovedljivi in velikokrat nepričakovani (Townsend in sod., 2008; Matthaei in sod., 2010). Močne soodvisnosti so bile prepoznane med npr. rabo tal in spremembo hidromorfoloških značilnosti vodotokov (Feld in Hering, 2007) ali obremenitvijo s hranili (Niyogi in sod., 2007). Vendar je v upravljavske namene pomembno prepoznati vplive posameznih antropogenih dejavnikov ter s pomočjo teh določiti prednostne upravljavske aktivnosti (Townsend in sod., 2008). Pavlin in sod. (2011) so na podlagi odziva združb bentoških nevretenčarjev v Sloveniji ugotovili, da lahko v velikem deležu razlikujemo med vplivi posameznih skupin antropogenih dejavnikov (raba tal, obremenjevanje s hranili, druge obremenitve). Med 'druge obremenitve' so zajeli tudi razred hidromorfološke spremenjenosti, vendar se niso posvetili posameznim hidromorfološkim spremenljivkam rečnih habitatov.

1.3 VREDNOTENJE KAKOVOSTI IN SPREMENJENOSTI HABITATOV TEKOČIH VODA

1.3.1 Metode vrednotenja hidromorfološkega stanja tekočih voda

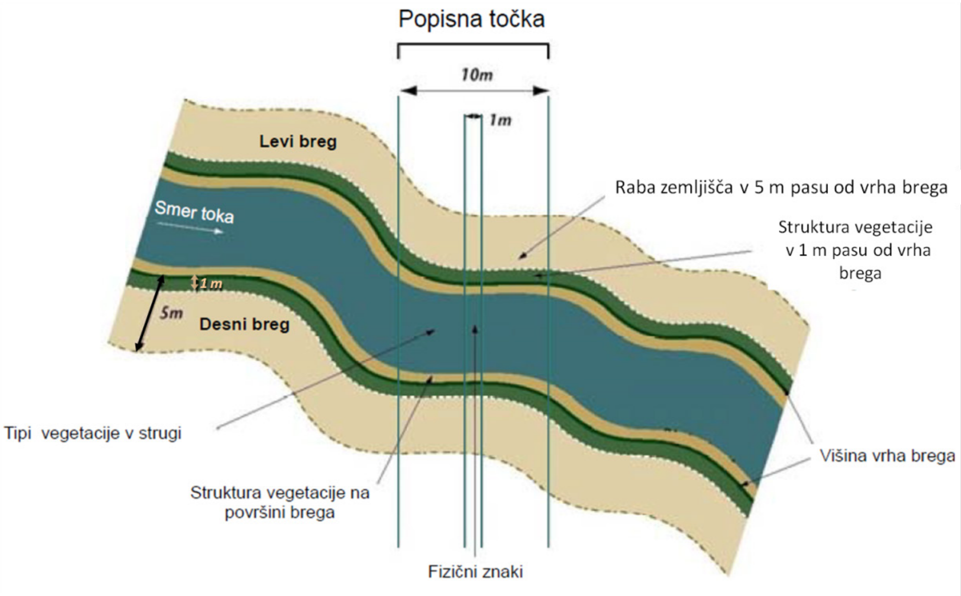
Za opis naravnih lastnosti in sprememb rečnih habitatov je bilo predvsem v zadnjih desetletjih razvitih veliko metod (Rinaldi in sod., 2013). Omenjene metode se v glavnem razlikujejo zaradi treh vzrokov: namena uporabe in časa, namenjenega za uporabo, ter dejstva, ali zajemajo le popis ali tudi vrednotenje lastnosti vodotokov (Fernandez in sod., 2011). Razlike se pojavljajo predvsem v številu zajetih lastnosti, dolžini popisnega odseka na vodotoku in širine popisnega območja ob vodotoku ter sistema vrednotenja različnih lastnosti (Raven in sod., 2002; Fernandez in sod., 2011). V Sloveniji je bila za oceno hidromorfološkega stanja v rečnem koridorju preverjena uporabnost več širše znanih metod (Bizjak, 2003; Batistič, 2005; Lavrenčič, 2005; Mikoš in Bizjak, 2007), na podlagi česar je bil razvit tudi predlog sintezne metode z obsežnim naborom hidromorfoloških spremenljivk (Bizjak, 2003). Uporaba različnih metod otežuje primerjave rečnih habitatov med državami ali celo znotraj države, zato je bila predvsem za potrebe Vodne direktive izdelana standardna metoda za vrednotenje sprememb hidromorfoloških lastnosti vodotokov (CEN) (Boon in sod., 2010). Metoda CEN za vrednotenje hidromorfološke spremenjenosti vodotokov je bila razvita na podlagi obstoječih metod ter daje okvir za primerjavo obstoječih ter razvoj novih metod vrednotenja na ravni posamezne države.

Ena najbolj izčrpnih metod za vrednotenje rečnih habitatov, uporabljena tudi pri razvoju standarda CEN, je angleška metoda sistem rečnih habitatov (River Habitat Survey; RHS; Raven in sod. 1998, 2003). Na podlagi popisanih in ovrednotenih lastnosti vodotokov daje metoda RHS dobro izhodišče za različne primerjave hidromorfoloških lastnosti med rečnimi habitati ter raziskave povezav le-teh z združbami vodnih organizmov (Raven in sod., 2010). Za vodotoke južne Evrope so metodo RHS nadgradili (Buffagni in Kemp, 2002), uporabnost metode RHS pa je bila preverjena še v več evropskih državah (Balestrini in sod., 2004; Szoszkiewicz in sod., 2006; Tavzes in sod., 2006; Bona in sod., 2008; Raven in sod., 2010). Pogostost ter preveritev metode RHS na širšem naboru tipov evropskih vodotokov sta bili razlog za izbor metode RHS kot osnove za razvoj metode vrednotenja morfoloških lastnosti po Slovenskem hidromorfološkem sistemu (SIHM) (Tavzes in Urbanič, 2009).

1.3.2 Slovenski hidromorfološki sistem (SIHM)

Slovenski hidromorfološki (SIHM) sistem sestavljata dva dela: vrednotenje kakovosti in sprememb morfoloških lastnosti ter vrednotenje sprememb vzdolžne povezanosti in s tem povezanih hidroloških lastnosti (Tavzes in Urbanič, 2009; Urbanič in sod., 2013).

Vrednotenje morfoloških lastnosti izhaja iz metode RHS, po kateri se na podlagi prilagojenega obrazca (Priloga A) popiše morfološke lastnosti vzdolž 500 m struge (popisni odsek; Tavzes in Urbanič, 2009). Na desetih popisnih točkah, ki so med seboj oddaljene 50 m, se pravokotno na strugo (Slika 6) popiše prevladujoči material brega, lastnosti, ki prispevajo k razgibanosti obrežnih habitatov (klif, prodišča), ter možne spremembe v oblikovanosti brežin (npr. utrditev, nasip). Podobno se popiše tudi strugo, vključujoč še prevladujoči tip toka. Na vseh desetih točkah se popiše tudi vegetacijo struge in bregov ter rabo zemljišča v petmetrskem pasu od vrha brega. Poleg morfoloških lastnosti na popisnih točkah se opravi še celovit pregled popisnega odseka, kjer se poleg lastnosti struge in bregov zabeleži tudi rabo zemljišča v petdesetmetrskem pasu od vrha brega, profile bregov, posebne značilnosti na bregu in v strugi ter drugo. Na vsakem popisnem odseku se popiše 22 lastnosti kakovosti habitata (RHQ) in 11 lastnosti spremenjenosti habitata (RHM). V okviru razvoja sistema SIHM se je posameznim kategorijam lastnosti RHQ in RHM dodelilo uteži glede na njihov vpliv na združbe bentoških nevretenčarjev (Tavzes in Urbanič, 2009; Urbanič in sod., 2013a). Višje vrednosti lastnosti RHQ so znak večje habitatske pestrosti popisnega odseka, medtem ko so višje vrednosti lastnosti RHM znak večjih sprememb habitatskih lastnosti popisnega odseka. Na podlagi tako določenih spremenljivk se izračuna indeks kakovosti rečnih habitatov (RHQ) in indeks spremenjenosti rečnih habitatov (RHM).

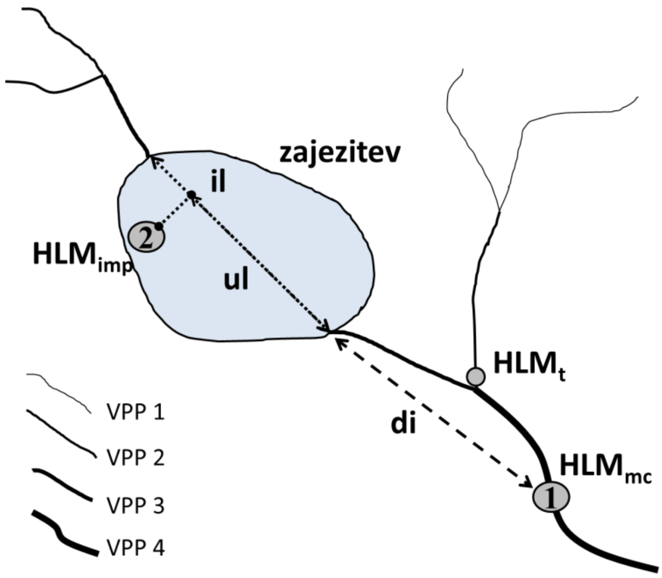


Slika 6. Del popisnega odseka za RHS (Krušnik in sod., 2001: 4)

Figure 6. Part of sampling strech for RHS (Krušnik in sod., 2001: 4)

Za vrednotenje sprememb vzdolžne povezanosti je bil razvit indeks hidrološke spremenjenosti (HLM) (Tavzes in Urbanič, 2009; Urbanič, 2009). Z indeksom HLM je pri vrednotenju vpliva pregrad nad in pod popisnim odsekom upoštevan zadrževalni čas in upočasnitev vodnega toka kot posledica pregrade, oddaljenost popisnega odseka od pregrade ter vpliv pritokov med popisnim odsekom in pregrado (Slika 7). Na vrednost indeksa HLM imajo vpliv tudi velikostni razred vodotoka s popisnim odsekom ter vseh pritokov med popisnim odsekom in pregrado. V indeks HLM je tako vključen vpliv pregrad v prispevnem območju popisnega odseka.

Na podlagi indeksov RHQ, RHM in HLM se izračuna indeks hidromorfološke kakovosti in spremenjenosti (HQM). Pred izračunom indeksa HQM je treba vrednosti indeksov RHQ in RHM pretvoriti na razpon 0 – 1 glede na vrednosti izhodiščnih hidromorfoloških razmer, ki so značilne za ekološki tip vodotoka.



Slika 7. Shematski prikaz upoštevanih podatkov pri izračunu indeksa hidrološke spremenjenosti (HLM) na odseku pod pregrado (1) in odseku znotraj zajezitve (2). di - oddaljenost od pregrade, il - dolžina zajezitve, ul - oddaljenost gorvodno od pregrade; VPP – velikostni razred prispevnega območja; mc – glavna struga, t – pritok, imp – zajezitev (Tavzes in Urbanič, 2009: 14-15; Urbanič, 2009: 20-21).

Figure 7. Shematic view of the information necessary to calculate the hydrological modification index (HLM) at the sampling site below the (1) or inside the impoundment (2). di - distance from the impoundment, li - length of the impoundment. ul distance from the impoundment upstream, VPP – catchment size class, mc – main channel, t – tributary, imp – impoundment (Tavzes and Urbanič, 2009: 14-15; Urbanič, 2009: 20-21).

Sisteme vrednotenja kakovosti in spremenjenosti habitatov je s ciljem zagotovitve trajnostnega upravljanja z rečnimi sistemi treba povezati z odzivom združb vodnih organizmov. Povezava z različnimi združbami vodnih organizmov je bila ugotovljena za naravne hidromorfološke značilnosti vodotokov in njihove spremembe, vendar so bile v raziskavah redko uporabljene posamezne morfološke značilnosti, ki so vključene v uradno sprejete sisteme vrednotenja. V raziskavah o povezavah med združbami vodnih organizmov in značilnostmi habitatov so bile največkrat uporabljene spremenljivke, ki izhajajo iz metode RHS (Erba in sod., 2006; Hughes in sod., 2008; Dunbar in sod., 2010). Za indekse sistema SIHM je bila ugotovljena dobra soodvisnost z združbami bentoških nevretenčarjev (Urbanič, 2014), ni pa se še raziskalo povezave s posameznimi spremenljivkami sistema SIHM.

1.4 CILJI RAZISKOVANJA

Prvi cilj naše raziskave je bil ugotoviti povezanost hidromorfoloških spremenljivk različnih prostorskih ravni v vodotokih Slovenije in po posameznih ekoregijah.

Drugi in glavni cilj je bil ugotoviti, kolikšen delež variabilnosti združb bentoških nevretenčarjev lahko pojasnimo z vsako od obravnavanih hidromorfoloških spremenljivk, ter ugotoviti hidromorfološke spremenljivke, ki pomembno vplivajo na združbe bentoških nevretenčarjev v vodotokih Slovenije in po posameznih ekoregijah.

Tretji cilj je bil ugotoviti, kolikšen delež variabilnosti združb bentoških nevretenčarjev lahko pojasnimo s posamezno skupino okoljskih spremenljivk: pokrajinske regionalne značilnosti, raba tal, kakovost rečnih habitatov, spremenjenost rečnih habitatov, ter kolikšen hkrati z več skupinami okoljskih spremenljivk.

Četrti cilj je bil preveriti vpliv posameznih hidromorfoloških spremenljivk na habitatsko pestrost. Ugotoviti smo želeli, kakšna je vodilna slika oziroma potencialno naravno stanje na podlagi ekološko pomembnih hidromorfoloških spremenljivk ter ali se razlikuje glede na obravnavano ekoregijo.

Peti cilj je bil ugotoviti, kolikšen delež variabilnosti združb bentoških nevretenčarjev lahko pojasnimo s kombinacijami hidromorfoloških spremenljivk v primerjavi z deležem variabilnosti, ki ga pojasnimo s posameznimi spremenljivkami.

1.5 DELOVNE HIPOTEZE

Hipoteza 1. S hidromorfološkimi spremenljivkami višjih prostorskih ravni lahko pojasnimo del variabilnosti hidromorfoloških spremenljivk nižjih ravni.

Hipoteza 2. Tako naravne hidromorfološke lastnosti vodotokov kot tudi antropogene spremembe le-teh pojasnijo velik delež variabilnosti združb bentoških nevretenčarjev.

Hipoteza 3. Delež pojasnjene variabilnosti združb bentoških nevretenčarjev na podlagi hidromorfoloških spremenljivk je odvisen od obravnavane prostorske ravni in se razlikuje glede na obravnavano ekoregijo.

Hipoteza 4. Hidromorfološke spremenljivke višjih prostorskih ravni delno določajo hidromorfološke spremenljivke nižjih prostorskih ravni in združbe bentoških nevretenčarjev. Zato se ne da popolnoma ločiti med vplivi skupin hidromorfoloških spremenljivk različnih prostorskih ravni.

Hipoteza 5. Iste hidromorfološke spremenljivke različno vplivajo na habitatsko pestrost in oceno hidromorfološkega stanja vodotokov glede na ekoregijo.

Hipoteza 6. Kombinacija hidromorfoloških spremenljivk pojasni večji delež variabilnosti združb bentoških nevretenčarjev, kot bi bila vsota deležev pojasnjene variabilnosti na podlagi posameznih spremenljivk.

Slika 8. Motiv z mesta vzorčenja Bloščica, Ogrnik

Figure 8. A theme from sampling site Bloščica, Ogrnik

2 ZNANSTVENA DELA

2.1 OBJAVLJENA ZNANSTVENA DELA

2.1.1 Članek I

Povezanost morfoloških parametrov in združb bentoških nevretenčarjev ter splošne usmeritve za upravljanje s hidromorfološkimi lastnostmi ekosistemov tekočih voda

The links between morphological parameters and benthic invertebrate assemblages, and general implications for hydromorphological river management

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Vesna PETKOVSKA, Gorazd URBANIČ

V zadnjih desetletjih je v upravljanju z ekosistemi tekočih voda več pozornosti namenjeno spremenjenosti hidromorfoloških lastnosti, kar poudarja pomembnost razumevanja povezave med hidromorfološkimi značilnostmi in združbami vodnih organizmov. V prispevku smo se ukvarjali s splošnimi vzorci odziva združb bentoških nevretenčarjev na posamezne morfološke značilnosti v naravno pestrih slovenskih vodotokih. Celoten razpon lastnosti kakovosti (RHQ lastnosti) in sprememb rečnih habitatov (RHM lastnosti) smo zajeli glede na Slovenski hidromorfološki sistem. Z regionalnimi pokrajinskimi značilnostmi smo pojasnili relativno nizek delež variabilnosti lastnosti RHQ in RHM, kar nakazuje na neregionalno prisotnost morfoloških lastnosti. Kot najpomembnejše izmed lastnosti RHQ za zgradbo združbe bentoških nevretenčarjev smo ugotovili prevladujoč tok in substrat struge. V primerjavi z lastnostmi RHQ smo za lastnosti RHM ugotovili nizko pojasnjevalno sposobnost. Združba bentoških nevretenčarjev se po naših ugotovitvah manj odziva na sam objekt spremembe kot pa na učinek te spremembe na lastnosti kakovosti rečnih habitatov. Z delitvijo pojasnjene variabilnosti med tri skupine okoljskih spremenljivk smo ugotovili predvsem neodvisne deleže pojasnjene variabilnosti združbe bentoških nevretenčarjev (69 %), najvišje na podlagi regionalnih pokrajinskih značilnosti (30 %) in lastnosti RHQ (31 %). Ker so združbe bentoških nevretenčarjev prilagojene na habitatske razmere pred človekovim vplivom, se lahko različno odzivajo na enake morfološke spremembe v odvisnosti od regionalnih značilnosti. Zato se je lahko uporaba združenega niza podatkov iz različnih regij odrazila v nizki pojasnevalni sposobnosti lastnosti RHM. Naše ugotovitve dajejo splošni okvir za upravljanje z ekosistemi tekočih voda. Za bolj natančno določitev pomembnosti posameznih hidromorfoloških sprememb priporočamo analize na bolj homogenih območjih glede na regionalne pokrajinske značilnosti.

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The links between morphological parameters and benthic invertebrate assemblages, and general implications for hydromorphological river management

Vesna Petkovska[1]* and Gorazd Urbanič[1,2]

[1] *Institute for Water of the Republic of Slovenia, Hajdrihova 28c, 1000, Ljubljana, Slovenia*
[2] *Biotechnical Faculty, Department of Biology, University of Ljubljana, Večna pot 111, 1000, Ljubljana, Slovenia*

ABSTRACT

In the last decades, hydromorphological degradation of rivers has gained more attention in river management, stressing the importance of understanding the links between hydromorphology and aquatic assemblages. The present study investigated general patterns in the response of benthic invertebrate assemblages to single morphological features along naturally diversified Slovenian rivers. The whole gradient of local habitat quality (river habitat quality, RHQ) and habitat modification (river habitat modification, RHM) features, according to the Slovenian hydromorphological assessment method, was covered. Regional natural characteristics explained the low share of RHQ and RHM variability, indicating nonregional presence of morphological features. The analysis identified predominant flow and predominant channel substrate as the most important RHQ features. We found that in contrast to RHQ features, RHM features had low explanatory power. These results suggest a weaker response of benthic invertebrate assemblages to the physical alteration itself than to the effect that the alteration exerts on habitat quality features. Variance partitioning among three environmental variable groups revealed predominantly independent effects (69%) on benthic assemblages, mostly on account of regional natural characteristics (30%) and RHQ features (31%). As benthic invertebrate assemblages are adapted to the former natural conditions, a similar modification may result in different effects with regard to regional natural differences. Therefore, the low proportion of variability, explained by RHM features, might be the consequence of joint dataset from different regions. Our study gives general implications for river management, but in order to more clearly define the significance of particular modification features, we suggest further analysis within more homogeneously defined habitats that encompass regional natural characteristics.

KEY WORDS benthic invertebrates; Slovenian hydromorphological assessment method; variance partitioning; hydromorphology; River Habitat Survey

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INTRODUCTION

Hydromorphological degradation represents one of the most important anthropogenic pressures affecting river and stream environments (Richter *et al*., 1997; Raven *et al*., 2002; Feld, 2004; Schinegger *et al*., 2012). Direct modifications on rivers include channelization, weir and dam construction, disconnection of floodplains and clearance of riparian vegetation (Pedersen, 2009; Verdonschot, 2009), which diminish habitat diversity of rivers. With the increasing severity of morphological degradation, the connection between physical river habitat and aquatic assemblages is gaining increased attention (Davy-Bowker and Furse, 2006; Friberg *et al*., 2009a; Vaughan *et al*., 2009). Managing river systems often includes a variety of restoration projects, with the general aim to reestablish lost physical diversity by substrate manipulation (Muotka *et al*., 2002; Jähnig and Lorenz, 2008), including the introduction of large woody debris (Kail *et al*., 2007; Hrodey *et al*., 2008; Testa *et al*., 2011) or in-stream structures (Harrison *et al*., 2004) and rehabilitation of natural riparian vegetation (Allan, 2004; Death and Collier, 2009; Riley and Dodds, 2012). However, the results of these restoration projects indicate a negligible response of aquatic biota (Lepori *et al*., 2005; Jähnig *et al*., 2010; Palmer *et al*. 2010; Haase *et al*., 2012), emphasizing the need for improved understanding of the relationship between aquatic communities and morphological pressures.

In Europe, assessment of river status gained a new perspective with implementation of the Water Framework Directive (WFD, European Commission, 2000). The newly introduced term ‘hydromorphological’ signifies the importance of assessing habitat quality and modification in the ecological classification of rivers. In the last decades, several assessment methods that summarize the heterogeneous nature

*Correspondence to: Vesna Petkovska, Institute for Water of the Republic of Slovenia, Hajdrihova 28c, 1000 Ljubljana, Slovenia.
E-mail: vesna.petkovska@izvrs.si

of riverine physical habitat have been developed (Muhar *et al*., 1996, 1998; Agences de l'Eau & Ministère de l'Environnement, 1998; Raven *et al*., 1998, 2003; LAWA, 2000; Munne *et al*., 2003; Feld, 2004). One of the more comprehensive methods is the UK River Habitat Survey (RHS) method (Raven *et al*., 1998, 2003) with a Habitat Quality Assessment score and a Habitat Modification Score. The application of the RHS method was tested in several European countries (Balestrini *et al*., 2004; Szoszkiewicz *et al*., 2006; Tavzes *et al*., 2006; Bona *et al*., 2008; Urošev *et al*., 2009; Raven *et al*., 2010), and an adapted version was developed for use in southern Europe (Buffagni and Kemp, 2002). The RHS method also served as a basis for the Slovenian hydromorphological (SIHM) assessment method development, where evaluation of different categories of river features was made with regard to their influence on the benthic invertebrate community (Tavzes and Urbanič, 2009), resulting in 33 collected morphological features. Using these, it is possible to classify the morphological status of survey sites (Tavzes and Urbanič, 2009) by the calculation of a river habitat quality (RHQ) index and a river habitat modification (RHM) index.

According to the WFD, the main focus of assessment methods is on biological quality elements, and the direct assessment of hydromorphology serves only as additional evaluation. The most prevalent biological quality element (Birk and Hering, 2006), with the longest tradition in river assessment, are the benthic invertebrates (Kolkwitz and Marsson, 1909; Sladecek, 1973). Benthic invertebrates represent a diverse group that integrates ecosystem changes over time and responds to different environmental stressors (Sandin and Hering, 2004; Sandin *et al*., 2004; Friberg *et al*., 2009b). In Europe, several benthic invertebrate-based assessment methods exist (Birk *et al*., 2012), but only some of them address hydromorphological impact (Lorenz *et al*., 2004; Ofenböck *et al*., 2004; Urbanič, 2014).

Stressor-specific assessment methods detect impairment (e.g. organic pollution and eutrophication), but, particularly when considering hydromorphological alteration, the direct cause of degradation remains unknown. This is reflected in a large amount of unsuccessful restoration attempts. It is of high importance to establish more precise links of morphological characteristics and their alteration to the response of aquatic communities. A large number of studies demonstrate that benthic invertebrate assemblages are influenced by the quality of habitat features (Lammert and Allan, 1999; Sandin and Johnson, 2004; Rios and Bailey, 2006; Lorion and Kennedy, 2009; Syrovátka et al., 2009) and are also good indicators of morphological degradation (Erba *et al*., 2006; Feld and Hering, 2007; Larsen and Ormerod, 2010). However, the relationship between benthic invertebrate assemblages and single morphological features included in applied assessment methods was rarely analysed; and most studies considered only RHS features (Erba *et al*., 2006; Hughes *et al*., 2008; Cortes *et al*., 2009; Dunbar *et al*., 2010). Indices of the SIHM method were used as a stressor gradient in the development of the Slovenian ecological status assessment and classification method using benthic invertebrates (Urbanič, 2014) and showed good explanatory power. But no analysis was performed using single morphological features. As the SIHM method is used for hydromorphological assessment of rivers, knowledge of the relationship between single morphological features included in the SIHM method and the response of benthic invertebrate assemblages could represent a starting point for river management.

Generally, river management authorities need to have an understanding of how river ecosystems respond to anthropogenic changes and how to reverse the degradation process. There is a request for management concepts to be applicable across larger scales and not specifically focused on individual rivers or sites. Our data provide an overview of Slovenian river morphological characteristics and their alterations across a wide geographical gradient (Urbanič, 2011). We tested the possibility of finding general patterns in the response of benthic invertebrate assemblages to river morphological features. However, regional (large-scale) parameters are known to influence local (small-scale) physical features and biota (Frissell *et al*., 1986; Poff, 1997; Sandin and Johnson, 2004). This should be considered when analysing the relationship between morphological features and benthic invertebrate assemblages. Therefore, the most important regional natural characteristics, also relevant for Slovenian typological delineation (Urbanič, 2011), were used in our study as a separate set of environmental variables. With a focus on the relation of single morphological features included in the SIHM method to the response of benthic invertebrate assemblages, the main aims of the present study are (i) to investigate the relationship between regional natural characteristics and morphological quality or morphological modification features across the Slovenian landscape, (ii) to define the habitat parameters that are most important in structuring benthic invertebrate assemblages and discuss their explanatory power in comparison with regional characteristics and (iii) to define what share of benthic invertebrate assemblage composition can be attributed to distinctive effects among environmental variable sets (regional natural characteristics, morphological quality and morphological modification).

METHODS

Study area

Slovenia covers a total area of 20 273 km^2 and has 4573 km of river channels within catchments larger than 10 km^2. The rivers extend across three main ecoregions of the country (Alps, Dinaric Western Balkan and Pannonian lowland), which cover more than 99% of the area and the Po lowland that accounts for less than 1% of the area (Illies, 1978;

Urbanič, 2008a). The wide ecological variety of the area is also a consequence of the connection between two main river basins (Urbanič, 2008b), big karst area with karst phenomena (ams, 2004), variety of geologies and rivers of varied sizes (Urbanič, 2011). In Slovenia, the official river typology used for bioassessment (OGRS, 2009) was developed according to System B of the WFD Annex II. The four ecoregions are divided into 16 bioregions according to the predominant geology, altitude of the catchment area and division between the river basins (Urbanič, 2008b, 2011). Ecological river types are defined using bioregion and additional qualitative environmental parameters (e.g. river size, karst spring influence, periodical flooding and intermittency).

Benthic invertebrate data

Data on benthic invertebrate composition and abundance were obtained from 302 sites between the years 2002 and 2011 (Figure 1) as part of monitoring and assessment system development programmes in Slovenia (Urbanič *et al*., 2008). The aim of this study was to examine the relation of natural morphological features and their modification to benthic invertebrate assemblages. The selection of sites cover the gradient from natural to heavily altered morphological conditions. Only sites where morphological alteration was the presumed main stressor were included in the analyses. Sites showing a less than good ecological status for organic pollution (Slovenian Saprobic index – SIG3 < 0·6; Urbanič, 2011; $BOD_5 > 5{\cdot}4\,mg\,l^{-1}$) or nutrients (total phosphorus $> 205\,\mu g\,l^{-1}$, orthophosphate $> 84\,\mu g\,l^{-1}$ and nitrate $> 9{\cdot}5\,mg\,l^{-1}$) were *a priori* excluded. Rivers were sampled during low-to-medium-discharge conditions, generally between May and September, except some large or intermittent rivers were sampled in winter because of their natural hydrological regime. The sampling procedure followed the standardized Slovenian river bioassessment protocol (OGRS, 2009; Pavlin *et al*., 2011). Each site was sampled on a single occasion using a 500-mm mesh-size hand net. The sample on each site consisted of 20 subsampling units, with a total sampling area of 1·25 m^2 that was taken along a 100- to 250-m river stretch in proportion to the coverage of the microhabitat types (Urbanič *et al*., 2005). Microhabitat types were defined as a combination of substrate and flow type with at least 5% coverage. A total of 302 samples then underwent laboratory subsampling procedures, and benthic organisms from a quarter of each whole field sample were identified and enumerated (Petkovska and Urbanič, 2010). Benthic invertebrates were determined to the taxonomic level used for the assessment of ecological river status in Slovenia (OGRS, 2009), i.e. mostly to species level.

Environmental data

For each site, data on eight regional natural characteristics were obtained from the Slovenian river typology (typology variables – Table I). Sites were classified into four ecoregion

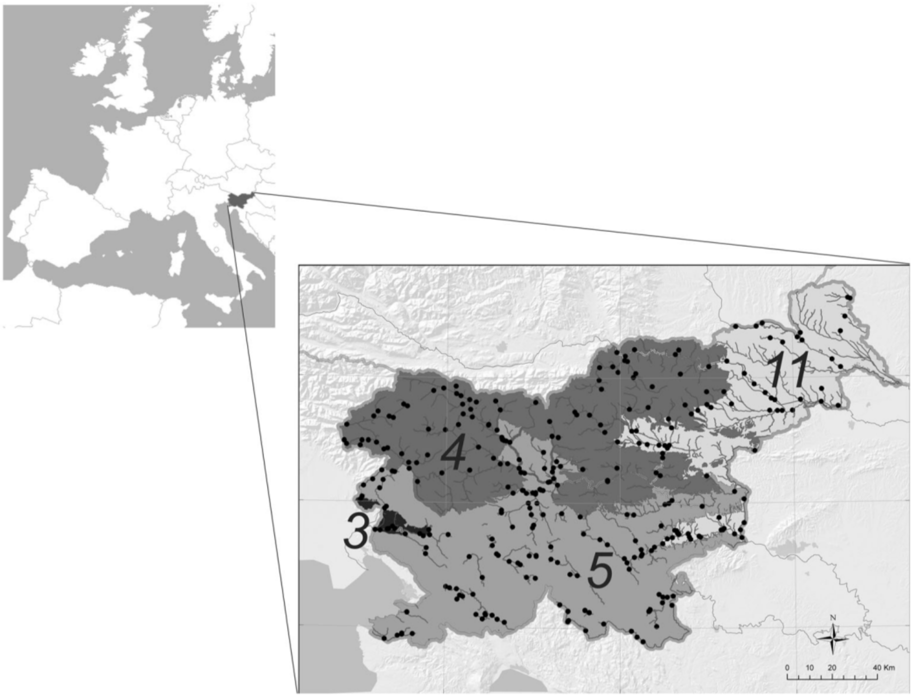

Figure 1. Study area with ecoregions (3, Po lowland; 4, Alps; 5, Dinaric Western Balkan; 11, Pannonian lowland) and sampling sites.

Table I. Summary of environmental characteristics of analysed sites with their affiliation to the variable group.

Environmental variable	Abbreviation	Unit	Variable group	Median[a] (min–max)	Occurrence frequency (%)
Region: lowland	ER3.11	Dummy	Typology	80	26
Ecoregion: Alps	ER4	Dummy	Typology	93	31
Ecoregion: Dinaric Western Balkan	ER5	Dummy	Typology	129	43
River size class	Size_cl	Classified 1–4	Typology	2 (1–4)	100
Karst spring influence	Kspring	Dummy	Typology	60	20
Intermittency	Intermit	Dummy	Typology	15	5
Altitude	Alt	m a.s.l.	Typology	283 (1–896)	100
Slope	Slope	%	Typology	4·4 (0–261)	98
Predominant natural bank material	bnm	Score total[b]	RHQ	16 (0–44)	96
Bank features	bf	Score total[b]	RHQ	1·5 (0–23)	66
Predominant channel substrate	cnm	Score total[b]	RHQ	33·5 (0–52)	99
Predominant flow	cft	Score total[b]	RHQ	32·5 (2–55)	100
Channel features	ct	Score total[b]	RHQ	1 (0–47)	51
Land use within 5 m	rl	Score total[b]	RHQ	46 (0–80)	100
Banktop vegetation structure	btv	Score total[b]	RHQ	21·5 (5·5–30)	100
Bankface vegetation structure	bfv	Score total[b]	RHQ	26·5 (4–30)	100
Channel vegetation types	cv	Score total[b]	RHQ	19 (0–43·6)	97
Land use within 50 m	lu	Score total[b]	RHQ	2·5 (0·6–8)	100
Natural bank profiles	bn	Score total[b]	RHQ	1·5 (0–3·5)	91
Extent of trees	rt	Score total[b]	RHQ	4·5 (0–5)	99
Shading of channel	rs	Score total[b]	RHQ	1 (0–2)	94
Overhanging boughs	rob	Score total[b]	RHQ	1 (0–2)	89
Exposed bankside roots	bbr	Score total[b]	RHQ	1 (0–2)	74
Underwater tree roots	bur	Score total[b]	RHQ	1 (0–2)	56
Fallen trees	bft	Score total[b]	RHQ	1 (0–2)	74
Coarse woody debris	cd	Score total[b]	RHQ	1 (0–2)	83
Flow types along 500 m	cf	Score total[b]	RHQ	5 (2–9)	100
Channel and bank features along 500 m	ff	Score total[b]	RHQ	3 (0–11)	80
Features of special interest along 500 m	fsi	Score total[b]	RHQ	1 (0–8)	71
Channel chocked with vegetation[c]	ccv	Score total[b]	RHQ	0 (0–1)	2
Predominant artificial bank material	bam	Score total[b]	RHM	2·5 (0–60)	65
Bank modifications	bm	Score total[b]	RHM	4·5 (0–70)	73
Artificial channel material[c]	cam	Score total[b]	RHM	0 (0–10)	7
Channel modifications	cm	Score total[b]	RHM	0 (0–50)	14
Artificial bank profiles	ba	Score total[b]	RHM	2 (0–5)	73
Dam/weir	sd	Score total[b]	RHM	0 (0–5)	28
Bridge	sb	Score total[b]	RHM	0 (0–5)	44
Ford[c]	sf	Score total[b]	RHM	0 (0–2)	8
Deflector[c]	sde	Score total[b]	RHM	0 (0–3)	2
Channel realignment	cmr	Score total[b]	RHM	0 (0–2)	12
Water impoundment by weir/dam	cmi	Score total[b]	RHM	0 (0–2)	23

Variable Groups: Typology, regional natural characteristics, RHQ, habitat quality features; RHM, habitat modification features.
[a] For dummy variables, number of sites coded as '1' is given.
[b] Calculated score of individual features according to the SIHM method (Tavzes and Urbanič, 2009).
[c] Variables excluded from further analysis owing to low occurrence frequency.

variables (Alps – ER4; Dinaric Western Balkan – ER5; Pannonian lowland – ER11; and Po lowland – ER3). However, we only had a few sampling sites in ER3. Because typological and natural morphological parameters are similar among ER3 and ER11, these sites were combined into a united region, lowland (ER3.11). Altitude and slope were calculated using a digital elevation model with 5-m accuracy. Each site was also classified into one of four river size classes determined by catchment area and mean annual discharge (1 – catchment size 10–100 km^2; 2 – catchment size 100–1000 km^2; 3 – catchment size 1000–2500 km^2 and mean annual discharge $< 50\, m^3\, s^{-1}$; 4 – catchment size $>2500\, km^2$ or mean annual discharge $50\, m^3\, s^{-1}$).

Data on morphological features (variables) were obtained along a 500-m-long stretch of the river using an adapted version of the UK RHS method (Raven *et al.*, 2003, Tavzes and Urbanič, 2009). Bank and channel features (predominant substrate, physical features of channel and banks, flow type, channel vegetation type, land use, vegetation structure of banks and adjacent land) were recorded at 10 spot checks,

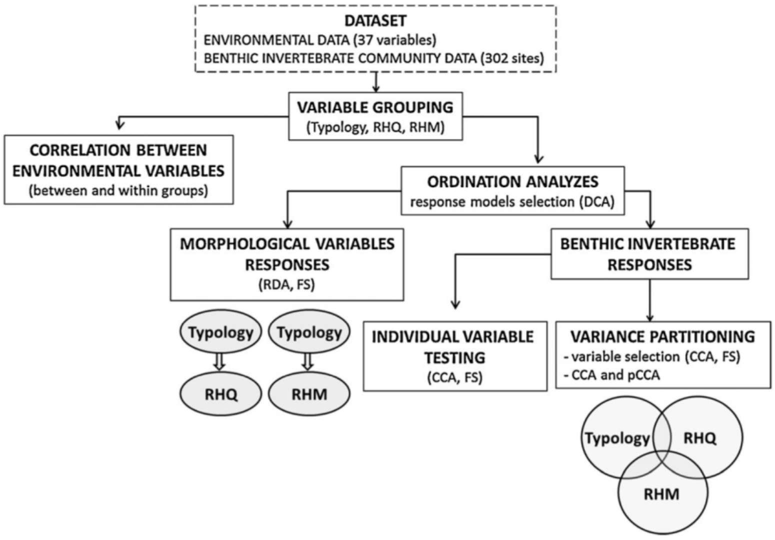

Figure 2. Flowchart of the analytical procedure. DCA, detrended correspondence analysis; RDA, redundancy analysis; CCA, canonical correspondence analysis; pCCA, partial canonical correspondence analysis; FS, automatic forward selection routine. For variable groups (typology, RHQ and RHM), see Table I.

spaced every 50 m. The sweep-up part of the survey along the whole stretch covers other features: land use in the 50-m stretch from the channel, bank profile, extent of trees, extent of bank and channel features, features of special interest and artificial features. The features recorded with the RHS method were upgraded in the SIHM method (Tavzes and Urbanič, 2009) where different weights were appointed to categories of each feature, depending on its influence on the benthic invertebrate community. Altogether, 33 features were recorded using the SIHM method (Table I). RHQ features (RHQ variables) represent characteristics of habitat quality, including river channel and banks, riparian features and land use within 50 m from the channel. Higher values of RHQ variables indicate greater habitat diversity. RHM features (RHM variables) are derived from data on extent and impact of bank and channel modifications, which are weighted because of their impact on natural habitat. Higher values of RHM variables are an indication of bigger morphological alteration.

Data analysis

Preliminary morphological variables were examined with regard to occurrence frequency and gradient range. Variables present at less than 10% of sampling sites were excluded (Table I). The remaining 29 morphological variables were used in the analyses – 21 and 8 from groups of RHQ features and RHM features, respectively. Regional natural characteristics were included in the analysis with eight variables. The region variables, karst spring influence and intermittency were coded as dummy (0/1) variables and river size as a variable with four classes. Altitude and slope were $\ln(x+1)$-transformed to approximate a normal distribution. River habitat variables were not transformed prior to analysis because the same unit score is used for all variables derived from the SIHM method (Tavzes and Urbanič, 2009). To investigate the relationship of environmental variables among and within analysed groups of variables, a Spearman rank correlation coefficient (R_{Sp}) was calculated for each pair of environmental variables using SPSS Statistics version 21.0 (IBM, 2012).

Ordination techniques were carried out to analyse associations among three groups of environmental variables, and between different groups of environmental variables and benthic invertebrate assemblages. Benthic invertebrate data were ln(x+1) transformed prior to analysis. All ordination techniques were conducted using the software package CANOCO 4.5 (ter Braak and Šmilauer, 2002); in all analyses, species were centred and standardized, and the option of downweighting rare species was enabled (emphasis was given to more commonly distributed species). When determining significant variables, the Monte Carlo permutation test (999 unrestricted permutations) with Bonferroni correction ($\alpha = 0{\cdot}05/n$, where n is the number of tests) was used. Firstly, a redundancy analysis with an automatic forward selection routine was used to investigate the significance and importance of typology variables in explaining variations of RHQ data or RHM data separately (Figure 2).

Furthermore, a detrended correspondence analysis performed on the benthic invertebrate dataset revealed the appropriateness of a unimodal response model (canonical correspondence analysis, CCA). The relationship between the environmental variables and benthic invertebrate data was therefore analysed using CCA (ter Braak and Prentice, 1988) and partial CCA (pCCA, Borcard *et al.*, 1992). For the first overview of the environment–community relations, a CCA analysis with an automatic forward selection routine was applied on all environmental variables. This process tested the individual effects of each of the environmental variables (marginal effects) and the effect that each variable has, in addition to other selected variables (conditional effects) (Lepš and Šmilauer, 2003). Secondly, the importance of the three variable groups (typology, RHQ and RHM) in explaining variability among benthic invertebrate assemblages was tested using pCCA. pCCA allows partitioning of the variation in a species-sample data matrix, owing to the unique effects of explanatory variables and their combined effects. Prior to pCCA, variables were selected within each variable group with automatic forward selection in CCA analysis. The total explained variance among benthic invertebrate assemblages with forward-selected environmental variables from three groups was partitioned into (i) the variance uniquely explained by each variable group, (ii) the variance explained by combined effects of each pair of variable groups and (iii) the variance explained by combined effects of all three variable groups together.

The sample size and the number of independent variables in the model influence the result of the pCCA (Kromrey and Hines, 1995). Hence, Ezekiel's adjustment of fractions was calculated using (Peres-Neto *et al.*, 2006)

$$R^2_{(Y/X)adj} = 1 - \frac{n-1}{n-p-1} * \left(1 - R^2_{(Y/X)}\right)$$

where n is the sample size, p is the number of predictors and $R^2_{Y/X}$ is the sample estimation of the assemblage variance $\rho^2_{Y/X}$. The same number of samples and a similar number of predictors (between 5 and 12) in all the models lead to the very similar ratio of explained variance among the variable groups (regression curve; $y = 0{\cdot}76x - 0{\cdot}0012$, $r^2 = 0{\cdot}977$, $P < 0{\cdot}05$).

RESULTS

Relationships among environmental variables

Several statistically significant relationships ($P < 0{\cdot}05$) between pairs of environmental variables were observed with Spearman rank correlation (R_{Sp}, Appendixes 1–6). Strong correlations ($|R_{Sp}| > 0{\cdot}7$) were observed only between variables within variable groups. In the RHQ group, land use within 5 m was strongly correlated with land use within 50 m and banktop vegetation structure; shading of channel also showed a strong correlation with overhanging boughs. The RHM group includes three variables among which a strong correlation was observed (predominant artificial bank material, bank modifications and channel modifications). All strong correlations were positive. Few variable pairs of different variable groups showed moderate correlations ($0{\cdot}50 < |R_{Sp}| < 0{\cdot}70$). Slope was positively correlated with features of special interest along 500 m. Predominant natural bank material was negatively correlated with bank modifications. Other moderate correlations were observed within variable groups. In the typology group the Dinaric Western Balkan ecoregion was negatively correlated with the Alps ecoregion and the lowland region. Slope showed a positive correlation with the Alps ecoregion and a negative correlation with the river size class. In the RHQ group, some expected moderate correlations were observed. Predominant channel substrate correlated positively with predominant flow and predominant natural bank material. Also, among tree-associated variables (shading of channel, overhanging boughs, exposed bankside roots, fallen trees and coarse woody debris), positive moderate correlations were observed.

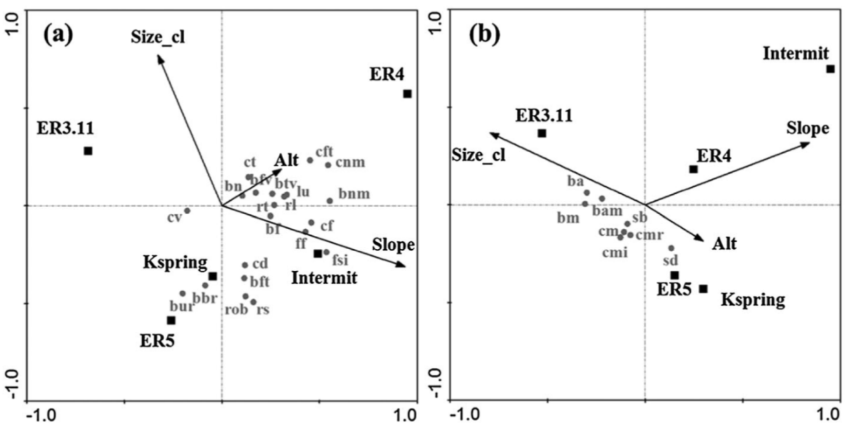

Figure 3. Redundancy analysis ordination diagrams with typology variables as independent variables and (a) RHQ variables or (b) RHM variables as dependent. Black squares represent dummy variables. Codes of all variables are given in Table I.

Correlations between most pairs of variables were weak ($|R_{Sp}| < 0{\cdot}5$).

Associations among three groups of environmental variables

The associations among three groups of environmental variables were evaluated using the redundancy analysis. Typology variables explained 19% of the variability in RHQ variables (Figure 3a) with four statistically significant variables in the forward selection and only 7% of the variability in RHM variables (Figure 3b) with two statistically significant variables. In both datasets, statistically significant variables included slope and river size class. The most explanatory among typology variables was slope, explaining 9% and 3% of the variability in RHQ and RHM variables, respectively. Karst spring influence and intermittency were among the least explanatory variables in both datasets.

Benthic invertebrate responses to environmental variables

The total explained variance of 302 sites and 453 benthic invertebrate taxa dataset was 0·95 (27%). The highest explanatory power of individual variables was observed for slope (0·19), predominant flow and Alps ecoregion (0·17) (Table II). Also, some other variables showed considerable explanatory power, 0·14–0·09 (predominant channel substrate, lowland region, river size class, features of special interest along 500 m and flow types along 500 m). The

Table II. Explained variance (λ) and significance (P) of benthic invertebrate assemblages by each environmental variable.

		Before FS	After FS all		After FS groups	
Environmental variable	Variable group	λ	λ	P	λ	P
Region: Lowland	Typology	0·10	0·06	0·001	0·04	0·001
Ecoregion: Alps	Typology	0·17	0·05	0·001	0·08	0·001
Ecoregion: Dinaric Western Balkan	Typology	0·08				
Catchment size class	Typology	0·10	0·04	0·001	0·06	0·001
Karst spring influence	Typology	0·06	0·06	0·001	0·06	0·001
Intermittency	Typology	0·03	0·02	0·001	0·02	0·001
Altitude	Typology	0·08	0·02	0·001	0·03	0·001
Slope	Typology	0·19	0·19	0·001	0·19	0·001
Predominant natural bank material	RHQ	0·08			0·02	0·002
Bank features	RHQ	0·05	0·02	0·001		
Predominant channel substrate	RHQ	0·14	0·03	0·001	0·04	0·001
Predominant flow	RHQ	0·17	0·11	0·001	0·17	0·001
Channel features	RHQ	0·02				
Land use within 5 m	RHQ	0·04	0·02	0·001		
Banktop vegetation structure	RHQ	0·04	0·02	0·001		
Bankface vegetation structure	RHQ	0·02	0·01	0·001	0·02	0·004
Channel vegetation types	RHQ	0·06	0·03	0·001	0·05	0·001
Land use within 50 m	RHQ	0·05			0·02	0·001
Natural bank profiles	RHQ	0·02				
Extent of trees	RHQ	0·04				
Shading of channel	RHQ	0·04	0·02	0·001	0·03	0·001
Overhanging boughs	RHQ	0·04				
Exposed bankside roots	RHQ	0·04			0·02	0·001
Underwater tree roots	RHQ	0·06			0·02	0·001
Fallen trees	RHQ	0·04				
Coarse woody debris	RHQ	0·03				
Flow types along 500 m	RHQ	0·09			0·02	0·003
Channel and bank features along 500 m	RHQ	0·08			0·02	0·001
Features of special interest along 500 m	RHQ	0·09			0·06	0·001
Predominant artificial bank material	RHM	0·02			0·03	0·001
Bank modifications	RHM	0·03			0·03	0·001
Channel modifications	RHM	0·02				
Artificial bank profiles	RHM	0·03			0·02	0·003
Dam/weir	RHM	0·02			0·03	0·001
Bridge	RHM	0·01				
Channel realignment	RHM	0·02				
Water impoundment by weir/dam	RHM	0·04	0·02	0·002	0·04	0·001

Independent effects: before FS, before forward selection. Conditional effects: after FS all, after forward selection with all variables; after FS groups, after forward selection within each variable group. For variable groups (Typology, RHQ, RHM) see Table I.

lowest explanatory power was observed for bridge (0·01). Among the RHM variables, the most explanatory was water impoundment by weir/dam (0·04). By using an automatic forward selection routine on all environmental variables, 16 statistically significant variables were selected (Table II). The model of 16 selected variables explained 0·72 (21%) of the benthic invertebrate dataset (Figure 4). The 16 selected variables belong to all three groups, eight and seven variables were chosen from the RHQ and typology groups, respectively, and only one variable was chosen from RHM group. Of the 16 selected variables, only three variables from the RHQ group were not chosen when running the forward selection for each variable group separately (bank features, land use within 5 m, and banktop vegetation structure).

Variance partitioning of three groups of environmental variables and benthic invertebrate assemblages

Variance partitioning was run with 24 variables selected after forward selection routine for each variable group separately. Three variable groups consisted of 5–12 selected variables (Table II), with the highest number in the RHQ group (12 out of 21), followed by the typology group (seven out of eight) and RHM group (five out of eight). All 24 selected variables together explained 24% of the benthic invertebrate assemblages' variability. Clearly, unique effects of variable groups were more important in explaining variability in the benthic invertebrate composition than joint effects (69% and 31% of the explained variance, respectively, Figure 5). A similar share of unique effects was explained by the typology (30%) and RHQ (31%) groups, but the explanatory power of the RHM group was considerably smaller (8%). Among joint

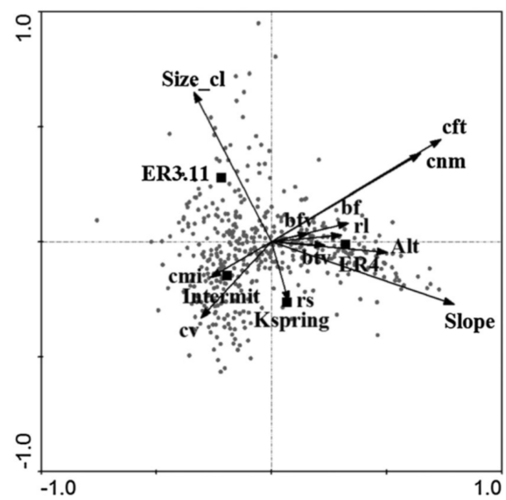

Figure 4. Canonical correspondence analysis ordination diagram of 302 sites and the 16 forward-selected environmental variables. Black squares represent dummy variables. Codes of environmental variables are given in Table I.

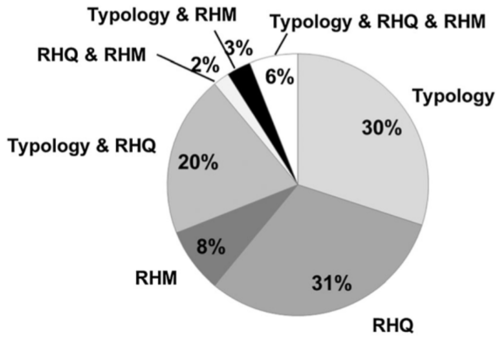

Figure 5. Unique and joint effect contribution of the environmental variable groups to the explained variability of benthic invertebrate assemblages.

effects, the interaction between the typology and RHQ groups was most important, accounting for 20% of explained variance. Other interactions between pairs of groups were less important. Joint effects of all three variable groups explained 6% of variability.

DISCUSSION

The relation of regional natural characteristics to local morphological features

The occurrence and shape of local river morphological features depend on regional factors (Frissell *et al.*, 1986; Poff, 1997). Regional natural characteristics (typological variables) in Slovenian rivers explained a considerable amount of variation in local habitat quality features (RHQ). The highest explanatory power among typological variables was observed for slope, followed by river size class and Alps ecoregion. Slope is commonly recognized as an important parameter structuring channel morphology (Allan, 2004), and the thesis is confirmed also by low, but mostly significant, positive correlations between slope and most of the RHQ variables in our study. Steeper slopes are mostly found in upland regions and connected to narrow valleys with small rivers. Tavzes and Urbanič (2009) reported that Slovenian rivers of the Alps ecoregion have habitat quality characteristics typical of alpine streams – related to high-energy flows (Szoszkiewicz *et al.*, 2006). Hence, the significance of the Alps ecoregion in our analysis was not surprising. The significance of river size partly depends on highly energetic streams of the Alps ecoregion, influencing river flow and channel substrate heterogeneity, but the negative correlation of river size to riparian zone quality features also suggests more naturalness with smaller river size.

Because a relationship between regional factors and local RHQ characteristics exists, regional factors could define the alteration of river morphological habitat to some extent. Alpine regions with narrow and remote river valleys are less suitable for human settlement. However, these attributes are becoming more and more interesting for different human activities (e.g. tourism and hydropower plants), and high-energy flows of alpine rivers causing in-stream instability represent an obstacle. For this reason, many streams in the Alpine area are now affected by morphological alterations, such as resectioning and reinforcement of banks, bridges and weirs (Bona *et al*., 2008; Tavzes and Urbanič, 2009; Wyżga *et al*., 2011). Lowland rivers, on the other hand, have wider riparian zones, mostly connected to large floodplains. Human occupation of floodplains and riparian zones lead to a wide range of morphological alteration affecting lowland rivers (Pedersen, 2009; Pedersen and Friberg, 2009), such as straightening and deepening. Therefore, morphological degradation of river habitats occurs irrespective of regional factors, just as its ground reason differs. This thesis was confirmed in our study, as the typological variables explained an almost negligible amount of variation in local habitat modification features. A significant, although low, explanatory power was observed for slope and river size class. Whereas slope represents mostly a regional factor, by being steeper in upland and gentler in lowland regions, river size in Slovenia is not merely a regional factor, as small streams with their sources up to large rivers are found in mountainous and lowland regions. However, river size is still partly related to bank modifications. One possible reason for this correlation is the social view of larger rivers as more threatening, causing more erosion or flooding and thus requiring more regulation structures. The significance of river size class in the present study also demonstrates the nonregional presence of morphological modification.

Linking morphological features to the response of benthic invertebrate assemblages

The SIHM method was developed for the assessment of river habitat quality (RHQ) and modification (RHM) features. Higher values of RHQ features indicate a high diversity of habitat, whereas severe morphological degradation is characterized by high values of RHM features. We tested individual features of the SIHM method for their significance in structuring benthic invertebrate assemblages. Generally, habitat quality features revealed more explanatory power than habitat modification features. Among RHQ features, the highest explanatory power was observed for predominant flow and predominant channel substrate – the two variables most commonly observed in affecting aquatic assemblages (Richards *et al*., 1993; Lammert and Allan, 1999; Sandin, 2003; Sandin and Johnson, 2004, Syrovátka *et al*., 2009). The strong and more diversified river flow mostly relates to coarse and heterogeneous channel substrate (Statzner and Higler, 1986; Poff *et al*., 1997), but these variables were only moderately correlated in our study. Moreover, predominant flow compared with predominant channel substrate showed higher explanatory power in structuring benthic assemblages. River flow represents a direct physical force affecting organisms, but its indirect effects are also significant for benthic assemblages, including oxygen content of the stream, food delivery and substratum composition. Studies comparing the effects of both flow and substrate variables are rare (Urbanič *et al*., 2005; Friberg *et al*., 2009a; Sandin, 2009; Wyżga *et al*., 2011), but all revealed partly different relations of predominant flow and substrate to benthic assemblages. Besides flow, other mechanisms affect substrate composition and consequently biota (Wyżga *et al*., 2011). Different in-stream structures interrupting longitudinal continuity upstream can reduce the availability of substrate for fluvial transport (Kondolf, 1997), and the local riparian management can affect in-stream substrate and biota by the reduction or acceleration of bank erosion and by restraining the sediment input from the catchment (Allan, 2004). In fact, our study showed a positive correlation of channel substrate to the structure of riparian vegetation and land use.

Riparian vegetation is another habitat feature commonly exerting great influence upon habitat diversity and, consequently, the structure and function of aquatic assemblages (Cummins *et al*., 1989; Bis *et al*., 2000; Sandin, 2009). The SIHM method comprises several features describing riparian vegetation structure, and although all features significantly contribute to structuring benthic invertebrate assemblages, the highest explanatory power observed was still threefold lower than that of predominant flow and channel substrate. Also, in-stream vegetation that plays a vital role in increasing habitat diversity and creating aquatic refugia for biota (Sandin and Johnson, 2004; Pinto *et al*., 2006) explained as low amount of benthic assemblages' variability as riparian vegetation features. Our results suggest that the structure of benthic assemblages depends more on flow and substrate characteristics than on riparian and in-stream vegetation structure. These findings are important guidance for river management, as riparian vegetation reestablishment is one of the most common river rehabilitation practices today (Death and Collier, 2009; Riley and Dodds, 2012). Also, Greenwood *et al*. (2012) imply that poor in-stream habitat, due to changed flow dynamics and sedimentation, can limit the effectiveness of riparian management. On the other hand, Urban *et al*. (2006) found that riparian vegetation was a stronger predictor of benthic invertebrate community than habitat and reach in-stream variables, the latter including substrate and stream discharge. However, the habitat, reach and riparian spatial scale were much smaller than in the present study (up to 150 m). The importance of flow and substrate diversity in our study was also reflected in reach-scale variables (500 m), with the explanatory power higher than that of any riparian vegetation feature.

Human modifications of river habitat are reflected in RHM features, all of them showing very low explained variability of benthic invertebrate assemblages. The possible reason for a lower explanatory power of RHM than of RHQ features is the nature of the survey, where RHM features might be as equally present as absent, in contrast to RHQ features that can almost always be assigned to one of the categories (Raven *et al.*, 1997; Tavzes and Urbanič, 2009). However, even frequent RHM features did not explain a greater amount of assemblages' variability across the whole study area. The most important RHM feature seems to be water impoundment by dam/weir, in agreement with the findings of Marzin *et al.* (2012), where the presence of an impoundment emerged as the main human pressure factor shaping the fish and macroinvertebrate assemblages at the reach scale. Similar to the most explanatory RHQ variable (predominant flow), the change of flow characteristics caused by impoundment affects other morphological features (e.g. channel substrate) and results in direct and indirect effects on benthic invertebrate assemblages. On the other hand, studies across Europe identified bank resectioning and reinforcement as the most typical modification of rivers (Feld, 2004; Szoszkiewicz *et al.*, 2006). The correlation of bank modification to benthic invertebrate metrics, observed by Erba *et al.* (2006), and the feature being one of the best explanatory RHM variables in our study confirm the importance of bank beside channel alteration.

The low explanatory power of morphological modification features might also reflect the overriding effect of habitat quality features. To some extent, RHQ features exert human influence. Namely, bank modification, such as straightening, influences predominant flow and channel substrate, as well as channel and bank natural features (Negishi *et al.*, 2002; Pedersen, 2009). Also, riparian zone clearing lowers the values of riparian vegetation features and, owing to lessened shadowing, accelerates growth of in-stream vegetation (Julian *et al.*, 2011). Additionally, a four times higher explanatory power of predominant flow, in comparison with that of water impoundment by dam/weir, was observed. According to the results of the present study, a higher importance in structuring benthic assemblages is suggested for the habitat quality and its diminishment by human influence than for morphological alteration features itself.

Co-influence of regional natural characteristics and local morphological features

As observed before, habitat features on local scales might be influenced by regional parameters (typology), and hence, the real effect on aquatic assemblages might be obscured (Richards *et al.*, 1997; Cortes *et al.*, 2009). The issue of hierarchical interaction of multiscale factors has been of special concern for studies relating natural characteristics and human alterations to river communities, with authors emphasizing the importance of larger scales (Roth *et al.*, 1996; Lammert and Allan, 1999) or of smaller scales (Ormerod *et al.*, 1993; Richards *et al.*, 1993; Heino *et al.*, 2004). Marginal effects of different scale variables in the present study revealed a similar explanatory power of the best local habitat quality features (predominant flow and channel substrate) and best regional natural variables (Alps ecoregion and slope). Moreover, using variance partitioning, we observed almost even distinct effects of typological and local habitat quality variables. This implies the importance of quality parameters at both scales, which is in accordance with the findings of other authors (Brosse *et al.*, 2003; Sandin, 2003; Johnson *et al.*, 2007). The observed amount of joint effects between habitat quality features and typological parameters was considerable but lower than that of distinct effects. The interaction of parameters on both scales, and aforementioned explanatory power of regional natural parameters on habitat quality characteristics, lead to two definitive conclusions – the larger-scale parameters constrain the processes on smaller scales to a certain extent, and the resulting physical patterns influence the biology of stream, which is agreed also by other authors (Richards *et al.*, 1997; Verdonschot, 2006; Li *et al.*, 2012, Marzin *et al.*, 2012). But the observed large share of distinct effects implies that there is a considerable part of benthic invertebrate assemblage variability in Slovenia dependent on habitat quality features irrespective of typological characteristics.

In contrast to habitat quality features, we cannot make any presumptions for habitat modification features, as either their distinct or joint effects with typological parameters were too low. One of the possible reasons is, on the one hand, the high diversity of regional and local characteristics of Slovenian landscape, influencing the adjustment of benthic assemblages and, on the other hand, the presence of a wide variety of modification features irrespective of the region. As benthic assemblages are adapted to the former natural conditions, similar modification features might result in different effects with regard to regional characteristics. Bank stabilization by concrete or rip-rap in alpine rivers, with natural banks consisting of rocks or stones, results in effects different than those in lowland rivers, where naturally, sand or earth forms bank profiles. Consequently, using the dataset from different regions jointly might obscure the effects of morphological modification.

CONCLUSIONS

Several conclusions can be drawn from our analysis of RHQ and RHM features, according to the Slovenian hydromorphological (SIHM) assessment method. In our study, a large heterogeneous area was sampled. Therefore, we did not expect the great explanatory power of local morphological features but aimed at defining general patterns. The most important local habitat characteristics for structuring benthic invertebrate assemblages were identified, with predominant flow and channel substrate as the best explanatory variables. Almost all habitat quality features proved important, but the effects of habitat modification features were marginal. We suggest that benthic invertebrate assemblages respond less to the physical alteration itself and more to the effect that the alteration exerts on habitat quality features. Moreover, local habitat quality features depend on regional characteristics, but only to some extent. When discussing management options, general guidelines are most welcome, but even more desirable are their high confidence levels. To lessen the effect of regional parameters, analyses on regional scale should be conducted. Because our study revealed the great importance of ecoregions for structuring benthic assemblages, we propose further analyses on the ecoregion scale. With the whole gradient of habitat alteration covered, we also expect these analyses within more homogeneous natural habitat to more clearly reveal the significance of modification features. Finally, the most relevant morphological features, according to our findings, are directly connected to river flow. Hence, for more effective planning of management practices, we suggest further study for more detailed determination of the interaction between hydrological and morphological parameters on aquatic assemblages.

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APPENDIX 1. Statistically significant Spearman's correlation coefficients (R_{Sp}) for the combinations of environmental variables between the typology and RHQ groups.

Variable	ER3.11	ER4	ER5	Size_cl	Kspring	Intermit	Alt	Slope
bnm	−0·272**	0·343**		−0·138*		0·150**	0·119*	0·476**
bf	−0·176**	0·191**		−0·162**				0·359**
cnm	−0·135*	0·376**	−0·230**			0·141*	0·165**	0·426**
cft	−0·120*	0·472**	−0·333**			−0·261**	0·266**	0·394**
ct	−0·158**	0·163**						0·292**
rl	−0·131*	0·236**		−0·156**			0·144*	0·242**
btv		0·161**				0·121*		0·172**
bfv	−0·113*	0·167**						
cv		−0·207**	0·282**	0·131*	0·308**			−0·162**
lu	−0·139*	0·198**		−0·127*		0·142*	0·179**	0·236**
bn		0·138*						
rt	−0·145*	0·222**					0·136*	0·250**
rs			0·167**	−0·464**				0·332**
rob			0·184**	−0·401**				0·283**
bbr		−0·241**	0·248**	−0·241**				
bur		−0·366**	0·322**	−0·203**			−0·187**	
bft	−0·159**		0·202**	−0·278**				0·213**
cd				−0·238**				0·229**
cf	−0·255**	0·279**		−0·244**			0·219**	0·445**
ff	−0·237**	0·203**		−0·241**			0·127*	0·471**
fsi	−0·311**	0·308**		−0·468**			0·317**	**0·597****

$R_{Sp} > 0·5$ are in bold.
*$P < 0·05$.
**$P < 0·01$.

APPENDIX 2. Statistically significant Spearman's correlation coefficients (R_{Sp}) for the combinations of environmental variables between the typology and RHM groups.

Variable	ER3.11	ER4	ER5	Size_cl	Kspring	Intermit	Alt	Slope
bam	0·124*		−0·124*	0·238**		−0·181**		−0·138*
bm	0·194**			0·224**		−0·170**		−0·247**
cm	−0·128*		0·162**		0·122*			−0·134*
ba	0·169**		−0·162**	0·240**		−0·174**		−0·167**
sd	−0·181**			−0·163**	0·119*	−0·142*	0·137*	
sb								
cmr								
cmi			0·134*		0·135*			−0·172**

*$P < 0·05$.
**$P < 0·01$.

APPENDIX 3. Statistically significant Spearman's correlation coefficients (R_{Sp}) for the combinations of environmental variables between the RHM and RHQ groups.

Variable	bam	bm	cm	ba	sd	sb	cmr	cmi
bnm	−0·494**	**−0·563****	−0·211**	−0·442**	−0·189**	−0·268**	−0·329**	−0·131*
bf	−0·202**	−0·316**	−0·124*	−0·219**		−0·136*	−0·183**	−0·182**
cnm			−0·191**		−0·148*		−0·223**	−0·205**
cft	0·169**			0·164**				−0·302**
ct		−0·199**		−0·138*			−0·197**	
rl	−0·420**	−0·458**	−0·189**	−0·362**	−0·219**	−0·319**	−0·253**	−0·154**
btv	−0·423**	−0·433**	−0·188**	−0·346**	−0·243**	−0·298**	−0·322**	−0·175**
bfv	−0·400**	−0·422**	−0·219**	−0·351**	−0·262**	−0·319**	−0·294**	−0·148**
cv								
lu	−0·324**	−0·390**	−0·222**	−0·271**	−0·233**	−0·394**	−0·247**	−0·164**
bn	−0·139*	−0·246**	−0·162**	−0·154**		−0·209**	−0·232**	
rt	−0·301**	−0·360**	−0·206**	−0·269**	−0·136*	−0·250**	−0·269**	
rs	−0·215**	−0·204**		−0·214**				
rob	−0·257**	−0·260**		−0·250**				−0·122*
bbr	−0·356**	−0·341**	−0·153**	−0·334**		−0·134*	−0·145*	
bur	−0·205**	−0·139*		−0·143*				
bft	−0·405**	−0·421**		−0·361**			−0·182**	
cd	−0·292**	−0·319**	−0·124*	−0·249**			−0·133*	
cf		−0·154**					−0·125*	−0·158**
ff	−0·262**	−0·376**	−0·144**	−0·292**	−0·127*	−0·116*	−0·208**	−0·187**
fsi	−0·359**	−0·410**	−0·200**	−0·338**	−0·151**		−0·193**	−0·319**

$R_{Sp} > 0{\cdot}5$ are in bold.
*$P < 0{\cdot}05$.
**$P < 0{\cdot}01$.

APPENDIX 4. Statistically significant Spearman's correlation coefficients (R_{Sp}) for the combinations of environmental variables within the typology group.

Variable	ER3.11	ER4	ER5	Size_cl	Kspring	Intermit	Alt
ER4	−0·400**						
ER5	**−0·518****	**−0·576****					
Size_cl	0·358**	−0·177**	−0·154**				
Kspring	−0·299**		0·224**				
Intermit	−0·137*	−0·153**	0·265**	−0·141*			
Alt	−0·435**	0·492**		−0·340**	0·154**		
Slope	−0·390**	**0·502****	−0·120*	**−0·618****			0·362**

$R_{Sp} > 0{\cdot}5$ are in bold.
*$P < 0{\cdot}05$.
**$P < 0{\cdot}01$.

APPENDIX 5. Statistically significant Spearman's correlation coefficients (R_{Sp}) for the combinations of environmental variables within the RHM group.

Variable	bam	bm	cm	ba	sd	sb	cmr
bm	**0·869****						
cm	0·189**	0·212**					
ba	**0·814****	**0·786****					
sd	0·250**	0·225**	0·337**	0·189**			
sb	0·337**	0·319**	0·173**	0·312**	0·155**		
cmr	0·297**	0·474**	0·266**	0·219**	0·196**	0·236**	
cmi	0·184**	0·133*	0·288**		**0·558****		

$R_{Sp} > 0{\cdot}5$ are in bold.
*$P < 0{\cdot}05$.
**$P < 0{\cdot}01$.

APPENDIX 6. Statistically significant Spearman's correlation coefficients (R_{Sp}) for the combinations of environmental variables within the RHM group.

Variable	bnm	bf	cnm	cft	ct	rl	btv	bfv	cv	lu	bn	rt	rs	rob	bbr	bur	bft	cd	cf	ff
bf	0·409**																			
cnm	0·536**	0·325**																		
cft	0·252**	0·255**	0·563**																	
ct	0·419**	0·360**	0·398**	0·291**																
rl	0·482**	0·261**	0·310**		0·263**															
btv	0·395**	0·227**	0·267**		0·212**	0·763**														
bfv	0·363**	0·166**	0·175**		0·141*	0·414**	0·594**													
cv		−0·193**	−0·118**			−0·206**	−0·193**													
lu	0·464**	0·250**	0·341**	0·122*	0·240**	0·762**	0·645**	0·371**	−0·144*											
bn	0·298**		0·136*	0·115*	0·143*	0·129*		0·161**		0·115*										
rt	0·429**	0·289**	0·243**	0·199**	0·217**	0·494**	0·556**	0·644**	−0·247**	0·480**	0·165**									
rs		0·123*	−0·115*									0·188**								
rob		0·124*	−0·142*					0·157**				0·304**	0·799**							
bbr	0·141*	0·172**	−0·203**	−0·146*		0·144*		0·122*				0·193**	0·586**	0·628**						
bur			−0·251**	−0·230**		−0·146*							0·424**	0·483**	0·602**					
bft	0·283**	0·242**			0·173**	0·273**	0·151**	0·169**		0·193**	0·145*	0·273**	0·536**	0·546**	0·574**	0·429**				
cd	0·236**	0·278**			0·134*	0·185**					0·185**	0·270**	0·488**	0·508**	0·572**	0·356**	0·659**			
cf	0·344**	0·446**	0·446**	0·380**	0·518**	0·279**	0·210**		−0·137*	0·243**		0·285**	0·190**	0·146*			0·242**	0·264**		
ff	0·539**	0·728**	0·378**	0·280**	0·597**	0·352**	0·223**	0·147*	−0·149**	0·311**		0·328**	0·278**	0·229**	0·296**		0·378**	0·319**	0·617**	
fsi	0·487**	0·467**	0·359**	0·373**	0·399**	0·405**	0·321**	0·188**	−0·131*	0·333**		0·390**	0·362**	0·330**	0·221**		0·318**	0·315**	0·603**	0·651**

$R_{Sp} > 0·5$ are in bold.
*$P < 0·05$.
**$P < 0·01$.

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Slika 9. Motiv z mesta vzorčenja Sava, Bodešče

Figure 9. A theme from sampling site Sava, Bodešče

2.1.2 Članek II

Povezanost morfoloških spremenljivk vodotokov in združb bentoških nevretenčarjev; primerjava treh evropskih ekoregij

The links between river morphological variables and benthic invertebrate assemblages; comparison among three European ecoregions

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Vesna PETKOVSKA, Gorazd URBANIČ

Dobro poznavanje povezav med naravnimi in spremenjenimi rečnimi habitati ter združbami rečnih organizmov je pomembno, a trenutno nezadostno, za vzpostavitev trajnostnega upravljanja z ekosistemi tekočih voda. V prispevku smo zato primerjali odnos med naravnimi morfološkimi lastnostmi vodotokov in njihovimi spremembami ter združbami bentoških nevretenčarjev v treh evropskih ekoregijah z različnimi naravnimi značilnostmi: Alpe, Panonska nižina in Dinaridi. Morfološke razmere smo ovrednotili s spremenljivkami lastnosti kakovosti (RHQ) in spremenjenosti rečnih habitatov (RHM) glede na Slovenski hidromorfološki sistem in jih povezali z združbami bentoških nevretenčarjev na podlagi multivariatnih analiz. V splošnem smo ugotovili precej večjo pomembnost spremenljivk RHQ v primerjavi s spremenljivkami RHM za oblikovanje zgradbe združb bentoških nevretenčarjev, vendar pa tudi pomembne razlike med ekoregijami. V vseh ekoregijah smo med najpomembnejšimi spremenljivkami ugotovili prevladujoč tok in substrat struge. Poleg teh spremenljivk so za zgradbo združb bentoških nevretenčarjev v Alpah bolj pomembne spremenljivke bregov, medtem ko so v Panonski nižini bolj pomembne razmere v strugi. V Dinaridih je za zgradbo združb pomembna kombinacija spremenljivk bregov in struge. Med spremenljivkami RHM smo v vseh ekoregijah prepoznali pomembnost spremenljivke umetni profili bregov. Enako pojasnjevalno sposobnost smo v Alpah ugotovili še za spremenljivki zastoj vode zaradi jezu in spremembe bregov, medtem ko v Panonski nižini le za spremenljivko umetni material brega in za nobeno od RHM spremenljivk v Dinaridih. Upoštevanje sprememb rečnih habitatov je po naših ugotovitvah sicer pomembno za upravljanje z ekosistemi tekočih voda, vendar bi se morali posvetiti prav lastnostim kakovosti habitatov. Zaradi ugotovljenih razlik med ekoregijami poudarjamo, da je pomemben vsaj regionalen pristop k upravljanju.

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The links between river morphological variables and benthic invertebrate assemblages: comparison among three European ecoregions

Vesna Petkovska · Gorazd Urbanič

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Abstract Understanding the relationship between river natural and degraded habitats and river assemblages is crucial but yet insufficient for the desired sustainable river management. Our paper therefore compares the relation of river natural morphological features and their modification to benthic invertebrate assemblages among European ecoregions Alps, Pannonian lowland, and Dinaric western Balkan with varied natural characteristics. Morphological conditions were assessed using the habitat quality (RHQ) and modification (RHM) variables, according to Slovenian hydromorphological assessment method, and linked to benthic invertebrate assemblages using multivariate analyses. The overall results indicate markedly higher importance of RHQ variables in comparison with RHM variables for structuring benthic invertebrate assemblages, but reveal important differences among ecoregions. Predominant flow and predominant channel substrate were found among the most important RHQ variables across all ecoregions. Beside these, benthic invertebrate assemblages of the Alps were influenced most by bank variables, whereas of the Pannonian lowland by features linked directly to channel conditions. In Dinaric western Balkan a combination of bank and channel variables influenced the assemblages. Among habitat modification features artificial bank profiles appeared important across all ecoregions. However, in the Alps equal explanatory power was observed for variables water impoundment by weir/dam and bank modifications, whereas in the Pannonian lowland only for variable artificial bank material and even for none in Dinaric western Balkan. According to our findings it is important to consider habitat modification in river management, but more weight should be given to habitat quality features. Moreover, the differences among ecoregions emphasize the need for ecoregion-specific approach.

Keywords Benthic invertebrates · Slovenian hydromorphological assessment method · River Habitat Survey · Ecoregions · River management · Variance partitioning · Hydromorphology

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V. Petkovska (✉) · G. Urbanič
Institute for Water of the Republic of Slovenia, Hajdrihova 28c, 1000 Ljubljana, Slovenia
e-mail: vesna.petkovska@izvrs.si

G. Urbanič
Department of Biology, Biotechnical Faculty, University of Ljubljana, Večna pot 111, 1000 Ljubljana, Slovenia

Introduction

Rivers and their surroundings have been managed for decades for different purposes, but recently the

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multiple use of the phrase sustainable contributed new insight. In Europe holistic and sustainable approach to water management was established with the implementation of the Water Framework Directive (WFD, European Union 2000) and its leading goal—good ecological status for all water bodies. The rationale is to include all management principles that exist for different water uses and guide them simultaneously toward achievement of sustainable water ecosystems that are reflected in good ecological status. The assessment of ecological status is based on aquatic assemblages and hence comprises holistic ecosystem functioning, but it often cannot identify the specific contributing stressor (Brack et al. 2009). A better understanding of ecosystem functioning and the development of an appropriate stressor-specific assessment method has been recognized in last decade as an important step toward the implementation of the ecological status concept.

One of the major factors influencing structure and functioning of river assemblages is the hydromorphological naturalness and its alteration (Raven et al. 2002; Lorenz et al. 2004a; Urbanič 2014). For a long time rivers have been managed in a way leading to hydromorphological degradation, e.g., channelization, weir and dam construction, disconnection of floodplains from the channel, and riparian vegetation clearance (Pedersen 2009; Verdonschot 2009). Several methods have been developed as a means to summarize the heterogeneous nature of riverine physical habitat characteristics and modifications (Muhar et al. 1996, 1998; Raven et al. 1998, 2003; LAWA 2000; Feld 2004; Rinaldi et al. 2013a), with one of the more comprehensive methods being the UK River Habitat Survey method (RHS; Raven et al. 1998, 2003). The application of the RHS method was tested in several European countries (Balestrini et al. 2004; Szoszkiewicz et al. 2006; Tavzes et al. 2006; Bona et al. 2008; Raven et al. 2010) and was adapted further for use in Southern Europe (Buffagni and Kemp 2002). The morphological part of the Slovenian hydromorphological (SIHM) assessment method is based on the RHS method, but with weighting different categories of river features with regard to their influence on benthic invertebrate assemblages (Tavzes and Urbanič 2009), resulting in 33 collected morphological features. There is a growing body of the literature establishing general links between benthic invertebrate assemblages and either morphological quality of river habitat features (Lammert and Allan 1999; Sandin and Johnson 2004; Syrovátka et al. 2009), or morphological degradation of river habitat (Erba et al. 2006; Feld and Hering 2007; Larsen and Ormerod 2010), but comparison between the effects of both feature groups was rarely addressed (e.g., Hughes et al. 2008). For the purpose of WFD several benthic invertebrate-based assessment methods addressing hydromorphological pressure have been developed (Lorenz et al. 2004a; Rinaldi et al. 2013b; Urbanič 2014). These methods enable the impact of all hydromorphological parameters to be evaluated simultaneously, but disentangling the effect of individual hydromorphological components leads toward more practical and effective guidance for river management. The relationship between benthic invertebrate assemblages and individual morphological features that are included in applied assessment methods was rarely analyzed, and most studies considered only RHS features (Erba et al. 2006; Hughes et al. 2008; Cortes et al. 2009; Dunbar et al. 2010). Petkovska and Urbanič (2015) investigated SIHM features, but only on a large scale of the whole Slovenian area.

Management authorities welcome concepts that are applicable across large scales, e.g., general guidelines that would hold true irrespective of the region or river type. However, the regional differences of river assemblages (Lorenz et al. 2004b; Pinto et al. 2006; Urbanič and Toman 2007) and morphological characteristics of rivers (Frissel et al. 1986; Szoszkiewicz et al. 2006; Harnischmacher 2007; Splinter et al. 2010) might obscure their association if the investigation extends over different regions. On the basis of similar climate, soils, topography and other characteristics in Europe and USA ecoregions were delineated for regional definition of water quality and management goals (Illies 1978; Omernik 1987). Besides considering abiotic factors, the delineation of European ecoregions was verified using aquatic assemblages (Lorenz et al. 2004b; Urbanič 2008). Slovenian landscape yields high geographical and geomorphological diversity and shares four distinct European ecoregions on a quite small area (Urbanič 2011). Thus, there are high possibilities for comparison of pressure–impact relationship on a regional level which might give a better focus for region-specific river management. The general objective of our study was to compare the association between morphological features of river habitat and benthic invertebrates assemblages among three distinct European ecoregions. Our results complement and upgrade similar studies in some Western and Central Europe mountain and lowland regions (e.g., Hering et al. 2006; Feld and Hering 2007; Bona et al. 2008; Dunbar et al. 2010), but to our knowledge, the results considering Dinaric western Balkan ecoregion are the first of this kind in the region with spring-fed karst streams and rivers. Although the ecoregions represent more homogeneous units, the variability of some physiographic factors (e.g., slope, altitude) is still present within (Urbanič and Toman 2007; Urbanič 2009; Hrovat et al. 2014). Since there might be some interaction effects between morphological features and physiographic factors that affect aquatic assemblages (Petkovska and Urbanič 2015), we included those in the analysis as an additional set of environmental variables.

The main questions addressed in our study were as follows:

1. What are the most explanatory river morphological features for structuring benthic invertebrate assemblages in the lowland, alpine and Dinaric rivers?
2. How much of the variability in benthic invertebrate assemblages is explained by river morphological quality features in comparison with river morphological modification features in each of three ecoregions and what is their share of explained variability in comparison with that of physiographic factors?

Materials and methods

Study area and environmental variables

Slovenia is a small European country with a total area of 20,273 km^2, where 4573 km of rivers within catchments larger than 10 km^2 flow over four ecoregions (delineated by Illies 1978; Urbanič 2008; Alps—ER4, Dinaric western Balkan—ER5, Pannonian lowland—ER11, and Po lowland—ER3). The area of the main three ecoregions (ER4, ER5, and ER11), covering more than 99 % of Slovenia (Urbanič 2008), was selected for our study. Since the objective of our study was to determine the relation of morphological features to benthic invertebrate assemblages, the selection of sites covers mainly the gradient from natural to heavily altered morphological conditions. In order to measure response of the assemblages mainly to hydromorphological pressures, sites impacted with other relevant pressures were a priori excluded (less than good ecological status sites according to the benthic invertebrate-based Slovenian Saprobic index—EQR < 0.6 and following general physico-chemical parameters $BOD_5 > 5.4$ mg/L, total phosphorus > 205 µg/L, orthophosphate > 84 µg/L, nitrate > 9.5 mg/L). Good status criteria were developed in accordance with the Water Framework Directive (Directive 2000/60/EC), and biological methods were intercalibrated at the European Union level (Poikane et al. 2014). Data were organized in three ecoregion datasets which comprised 93 sites (ER4), 129 sites (ER5), and 73 sites (ER11).

For each site data on important physiographic factors (river size class, intermittency, karst spring influence) were obtained from the Slovenian river typology (Table 1; for details, see Urbanič 2011; Petkovska and Urbanič 2015). Four river size classes were used: 1—10–100 km^2, 2—>100–1000 km^2, 3—>1000–2500 km^2 and mean annual discharge <50 m^3/s, and 4—>2500 km^2 or mean annual discharge >50 m^3/s. Intermittency and karst spring influence are parameters in alpine and Dinaric region, which indicate rivers with (usually summer) dry bed and downstream of karst spring, respectively. Additionally altitude and slope were calculated using a Digital Elevation Model with 5 m accuracy.

Data on morphological features (variables) were obtained once in a study period (mostly between 2005 and 2011, in the season of low-to-medium discharge) along a 500-m-long stretch of the river using an adapted version of the UK River Habitat Survey (RHS) method (Raven et al. 2003) as a part of the SIHM method (Tavzes and Urbanič 2009). A variety of bank and channel features were recorded at 10 spot-checks (e.g., predominant substrate, physical features of channel and banks, flow type, channel vegetation type), spaced at every 50 m, and additional features with the sweep-up part of survey along the whole stretch (e.g., land use in the 50-m stretch from the channel, bank profile, extent of trees, artificial features). Present categories were recorded for each feature, and using the weighting factors joint to 22 river habitat quality features (RHQ variables) and 11 river habitat modification features (RHM variables)

Table 1 Summary of environmental characteristics with their affiliation to variable group (Typo—physiographic factors, RHQ—habitat quality features, RHM—habitat modification features); analyzed datasets: ER4 ecoregion Alps, ER5 ecoregion Dinaric western Balkan, ER11 ecoregion Pannonian lowland

Environmental variable	Code	Unit	Group	Median (Min–Max)[c]		
				ER4	ER5	ER11
River size class	Size_cl	Class 1–4	Typo	1 (1–4)	1 (1–4)	3 (1–4)
Karst spring influence	Kspring	Dummy	Typo	21	39	0
Intermittency	Intermit	Dummy	Typo	0	15	0
Altitude[b]	Alt	m.a.s.l.	Typo	395 (157–896)	285 (1–745)	208 (132–354)
Slope[b]	Slope	‰	Typo	13.9 (0–261)	4.0 (0–89.7)	1.7 (0–12.9)
Predominant natural bank material	bnm	Sc total[a]	RHQ	20.5 (0–42.5)	14 (0–44)	12 (0–34.5)
Bank features	bf	Sc total[a]	RHQ	2.5 (0–15.8)	1.5 (0–16.5)	0.5 (0–23)
Predominant channel substrate	cnm	Sc total[a]	RHQ	37 (26–49)	30 (0–52)	30 (0–51.5)
Predominant flow	cft	Sc total[a]	RHQ	40.5 (10–55)	29 (2–51)	30 (10–53)
Channel features	ct	Sc total[a]	RHQ	2.5 (0–18)	1 (0–27)	0 (0–47)
Land use within 5 m	rl	Sc total[a]	RHQ	55 (15–80)	44 (0–80)	38 (7.5–80)
Banktop vegetation structure	btv	Sc total[a]	RHQ	23 (9.5–30)	20.5 (5.5–30)	20.5 (7–30)
Bankface vegetation structure	bfv	Sc total[a]	RHQ	27.5 (10.5–30)	26 (10–30)	25 (4–30)
Channel vegetation types	cv	Sc total[a]	RHQ	16 (0–36.5)	21.4 (0–43.6)	16.8 (0–43.3)
Land use within 50 m	lu	Sc total[a]	RHQ	2.8 (1.3–8)	2.4 (0.8–8)	2.2 (0.6–8)
Natural bank profiles	bn	Sc total[a]	RHQ	1.7 (0–3)	1.5 (0–3)	1.4 (0–3.5)
Extent of trees	rt	Sc total[a]	RHQ	5 (0–5)	4 (0–5)	4 (0–5)
Shading of channel	rs	Sc total[a]	RHQ	1 (0–2)	2 (0–2)	1 (0–2)
Overhanging boughs	rob	Sc total[a]	RHQ	1 (0–2)	1 (0–2)	1 (0–2)
Exposed bankside roots	bbr	Sc total[a]	RHQ	1 (0–2)	1 (0–2)	1 (0–2)
Underwater tree roots	bur	Sc total[a]	RHQ	0 (0–2)	1 (0–2)	1 (0–2)
Fallen trees	bft	Sc total[a]	RHQ	1 (0–2)	1 (0–2)	1 (0–2)
Coarse woody debris	cd	Sc total[a]	RHQ	1 (0–2)	1 (0–2)	1 (0–2)
Flow types along 500 m	cf	Sc total[a]	RHQ	6 (2–8)	5 (2–9)	4 (2–8)
Channel and bank features along 500 m	ff	Sc total[a]	RHQ	4 (0–11)	3 (0–11)	2 (0–7)
Features of special interest along 500 m	fsi	Sc total[a]	RHQ	2 (0–8)	1 (0–8)	1 (0–5)
Channel chocked with vegetation	ccv	Sc total[a]	RHQ	0 (0–1)[d]	0 (0–1)[d]	0 (0–0)[d]
Predominant artificial bank material	bam	Sc total[a]	RHM	2.8 (0–36)	1.3 (0–60)	4 (0–50)
Bank modifications	bm	Sc total[a]	RHM	4 (0–42)	4 (0–70)	8 (0–70)
Artificial channel material	cam	Sc total[a]	RHM	0 (0–3)[d]	0 (0–10)[d]	0 (0–3)[d]
Channel modifications	cm	Sc total[a]	RHM	0 (0–9)	0 (0–50)	0 (0–20)[d]
Artificial bank profiles	ba	Sc total[a]	RHM	2 (0–5)	1.8 (0–5)	2.2 (0–5)
Dam/weir	sd	Sc total[a]	RHM	0 (0–5)	0 (0–5)	0 (0–3)
Bridge	sb	Sc total[a]	RHM	1 (0–5)	0 (0–5)	0 (0–4)
Ford	sf	Sc total[a]	RHM	0 (0–2)[d]	0 (0–2)	0 (0–0)[d]
Deflector	sde	Sc total[a]	RHM	0 (0–2)[d]	0 (0–3)[d]	0 (0–0)[d]
Channel realignment	cmr	Sc total[a]	RHM	0 (0–2)[d]	0 (0–2)	0 (0–2)
Water impoundment by weir/dam	cmi	Sc total[a]	RHM	0 (0–2)	0 (0–2)	0 (0–2)

[a] Calculated total score of individual features according to SIHM method (Tavzes and Urbanič 2009)

[b] Data were ln(x + 1)-transformed prior to analysis

[c] For dummy variables number of sites coded as "1" is given

[d] Variables excluded from further analysis due to low occurrence frequency

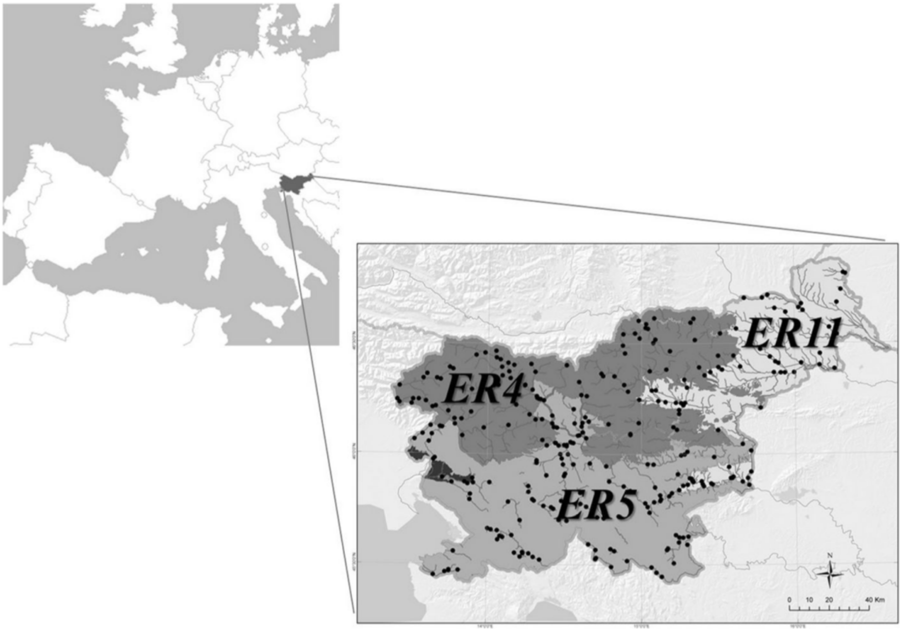

Fig. 1 Study area with the investigated ecoregions (ER4 Alps, ER5 Dinaric western Balkan, ER11 Pannonian lowland) and sampling sites

according to the SIHM method (Tavzes and Urbanič 2009). The SIHM method generally assigns higher weights to those categories of RHQ variables that indicate higher habitat diversity and higher weights to those categories of RHM variables, characterized by more severe degradation.

Benthic invertebrate data collection

Data on benthic invertebrate assemblage composition were obtained for each of the investigated sites once in a period from 2005 to 2011 (Fig. 1) as a part of monitoring and assessment system development programs in Slovenia (Urbanič et al. 2008). Rivers were sampled during low-to-medium-discharge conditions, generally between May and September, except some large or intermittent rivers were sampled in winter because of their natural hydrological regime. The sampling procedure followed the standardized Slovenian river bioassessment protocol, in detail given elsewhere (Pavlin et al. 2011; Urbanič 2014). The sample on each site consisted of twenty subsampling units with a total sampling area of 1.25 m^2 that were in proportion to the coverage of the microhabitat types (Urbanič et al. 2005). The twenty subsamples were combined in the field prior to further processing. For each sample benthic organisms from a quarter of the sample were identified and enumerated (Petkovska and Urbanič 2010). Benthic invertebrates were determined to the taxonomic level used for the assessment of ecological river status in Slovenia, mostly species and genus level (Urbanič 2014).

Data analysis

Environmental variables were arranged to three groups, physiographic factors (Typo), river habitat quality features (RHQ), and river habitat modification features (RHM). Physiographic factors were included in the analysis with 3–5 variables per dataset, depending on parameters used for the Slovenian river typology in selected ecoregions (Urbanič 2011). Morphological variables (RHQ, RHM) were preliminary checked for occurrence frequency, and variables present at less than 10 % of the sampling sites in each dataset were eliminated from further analyses (Table 1). Twenty-eight morphological variables were used for ER4 and ER11 datasets and 30 for ER5 dataset. For statistical analysis the physiographic factors karst spring influence and intermittency were coded as dummy (0/1) variables, river size as a variable with four classes, and altitude and slope were $\ln(x + 1)$-transformed. Morphological variables were not transformed because the same unit score is used for all variables derived from the SIHM method (Tavzes and Urbanič 2009).

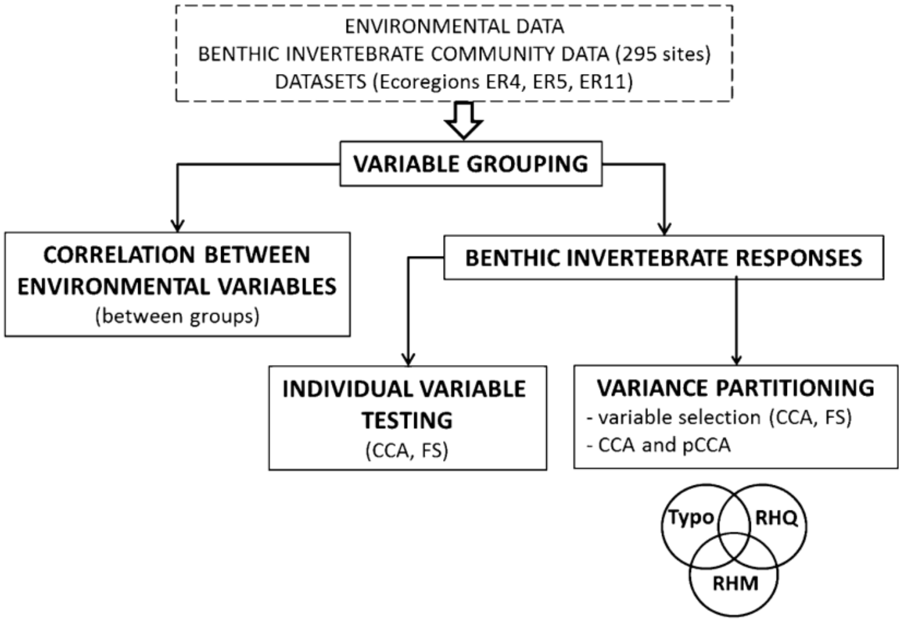

Fig. 2 Flowchart of the analytical procedure; ecoregions (ER4 Alps, ER5 Dinaric western Balkan, ER11 Pannonian lowland), *CCA* canonical correspondence analysis, *pCCA* partial canonical correspondence analysis, *FS* automatic forward selection routine; for variable groups (Typo, RHQ, RHM), see Table 1

The Spearman rank correlation coefficients (R_{Sp}) were calculated between all pairs of environmental variables using SPSS Statistics version 21.0 (IBM 2012). The rationale was to identify the associations between analyzed groups of variables and to compare them among different datasets (ecoregions).

The relation of different groups of environmental variables on benthic invertebrate assemblages was then analyzed using ordination techniques (Fig. 2) in the software package CANOCO 4.5 (ter Braak and Šmilauer 2002). Data on benthic invertebrate abundances were ln($x + 1$)-transformed prior to analysis, and downweighting of rare species option was enabled in all analyzes. Detrended Correspondence Analysis performed on each dataset (DCA; ter Braak and Šmilauer 2002) indicated that a unimodal response would adequately fit the species data (the length of the gradient = 2.6–3). Accordingly, canonical correspondence analysis (CCA) was selected (ter Braak and Prentice 1988). For the first overview of the relationship between the environmental variables and benthic invertebrate data, a CCA analysis with an automatic forward selection routine was applied on all environmental variables. This process specified the effects that each environmental variable added to the explained variance of the species data (marginal effects) and the remaining effect that each variable added to the model when other variables have already been loaded (conditional effects) (Lepš and Šmilauer 2003). The significant variables were selected with forward selection routine, using the Monte Carlo permutation test with 999 unrestricted permutations and Bonferroni correction ($\alpha = 0.05/n$, where n is the number of tests). To compare the explanatory power of variables among ecoregions, the hierarchy of environmental variables was derived by dividing the marginal effects of each variable with that of the most explanatory variable. Temporal dependence of benthic invertebrate assemblage's structure was not considered in the analyses as it was found less important even when samples were collected through the whole year (e.g., Urbanič and Toman 2007).

The same procedure was then applied within variable groups (Typo, RHQ, RHM). The selected variables were used for partitioning of the explained variance among benthic invertebrate assemblages using partial CCA (pCCA). This test allows investigation of the effects of one variable group while eliminating the effects of other variable groups and hence the partitioning of the variance into unique and combined effects of variable groups. The total explained variance among benthic invertebrate assemblages with forward-selected environmental variables from three groups was partitioned into (1) the variance uniquely explained by each variable group, (2) the variance explained by combined effects of each pair of variable groups, and (3) the variance explained by combined effects of all three variable groups together.

Table 2 Input data and results of canonical correspondence analysis for datasets separately (ER4 ecoregion Alps, ER5 ecoregion Dinaric western Balkan, ER11 ecoregion Pannonian lowland); FS automatic forward selection routine

Ecoregion	ER4	ER5	ER11
Number of taxa (n)	269	362	255
Number of all environmental variables (n)	32	35	31
Number of sites (n)	93	129	73
Total variance (λ)	2.224	3.153	2.781
Total explained variance (λ)	1.053	1.159	1.468
Monte Carlo permutation test P	0.001	0.001	0.001
Monte Carlo permutation test F	1.686	1.545	1.479
Total explained variance (%)	47	37	53
Selected variables with FS (n)	8	8	7
Explained variance (%) (FS variables)	22	16	24

The sample size and the number of independent variables in the model influence the result of the pCCA (Kromrey and Hines 1995). Hence, Ezekiel's adjustment of fractions was calculated using the following equation (Peres-Neto et al. 2006):

$$R^2_{(Y/X)adj} = 1 - \frac{n-1}{n-p-1} * \left(1 - R^2_{(Y/X)}\right)$$

where n is the sample size, p is the number of predictors, and $R^2_{Y/X}$ is the sample estimation of the assemblage variance $\rho^2_{Y/X}$. The similar number of samples (between 73 and 129) and predictors (between 2 and 7) in all the models leads to the very similar ratio of explained variance among the variable groups (regression curve r^2 was 0.937 for all datasets, $P < 0.001$).

Results

Relationships among environmental variable groups

Several statistically significant relationships ($P < 0.05$) between pairs of environmental variables were observed with the Spearman rank correlation (R_{Sp}, Online Resource—Tables 1–6). However, the statistically significant pairs of variables and the strength of correlation differed between datasets. Variables from Typo group had the lowest number of significant correlations with other groups, and except in five cases with RHQ group variables all significant correlations were weak $\left(|R_{Sp}| < 0.5\right)$. The moderate positive correlations $\left(0.50 < |R_{Sp}| < 0.70\right)$ were observed between slope and features of special interest along 500 m in ER4 and ER5 and between slope and channel and bank features along 500 m in ER5. In ER11 river size class was moderately negatively correlated with shading of channel and overhanging boughs. Between RHQ and RHM groups the only strong correlations $\left(|R_{Sp}| > 0.7\right)$ were observed in ER4, where predominant natural bank material was negatively correlated with bank modification variables (predominant artificial bank material, bank modifications, and artificial bank profiles). Some other RHQ variables were moderately correlated with bank modification variables, in ER4 banktop vegetation structure, bankface vegetation structure, land use within 5 m, and features of special interest along 500 m, and in ER11 predominant natural bank material and exposed bankside roots. In ER5 dataset only weak correlations were observed between environmental variables of RHQ and RHM groups.

Responses of benthic invertebrate assemblages to environmental variables

The total amount of variance in the benthic invertebrate dataset was highest in ER5 ($\lambda = 3.153$, Table 2), followed by ER11 (2.781) and ER4 (2.224). All environmental variables explained the highest amount of total variance in ER11 (53 %), lower in ER4 (47 %), and the lowest in ER5 (37 %). The highest explanatory power of individual variables was observed for slope (6.74 %) in ER4, predominant channel substrate (4.76 %) in ER5, and predominant flow (6.11 %) in ER11. Variables with comparable explanatory power (explaining at least half as much variance of benthic invertebrate assemblages as the most explanatory variables) were only from Typo and RHQ groups (Table 3). The variables from RHM group explained at best 0.47 as much as the most explanatory variables in ER11 (predominant artificial bank material and artificial bank profiles) and 0.33 in ER4 (bank modifications, artificial bank profiles, and water impoundment by weir/dam) or ER5 (artificial bank profiles). Using automatic forward selection routine on all environmental variables different number of statistically significant variables was selected in datasets (Table 2). The model of selected variables included mostly variables from Typo and RHQ groups, but in ER4 and ER5 also one variable from RHM group. Among all environmental variables only the variable river size class was selected in all datasets. The model with forward-selected variables (Fig. 3) explained the highest share of benthic invertebrate assemblages variability in ER11 (24 %), intermediate in ER4 (22 %), and the lowest in ER5 (16 %).

Selected explanatory variables for variance partitioning models

Performing forward selection on each variable group individually, variables that significantly contributed to the explained variance were selected for variance partitioning (Table 3). From Typo group 2–4 variables were selected, from RHQ group 4–7 variables, and 2–3 variables from RHM group, depending on dataset. Selected variables and their relative explanatory power differed among datasets (Table 3). Slope was the most explanatory among selected Typo variables in ER4 and ER5 datasets, whereas in ER11 dataset it was not among selected variables. In ER11 the most explanatory among Typo variables was river size class also selected in ER4 and ER5. Among RHQ variables, predominant flow was selected as one of the most explanatory variables in all datasets. Further, in two datasets, the variables channel vegetation type (in ER5 and ER11) and shading of the channel (in ER4 and ER11) were selected. From RHM group no variable was selected in all datasets, but among most explanatory variables water impoundment by weir/dam and artificial bank profiles were selected in two datasets (in ER4 and ER5).

Variance partitioning of three groups of environmental variables

The total explained variance with forward-selected variables by environmental group was highest in ER4 (30.0 %, 14 selected variables), intermediate in ER11 (25.7 %, 9 selected variables), and lowest in ER5 (20.5 %, 12 selected variables). Each variable group individually explained between 3.0 and 16.9 % of the assemblage variability (Table 4). In all datasets the most explanatory was RHQ group and the least explanatory was RHM group. Variance partitioning among variable groups revealed high unique effects, ranging from 70 % of the explained variance in ER11 to 78 % in ER5 (Fig. 4). Highest unique effects were observed for RHQ group (from 34 % in ER4 to 42 % in ER5). For RHM group observed unique effects were always the lowest among variable groups, ranging between 10 % in ER5 and 15 % in ER11. Among combined effects the interaction between Typo and RHQ groups was most important, accounting for 14–18 % of explained variance. Other interactions between pairs of groups were less important, the least between Typo and RHM groups (2 % in ER11 and 0 % in other two datasets). Combined effects of all three variable groups also represented a very small amount of benthic invertebrate assemblage variation, only 2–6 %.

Discussion

Our findings suggest that regardless of the region investigated benthic invertebrate assemblages' structure in running waters is shaped more by river habitat quality features than by river habitat modification features. However, across investigated ecoregions the hierarchy of river habitat features' importance showed some similarities but also distinct differences, which are addressed in the following sections.

The patterns of river habitat quality variables

Predominant flow and predominant channel substrate were among the highest explanatory variables across all ecoregions. Flow and substrate are known variables affecting aquatic assemblages (Statzner and Higler 1986; Richards et al. 1993; Lammert and Allan 1999;

Table 3 The Relative explanatory power of environmental variables compared to the most explanatory variable; all—among all variables, group—within each variable group (ER4 ecoregion Alps, ER5 ecoregion Dinaric western Balkan, ER11 ecoregion Pannonian lowland)

Variable	Variable group	ER4		ER5		ER11	
		All	Group	All	Group	All	Group
River size class	Typo	0.67*	0.67*	0.40*	0.46*	0.94*	**1.00***
Karst spring influence	Typo	0.73*	0.73*	0.53*	0.62*	–	–
Intermittency	Typo	–	–	0.33	0.38*	–	–
Altitude	Typo	0.73	0.73*	0.20	0.23	0.88*	0.94*
Slope	Typo	**1.00***	**1.00***	0.87*	**1.00***	0.53	0.56
Predominant natural bank material	RHQ	0.40	0.60	0.47	0.47	0.29	0.29
Bank features	RHQ	0.33	0.50*	0.40	0.40	0.29	0.29
Predominant channel substrate	RHQ	0.53	0.80	**1.00***	**1.00***	0.76	0.76
Predominant flow	RHQ	0.67	**1.00***	0.93*	0.93*	**1.00***	**1.00***
Channel features	RHQ	0.27	0.40	0.33	0.33	0.24	0.24
Land use within 5 m	RHQ	0.40*	0.60	0.33	0.33	0.53*	0.53
Banktop vegetation structure	RHQ	0.40*	0.60	0.27	0.27*	0.35	0.35
Bankface vegetation structure	RHQ	0.27	0.40	0.20	0.20*	0.29	0.29
Channel vegetation types	RHQ	0.27	0.40	0.53*	0.53*	0.65*	0.65*
Land use within 50 m	RHQ	0.47	0.70	0.40	0.40	0.47	0.47
Natural bank profiles	RHQ	0.27*	0.40*	0.20	0.20	0.24	0.24
Extent of trees	RHQ	0.33	0.50	0.27	0.27	0.35	0.35
Shading of channel	RHQ	0.27	0.40*	0.40	0.40	0.65	0.65*
Overhanging boughs	RHQ	0.27	0.40	0.40	0.40	0.53	0.53
Exposed bankside roots	RHQ	0.20	0.30*	0.27	0.27	0.53	0.53
Underwater tree roots	RHQ	0.13	0.20	0.27	0.27	0.76*	0.76*
Fallen trees	RHQ	0.20	0.30	0.40*	0.40*	0.47	0.47
Coarse woody debris	RHQ	0.27	0.40	0.27	0.27	0.29	0.29
Flow types along 500 m	RHQ	0.53*	0.80*	0.53	0.53	0.29	0.29
Channel and bank features along 500 m	RHQ	0.33	0.50	0.67	0.67	0.35*	0.35
Features of special interest along 500 m	RHQ	0.67	**1.00***	0.47	0.47	0.29	0.29
Channel chocked with vegetation	RHQ	–	–	–	–	–	–
Predominant artificial bank material	RHM	0.27	0.80	0.20	0.60	0.47	**1.00***
Bank modifications	RHM	0.33	**1.00***	0.20	0.60	0.29	0.63
Artificial channel material	RHM	–	–	–	–	–	–
Channel modifications	RHM	0.13	0.40	0.20	0.60	–	–
Artificial bank profiles	RHM	0.33	**1.00**	0.33*	**1.00***	0.47	**1.00***
Dam/weir	RHM	0.20	0.60*	0.20	0.60	0.24	0.50
Bridge	RHM	0.20	0.60	0.20	0.60	0.29	0.63*
Ford	RHM	–	–	0.27	0.80	–	–
Deflector	RHM	–	–	–	–	–	–
Channel realignment	RHM	–	–	0.13	0.40	0.24	0.50
Water impoundment by weir/dam	RHM	0.33*	**1.00***	0.27	0.80*	0.29	0.63

The most explanatory variables are indicated in bold; the variables selected in forward selection routine are indicated with asterisk (*)

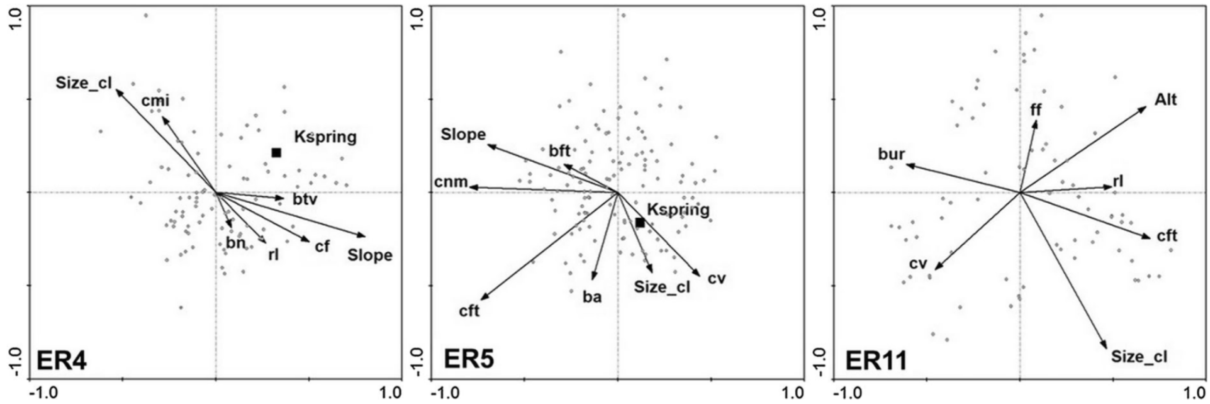

Fig. 3 CCA ordination diagram of sampling sites and the forward-selected environmental variables for each dataset: ER4 ecoregion Alps, ER5 ecoregion Dinaric western Balkan, ER11 ecoregion Pannonian lowland; *black squares* represent dummy variables; codes of environmental variables are given in Table 1

Table 4 Shares of the total explained variance (%) in the benthic invertebrate assemblages by each of the variable groups; datasets: ER4 ecoregion Alps, ER5 ecoregion Dinaric western Balkan, ER11 ecoregion Pannonian lowland); for variable groups (Typo, RHQ, RHM), see Table 3

Variable group	ER4	ER5	ER11
All groups	30.0	20.5	25.7
Typo	14.8	9.4	11.3
RHQ	16.9	13.1	16.3
RHM	6.4	3.0	7.3

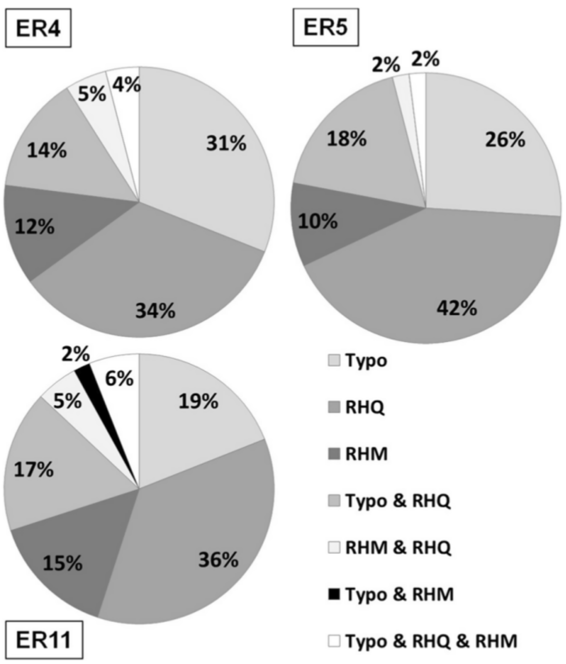

Fig. 4 Unique and combined effect contributions (%) of the variable groups to the total explained variance of benthic invertebrate assemblages; datasets: ER4 ecoregion Alps, ER5 ecoregion Dinaric western Balkan, ER11 ecoregion Pannonian lowland

Sandin and Johnson 2004). In the Alps ecoregion, however, the similar importance was observed for the variable features of special interest along 500 m. The variable gains higher values in the alpine region on account of high energy flows, moving larger sediment, and creating frequent riffle-pool or even step-pool sequence (Chin 2002). Predominant flow has a great influence on predominant channel substrate (Statzner and Higler 1986; Poff et al. 1997), but studies comparing the effects of both flow and substrate variables (Urbanič et al. 2005; Friberg et al. 2009, Wyzga et al. 2011) suggest partly different relation of predominant flow and substrate to benthic assemblages. The reason might be that flow also affects oxygen content in water, food delivery and represents a direct physical force on organisms, whereas in-stream substrate composition is also the result of local riparian management. Our study in the Dinaric western Balkan ecoregion confirmed the added value of both in structuring assemblages—despite the minimal difference in the explanatory power observed, both were chosen in forward selection procedure.

Another variable showed significant importance in structuring assemblages across ecoregions, shading of the channel. The known importance of shading lies in conditioning light availability and water temperature (Hynes 1970; Webb et al. 2008; Julian et al. 2011). Hence, the shading influences the oxygen content in water and organic matter processing (Odum 1956; Lagrue et al. 2011), and with the nutrient availability it drives the growth of primary producers (Sterner et al. 1997; Schiller et al. 2007; Bernot et al. 2010) and consequently affects habitat structure and benthic invertebrate assemblages (Melody and Richardson 2004; Haidekker and Hering 2007). However, our results revealed the highest explanatory power in the Pannonian lowland and lowest in the Alps. The possible explanation is the high energy flow in alpine region that on one side conditions the water temperature and oxygen content more than shading does and on the other limits the attachment and growth of primary producers. Therefore, the difference in light availability exerts less effect on the habitat structure and consequently aquatic assemblages compared to lowland regions.

Considering important habitat quality features few distinct differences were observed among ecoregions. Pannonian lowland was characterized by importance of vegetation features (channel vegetation types, underwater tree roots, exposed bankside roots), features increasing habitat diversity either on the bank sides or in channel and serving as refugia for benthic invertebrates (Harrison et al. 2004; Pinto et al. 2006). In the Alps, on the other hand, higher explanatory power was observed for natural bank material and bank features, having important role in diversifying river habitat and also acting as refugia during spates or low flow periods. The characteristic features of Dinaric western Balkan are somewhere between the other two ecoregions, indicating some similarities to the Pannonian lowland (high importance of channel vegetation types) and some to the Alps (the importance of natural bank material). Among river types found in the Dinaric western Balkan only Mediterranean rivers were considered by similar studies (Hughes et al. 2008; Gallo et al. 2010). Hughes et al. (2008) suggested the importance of the presence and complexity of riparian galleries in benthic invertebrate assemblages' change, which was confirmed in our study by the importance of bank vegetation structure.

The patterns of river habitat modification variables

The most important habitat modification variables were connected to river banks: artificial bank profiles in all investigated ecoregions, bank modifications in the Alps, and artificial bank material in the Pannonian lowland. This is in line with findings of Erba et al. (2006) where benthic invertebrate metrics showed good correlation with bank modification categories (resectioning and reinforcement). Resectioning or reinforcement leads to enhancement of flow discharge and diminishing of bank and channel depositional features, and consequently lowers natural habitat heterogeneity (Bona et al. 2008). In the lowland region, however, changing bank material seems to be more important for assemblages' structure, since it exerts another effect. Natural bank material in lowland region is often consisted of fine substrates (e.g., earth or sand; Szoszkiewicz et al. 2006). Hence, the use of artificial material such as riprap for bank resectioning or reinforcement results in a distinctive difference from natural material. Larger stones used for bank reinforcement commonly add to habitat heterogeneity, making it unnaturally high for lowland region. Larger habitat heterogeneity might lead to higher assemblage diversity on account of taxa occupying new non-natural habitat (Townsend and Hildrew 1994). This finding might also be the explanation for the relevance of bridge presence in structuring assemblages, as in the process of bridge building the river banks are often distinctly modified, and commonly some building blocks find a new place to rest in the river channel and form a new habitat for assemblages. Summing up, our findings indicate that higher habitat and assemblage diversity might not be the reflection of naturalness.

Most modification variables in our study primarily reflect morphological modifications of river habitat. However, the variable water impoundment by weir/-dam primarily addresses hydrological change, but this consequently includes the change of flow characteristics and dependent features, e.g., increase in sediment deposition (Kondolf 1997; Poff et al. 1997; Tavzes and Urbanič 2009; Mueller et al. 2011; Stefanidis and Stefanidis 2012). Across ecoregions water impoundment was observed as one of more important modification variables, implying the significant relevance of hydrological beside morphological changes for assemblages' structure. This is in agreement with findings of Marzin et al. (2012), where the presence of an impoundment emerged as the main human pressure factor shaping the fish and macroinvertebrate assemblages at the reach scale. However, although water impoundment was found as important variable across all ecoregions, in the Alps, the additionally selected variable dam/weir suggests that in high gradient rivers also the weir itself affects assemblages.

Simultaneous effect of river habitat features on assemblages with implications for river management

Our analysis revealed twice to even four times higher unique share of habitat quality variables compared to that of habitat modification variables across ecoregions. The extremely important role that physical environment plays in the functioning of the river and stream ecosystems has been known for a long time (e.g., Southwood 1977), but the simultaneous effects of morphological features and their modification on benthic invertebrate assemblages were rarely studied (e.g., Hughes et al. 2008). Our findings are in line with that of Hughes et al. (2008) that suggested higher importance of habitat quality parameters than of pressure variables. As already mentioned in our study the most significant features relevant for individual ecoregions were connected to habitat heterogeneity either within habitat quality or modification variables, suggesting that for more sustainable river management we should consider solutions with preserving the natural habitat heterogeneity as much as possible. The most important components defining natural habitat heterogeneity were outlined for investigated ecoregions and can serve as a starting point in river management planning in Slovenia or for further investigations on regional level.

Beside a clear effect of habitat quality and degradation gradient on regional level, an additional analysis using physiographic factors revealed also their important unique share in shaping benthic invertebrate assemblages and simultaneous effect with habitat quality features. The commonly recognized relevance of physiographic factors such as slope and river size for structuring river habitat features (Frissel et al. 1986; Allan and Castillo 2007; Repnik Mah et al. 2010) was confirmed. However, another factor on regional level is closely associated with these physiographic factors that might influence river morphological features and simultaneously aquatic assemblages—the change of land use. The changing of natural to agricultural or urban land use on different spatial scales might result in morphological modification of rivers (Richards and Host 1994; Nerbonne and Vondracek 2001; Shepherd et al. 2010), for example, either through changes in sediment input (Townsend et al. 2004) or in hydrological regime (Poff et al. 2006). It was therefore suggested that considering only local habitat diversity for river management is not enough (Palmer et al. 2010), but also processes behind the present state, driven by natural or anthropogenic factors on larger scales, should be taken into account. However, the changes in land use on a larger scale are reflected in river morphological features, and therefore, our study on river morphological features is an useful step in river management research. To gain more insight into interaction influence we suggest further studies including both levels. Moreover, as our findings revealed the important morphological variables for each region, the following research might try to develop thresholds for those parameters.

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

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Slika 10. Motiv z mesta vzorčenja Obrh, Goričice

Figure 10. A theme from sampling site Obrh, Goričice

2.1.3 Članek III

Raznolikost vodilnih slik ekosistemov tekočih voda, določenih na podlagi ekološko pomembnih lastnosti rečnih habitatov za alpsko, mediteransko, nižinsko in kraško regijo

Variety of the guiding image of rivers – defined for ecologically relevant habitat features at the meeting of the alpine, mediterranean, lowland and karst regions

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Vesna PETKOVSKA, Gorazd URBANIČ, Matjaž MIKOŠ

Zaradi dolgotrajnega človekovega delovanja na ekosisteme tekočih voda težko najdemo izvorne razmere, zato se je uveljavila uporaba vodilne slike, s katero opišemo današnje potencialno naravno stanje. Ker regionalne pokrajinske značilnosti delno določajo naravne lastnosti rečnih habitatov in združb organizmov na lokalni ravni, smo predvidevali, da se bodo regionalno razlikovale tudi vodilne slike. V prispevku smo določili vodilne slike štirih glavnih regij: alpske, nižinske, mediteranske in kraške z obravnavo habitatskih lastnosti vodotokov v štirih glavnih evropskih ekoregijah: Alpe, Panonska nižina, Submediteran in Dinaridi. Za določitev vodilne slike smo uporabili le tiste habitatske lastnosti, ki so se že pokazale kot ekološko pomembne. Ugotovili smo razlike v lastnostih rečnih habitatov med vsemi obravnavanimi regijami. Ob upoštevanju vseh referenčnih mest smo največji gradient ugotovili za lastnosti rečnih habitatov, ki so tesno povezane z dinamiko vodnega toka in plavin. Za te lastnosti smo ugotovili največje razlike med alpskimi in nižinskimi vodotoki, po drugi strani pa podobnosti med mediteranskimi in alpskimi vodotoki ter med kraškimi in nižinskimi vodotoki. Pomemben gradient smo ugotovili tudi na podlagi lastnosti obrežne in vodne vegetacije, za katere smo najvišje vrednosti opazili za alpske in mediteranske vodotoke ter nižje v kraških ali nižinskih vodotokih. Vendar pa preprosta zgradba vegetacije, ki jo lahko razberemo iz naših rezultatov, lahko ni reprezentativna slika naravnih razmer, zato je treba biti previden pri uporabi zaključkov za te lastnosti.

V prispevku smo predlagali prvi korak k določitvi vodilne slike vodotokov v štirih glavnih regijah. Na podlagi opažene raznolikosti nekaterih lastnosti rečnih habitatov znotraj posameznih regij predlagamo nadaljnje raziskave na ožjih skupinah vodotokov. Ne glede na to pa so prepoznane podobnosti in razlike med regijami v ekološko pomembnih lastnostih rečnih habitatov lahko vodilo za bolj trajnostno in stroškovno učinkovito upravljanje z ekosistemi tekočih voda.

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Variety of the guiding image of rivers – defined for ecologically relevant habitat features at the meeting of the alpine, mediterranean, lowland and karst regions

Vesna Petkovska [a,*], Gorazd Urbanič [a,b], Matjaž Mikoš [c]

[a] Institute for Water of the Republic of Slovenia, Hajdrihova 28c, 1000 Ljubljana, Slovenia
[b] University of Ljubljana, Biotechnical Faculty, Department of Biology, Večna pot 111, 1000 Ljubljana, Slovenia
[c] University of Ljubljana, Faculty of Civil and Geodetic Engineering, Jamova cesta 2, 1000 Ljubljana, Slovenia

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ABSTRACT

Due to a long history of human intervention in river ecosystems, pristine conditions hardly exist nowadays and therefore a concept of a 'guiding image' defines the present-day potential natural state. Since regional physiographic factors influence the natural habitat features and biota on local level, also guiding images are expected to differ regionally. In this study, the guiding images of rivers of four major regions were defined: alpine, lowland, mediterranean and karst. The habitat features of rivers were studied in four major European regions: the Alps, the Pannonian Lowland, the Submediterranean region and the Dinaric region. For the analysis only those river habitat quality features were used that were proven to be ecologically important. The results showed differences among habitat features of rivers of all investigated regions. On the whole dataset the major gradient among reference sites was observed for habitat features that are in tight relation to water flow and sediment dynamics. For these features the major differences were found between the alpine and the lowland rivers, and on the other hand the similarities were observed between the Mediterranean and the Alpine rivers and between the karst and the lowland rivers. Another important gradient was observed on account of habitat features of riparian and channel vegetation. The highest values of these features were observed for the alpine and the mediterranean rivers and lower in the karst or the lowland rivers. However, the simpler riparian vegetation structure suggested by our results might not be the representative picture of natural vegetation, so the values of these features for a guiding image should be used with caution.

In the present study the first step to the guiding images of the rivers in four major regions is proposed. Since the results showed considerable variability of some river habitat features present within regions, we suggest further investigation on even smaller groups. Nevertheless, the recognized differences and similarities among four regions in river habitat features that are ecologically relevant might serve as guidance for more sustainable and cost-effective river management.

1. Introduction

The management of riverine environment in Europe has reached an important turning-point with the implementation of the Water Framework Directive (WFD, European Commission, 2000). The main goals of the WFD require from Member States the assessment of ecological condition of rivers and the achievement or maintaining of good ecological status. A novel part included in the WFD is the assessment of hydromorphological pressures, acknowledged as one of the main pressures of our time (Richter et al., 1997; Schinegger et al., 2012). In the light of the WFD requirements river restoration is gaining increased attention. Many projects are being realized but with little desired outcomes (Jähnig et al., 2010; Palmer et al., 2010; Haase et al., 2012; Wolter et al., 2013). The fundamental part for definition of cost-effective measures and consequently achieving the desired WFD goals is the understanding of river ecosystem functioning and the connections between aquatic assemblages and their natural or anthropogenically disturbed environment. A substantial number of studies establish the links of river habitat quality and degradation to predominantly benthic invertebrate assemblages (Lammert and Allan, 1999; Sandin and Johnson, 2004; Erba et al., 2006; Feld and

* Corresponding author. Tel.: +386 1 4775330; fax: +386 1 4264162.
E-mail address: vesna.petkovska@izvrs.si (V. Petkovska).

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Hering, 2007; Larsen and Ormerod, 2010; Petkovska and Urbanič, 2015), but also fish (Smiley and Dibble, 2008; Wyżga et al., 2009), and other animal groups bound to river environment (Hering et al., 2006; O'Hare et al., 2006; Bona et al., 2008; Manenti et al., 2009). Due to the WFD requirements several aquatic assemblages-based assessment methods addressing hydromorphological pressure have been recently developed in different European countries (Birk et al., 2012; Rinaldi et al., 2013a).

These aquatic assemblages-based assessment methods enable the simultaneous evaluation of all hydromorphological pressures, but for river management defining the core factors causing the degradation is of equal importance. The program of measures for river basin management plans should be designed cost- effectively aiming at desired ecological status improvement. Therefore, it is essential to define the river habitat quality and modification factors that need to be managed. A large amount of methods have been developed for summarizing heterogeneous nature of riverine physical habitat characteristics and modifications (Muhar et al., 1996, 1998; Raven et al., 1998, 2003; LAWA, 2000; Rinaldi et al., 2013a). The methods differ mainly with respect to the objectives for which they were designed, the time required for their application and whether they measure physical characteristics or evaluate them (Fernández et al., 2011). Several of these methods were adopted for the WFD implementation in European countries (Rinaldi et al., 2013a), but only for a few of these methods the links with aquatic assemblages have been studied (e.g. Urbanič, 2014), mostly considering features of the UK River Habitat Survey method (RHS; Raven et al., 1998, 2003). RHS method represents one of the most comprehensive methods and is probably the most tested method in European countries (Balestrini et al., 2004; Szoszkiewicz et al., 2006; Tavzes et al., 2006; Bona et al., 2008; Urošev et al., 2009; Raven et al., 2010). The RHS method was adapted for use in Southern Europe (Buffagni and Kemp, 2002) and served also as a basis for the Slovenian hydromorphological (SIHM) assessment method development (Tavzes and Urbanič, 2009).

The hydromorphological assessment methods either measure characteristics or evaluate them, but in both cases the assessment depends on the reference conditions. The definition of reference conditions has long been a subject of discussion (Fryirs and Brierley, 2009; Pardo et al., 2012; Wyżga et al., 2012; Feio et al., 2014; Rinaldi et al., 2013b). Since river systems have been affected by human activities for a very long time (Marsh, 1864), the present state of rivers is the result of a long interplay between natural and human induced factors and finding the 'pristine' conditions nowadays is hardly feasible. Also the naturalness of the past river conditions is questionable (e.g. in previous centuries more intense land degradation from agricultural activities was present; Williams, 2000). In last decades, a largely accepted has become a concept of a 'leitbild' (Kern, 1992, 1994) or a 'guiding image' (Palmer et al., 2005) with the reference conditions defined as the present-day potential natural state under the omission of all uses and the removal of all reversible pressures, which are reached after redevelopment without socio- economic restrictions (Gellert et al., 2014). According to WFD the reference conditions are only characterized by no or minimal changes in their hydromorphological and physico-chemical characteristics so long as these do not have a significant effect on the ecosystem (Wallin et al., 2003).

It is recognized that regional physiographic factors influence the natural hydromorphological characteristics and biota on local level (Frissell et al., 1986; Sandin and Johnson, 2004), hence, affect guiding images. In various parts of the world numerous classification schemes suggest regional differences of river channels based on their physical characteristics (Kondolf et al., 2003; Repnik Mah et al., 2010; Splinter et al., 2010). On the other side, ecoregions were delineated based on similar associations of climate, soils, topography and other characteristics in Europe and America (Illies, 1978; Omernik, 1987) in order to define regional goals for water quality and management. Since the desired goal is sustainable water management, the priorities should be based on the links with aquatic biota. The parameters of applied hydromorphological assessment methods for the WFD purposes have rarely been related to aquatic assemblages, or only on the basis of expert judgement and not empirically. The relationships between single habitat features and benthic invertebrates have been investigated mostly for the RHS features (Erba et al., 2006; Cortes et al., 2009; Dunbar et al., 2010), and also for parameters of the SIHM method (Petkovska and Urbanič, 2015). Our study therefore focused on two main objectives:

i) to test the difference among some main European regions on the basis of the SIHM morphological parameters, which are in good relation with benthic invertebrate assemblages (Petkovska and Urbanič, 2015) and/or are important in morphological assessment (Tavzes and Urbanič, 2009), and
ii) to develop the guiding images for rivers of each of the investigated regions on the basis of the relevant SIHM morphological parameters.

The developed guiding images may then be used as a tool for sustainable river management in different regions.

2. Methods

2.1. Study area

Slovenia covers a total area of 20,273 km^2 and has no less than 4573 km of river channels within catchments larger than 10 km^2 and even more when counting all smaller streams. Moreover, there is a wide ecological variety of the area, resulting in very different hydromorphological, physico- chemical, and consequently biotic river types. One of the main possible descriptors for classification of river types in the European Water Framework Directive (Directive 2000/60/EC) are ecoregions, which were defined in Europe by Illies (1978). Since Illies (1978) did not consider all local characteristics, for Slovenian area a redelineation of the ecoregions was made (Urbanič, 2008). Four inland water ecoregions were defined, using abiotic factors (tectonic map, geology map, geographical maps, map of karstified area, terrain slope, landscape regions, and river regimes) and biological data (benthic invertebrate assemblages): the Alps (Ecoregion 4), Dinaric western Balkan (Ecoregion 5), Pannonian Lowland (Ecoregion 11), and Po Lowland (Ecoregion 3). The rivers of the area are also shared among two river basins that influence fish communities (Danube river basin, Adriatic river basin; Urbanič, 2011), dividing the ecoregions the Alps and the Dinaric western Balkan into two sub-ecoregions (Fig. 1).

2.2. Hydromorphological data and study sites

Hydromorphological characteristics were surveyed and calculated using Slovenian hydromorphological (SIHM) assessment method (Tavzes and Urbanič, 2009; Urbanič, 2014). Data on morphological features using the SIHM method are gathered along a 500 m long stretch of the river using an adapted version of the UK River Habitat Survey (RHS) method (Raven et al., 2003; Tavzes and Urbanič, 2009). At 10 spot-checks, spaced every 50 m, bank and channel features (predominant substrate, physical features of channel and banks, flow-type, channel vegetation type, land use, vegetation structure of banks and adjacent land) are recorded. Additionally, the sweep-up part of the survey along the whole stretch covers land use in the 50 m stretch from the channel, bank profile, extent of trees, extent of bank and channel features,

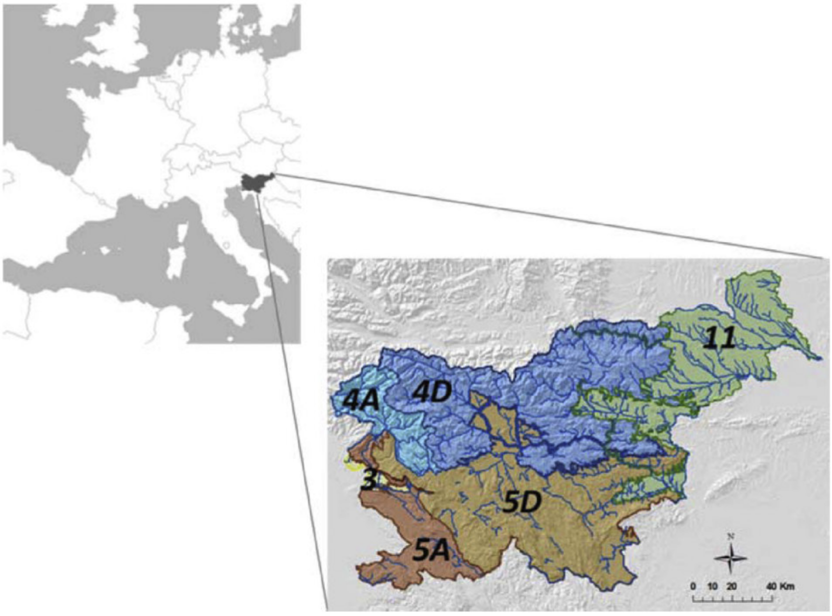


Fig. 1. Study area with delineation to ecoregions and sub-ecoregions; 4A – ecoregion Alps, Adriatic river basin, 4D – ecoregion Alps, Danube river basin, 3 – ecoregion Po Lowland, 5A – ecoregion Dinaric western Balkan, Adriatic river basin, 4D – ecoregion Dinaric western Balkan, Danube river basin, 11 – ecoregion Pannonian Lowland.

features of special interest and artificial features. The features recorded with the RHS method were upgraded in the SIHM method, using different weights for categories of each feature, depending on its effect on benthic invertebrate community (Appendix A; Tavzes and Urbanič, 2009). In general, natural features gained larger weight for categories that improve habitat quality or enhance habitat diversity for benthic invertebrates (Table A1), whereas for the artificial features weights were larger for the categories that have the most adverse effects on benthic invertebrates (Table A2). Altogether, 33 features are recorded using the SIHM method (Tables A1–A3), 22 for the river habitat quality (RHQ) characterization, combined to the RHQ index (Appendix B), and 11 for the river habitat modification (RHM) evaluation, combined to the RHM index (Appendix C). Moreover, also hydrological properties were evaluated with the SIHM method, where the data on impoundments recorded in the catchment of each sampling site are used to calculate the hydrological modification index (HLM; Tavzes and Urbanič, 2009; Urbanič, 2014).

As a part of the ecological status- assessment system development programs in Slovenia, more than 500 river segments were assessed using the SIHM method, mostly in the period 2006–2013. The surveys were conducted only once for each site. The intention of this study was to classify rivers of Slovenia due to their natural habitat characteristics. Hence, only the reference sites (sites with none or minimal anthropogenic impact) were included

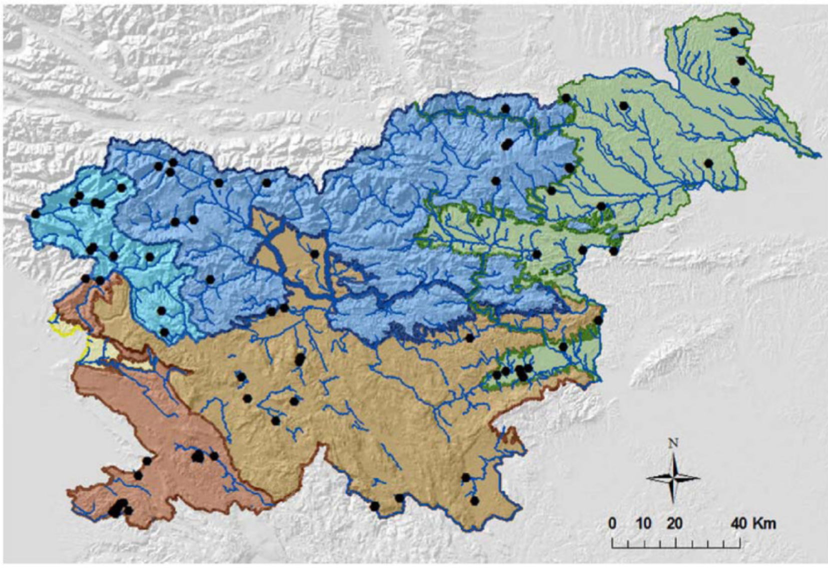


Fig. 2. Study area with the defined reference sampling sites.

Table 1
The summary of the 22 RHQ features with feature codes and the selection ("x") for the analysis due to criterion 1 (the feature is in the best quarter of RHQ variables due to Petkovska and Urbanič (2015)) or criterion 2 (median of study sites ≥0.05; Fig. 3).

RHQ feature	RHQ feature code	Criterion 1	Criterion 2
Predominant natural bank material	bnm	x	x
Bank features	bf		
Predominant channel substrate	cnm	x	x
Predominant flow	cft	x	x
Channel features	ct		
Land use within 5 m	rl		x
Banktop vegetation structure	btv		x
Bankface vegetation structure	bfv		x
Channel vegetation types	cv		x
Land use within 50 m	lu		
Natural bank profiles	bn		
Extent of trees	rt		
Shading of channel	rs		
Overhanging boughs	rob		
Exposed bankside roots	bbr		
Underwater tree roots	bur		
Fallen trees	bft		
Coarse woody debris	cd		
Flow types along 500 m	cf	x	
Channel and bank features along 500 m	ff	x	
Features of special interest along 500 m	fsi	x	
Channel chocked with vegetation	ccv		

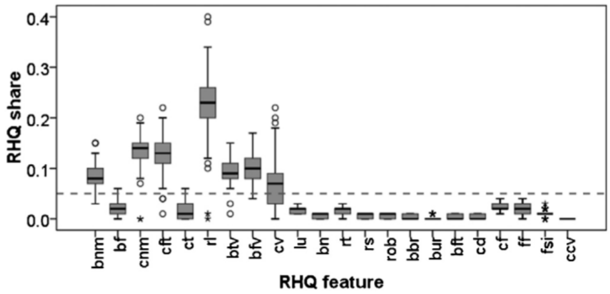


Fig. 3. Distribution of the RHQ index share for each of the 22 RHQ features (for feature codes see Table 1). The dotted line marks the criterion for selection of investigated features.

in the analysis. The potential reference sites were defined following the two criteria:

a) the value of the river habitat modification index (RHM) ≤ 5, extracting the sites with only slight morphological modification (e.g. present ford or bridge without reinforcement)1
b) the value of the hydrological modification index (HLM) ≥ 0.95, separating the sites with really minor influence of dams and weirs upstream.

Since other stressors might impact the RHQ features (e.g. addition of nutrients or fine sediment), the potential reference sites were checked with the Slovenian saprobic index (Urbanič, 2011), where benthic invertebrate samples were present. Sites showing less than good ecological status for organic pollution (Slovenian saprobic index – SIG3 < 0.6) or having no data on SIG3, and at the same time with the excessive presence of fine sediment and/or filamentous algae were eliminated. The procedure resulted in altogether 78 reference sites that were used in further analyses (Fig. 2), 64 sites with catchment area 10–100 km^2 and only 14 sites with catchment area larger than 100 km^2.

River habitat quality (RHQ) features represent characteristics of habitat quality, including river channel and banks, riparian features and land use within 50 m from the channel. For the morphological classification of rivers, out of the 22 RHQ features only those that meet at least one of the following criteria were selected (Table 1);

- are in the best quarter of RHQ variables for structuring benthic assemblages in Slovenian rivers (Petkovska and Urbanič, 2015),
- or show at least medium level of the importance for morphological assessment defined as the medium share of each feature to the RHQ index (median of study sites ≥0.05; Fig. 3).

2.3. Data analysis

The first aim of our study was to classify rivers of Slovenia according to important habitat quality features. With regard to the important typological parameters for structuring benthic invertebrate assemblages (Pavlin et al., 2011; Petkovska and Urbanič, 2015) we first used the top–down approach, comparing the selected RHQ features on the ecoregion level and the sub-ecoregion level. The information on the ecoregion and sub-ecoregion affiliation for each site was obtained from the Slovenian ecological river typology (Table 2; OGRS, 2009; Urbanič, 2011) using ArcGIS desktop (ESRI, 2014).

The comparison on the two selected levels was performed with the permutational multivariate analysis of variance (PERMANOVA; Anderson, 2001) using the program PAST 2.17 (Hammer et al., 2001). PERMANOVA is robust to departures from the distributional assumptions of parametric tests, and is therefore appropriate for

Table 2
The levels of analyses with site groups and the number of sites. Levels marked with asterisk (*) are defined in the Slovenian ecological river typology (OGRS, 2009; Urbanič, 2011)

Level	Site group	Site group code	Number of sites
Ecoregion*	Alps	ER4	26
	Dinaric western Balkan	ER5	33
	Pannonian Lowland	ER11	19
Sub-ecoregion*	Alps – Danube river basin	sER4-D	14
	Alps – Adriatic river basin	sER4-A	12
	Dinaric	sER5-Din	16
	Submediterranean	sER5-Med	17
	Pannonian Lowland	sER11	19
Morphological group	Alps	Alps	26
	Dinaric	Din	16
	Submediterranean	Med	17
	Pannonian Lowland	Low	19

the analysis of data in this study. The Bray–Curtis distance measure (Bray and Curtis, 1957) and 999 permutations of the raw data were used for PERMANOVA tests. Where the overall PERMANOVA test was significant ($P < 0.05$), pairwise comparisons between groups were used as a post-hoc test to define the groups that differ significantly.

On the level of site grouping defined in the PERMANOVA analysis (see "morphological group"; Table 2) the quartiles of data were defined for each of the investigated RHQ features and graphically visualized in boxplots to facilitate the comparison among site groups. Each median value of the RHQ features was validated with bootstrapping procedure (999 repetitions) using R 3.1.0 (R Development Core Team, 2013) with 'bootstrap' library (Tibshirani and Leisch, 2014). The differences between all pairs of site groups were investigated additionally using the non-parametric Mann–Whitney *U*-test. The boxplots and Mann–Whitney *U*-test were performed in SPSS Statistics version 21 (IBM, 2012).

We also investigated the main gradients among important RHQ features on the whole dataset. To identify the RHQ features varying most among the reference sites and to examine the possibility of grouping the important RHQ features the principal component analysis (PCA) was carried out in CANOCO 4.5 (ter Braak and Šmilauer, 2002).

3. Results

3.1. Definition of the morphological groups

PERMANOVA confirmed differences in river habitat quality characteristics (RHQ features) among the site groups on all investigated levels. On the ecoregion level higher explanation power was observed than on the sub-ecoregion level (the overall $F = 14.73$ and 11.03, respectively; $P = 0.001$). The pairwise comparisons revealed significant differences among all ecoregion groups (Table 3), with the highest explanatory power between the Alps (ER4) and the Pannonian Lowland (ER11) ($F = 32.88$; $P = 0.001$). The investigation on the sub-ecoregion level revealed significant differences among all pairs with one exception (Table 4). There was no significant difference apparent between the two sub-ecoregions the Alps–Danube river basin (sER4-D) and the Alps–Adriatic river basin (sER4 -A), and the explanation power is low ($F = 1.069$; $P > 0.05$). On the basis of pairwise comparisons four morphological groups were defined, two based on ecoregion level: the Alps and the Pannonian Lowland, and two based on sub-ecoregion level: the Dinaric region and the Submediterranean region (Table 2).

3.2. Definition of the main morphological gradients

Using ten selected RHQ features, the major contrasts among the reference sites were connected to water flow, channel substrate and dependent features (Fig. 4). All RHQ features increased along the first principal component axis (PC1). PC1 explained 44% of the variation, and the highest positive loadings were revealed by features of special interest along 500 m (fsi: 0.85) and predominant natural bank material (bnm: 0.85). The second important gradient was revealed for the riparian and channel vegetation structure. Along the second principal component axis (PC2), which explained 19% of the variation, the markedly highest positive loading was observed for channel vegetation types (cv: 0.7) and the highest negative loading for banktop vegetation structure (btv: −0.78), bankface vegetation structure (bfv: −0.55) and land use within 5 m (lu: −0.53).

Table 3
The *F* statistics from a pairwise PERMANOVA using the three ecoregions.

Ecoregion[a]	ER4	ER5
ER5	8.015*	
ER11	32.88*	10.38*

[a] ER4 Alps, ER5 Dinaric western Balkan, ER11 Pannonian Lowland.
* Significant at $p < 0.01$.

Table 4
The *F* statistics from a pairwise PERMANOVA using the five sub-ecoregions.

Sub-ecoregion[a]	sER4-D	sER4-A	sER5-Din	sER5-Med
sER4-A	1.069			
sER5-Din	9.079*	8.241*		
sER5-Med	3.866*	6.77*	9.296*	
sER11	20.44*	18.99*	4.615*	20.07*

[a] sER4-D Alps – Danube river basin, sER4-A Alps – Adriatic river Basin, sER5-Din Dinaric, sER5-Med Submediterranean, sER11 Pannonian Lowland.
* Significant at $p < 0.01$.

3.3. Morphological features and the guiding images of morphological groups

The analysis of distribution of RHQ feature values revealed different patterns among the four morphological groups and all patterns were validated (Fig. 5 and Table 5). The group Pannonian Lowland had the highest number of the RHQ features with significantly lowest values (Mann–Whitney *U*-test; $P < 0.05$) among groups (predominant channel substrate, flow types along 500 m, channel and bank features along 500 m, features of special interest along 500 m). Besides, for three other RHQ features (predominant natural bank material, land use within 5 m, banktop vegetation structure) the group Pannonian Lowland shared significantly lowest values with the Dinaric group. Between the groups Alps and Submediterranean significant difference was observed only for three of ten RHQ features (predominant flow, bankface vegetation structure, channel and bank features along 500 m), but the group Alps showed significantly higher values from

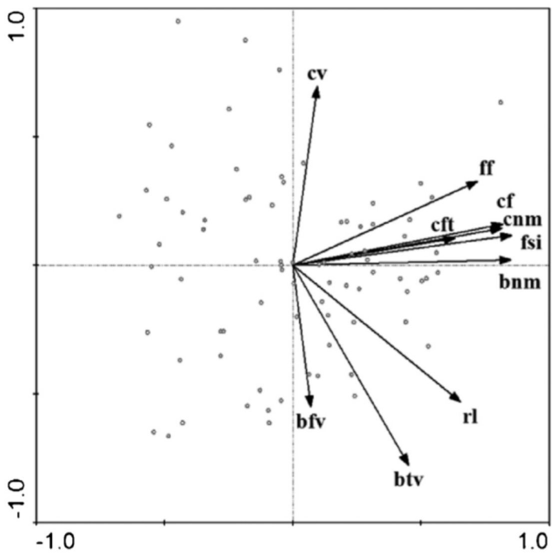


Fig. 4. Principal component analysis (PCA) plot on PC1 and PC2 axes for site distribution and the selected RHQ features. For the feature codes see Table 1.

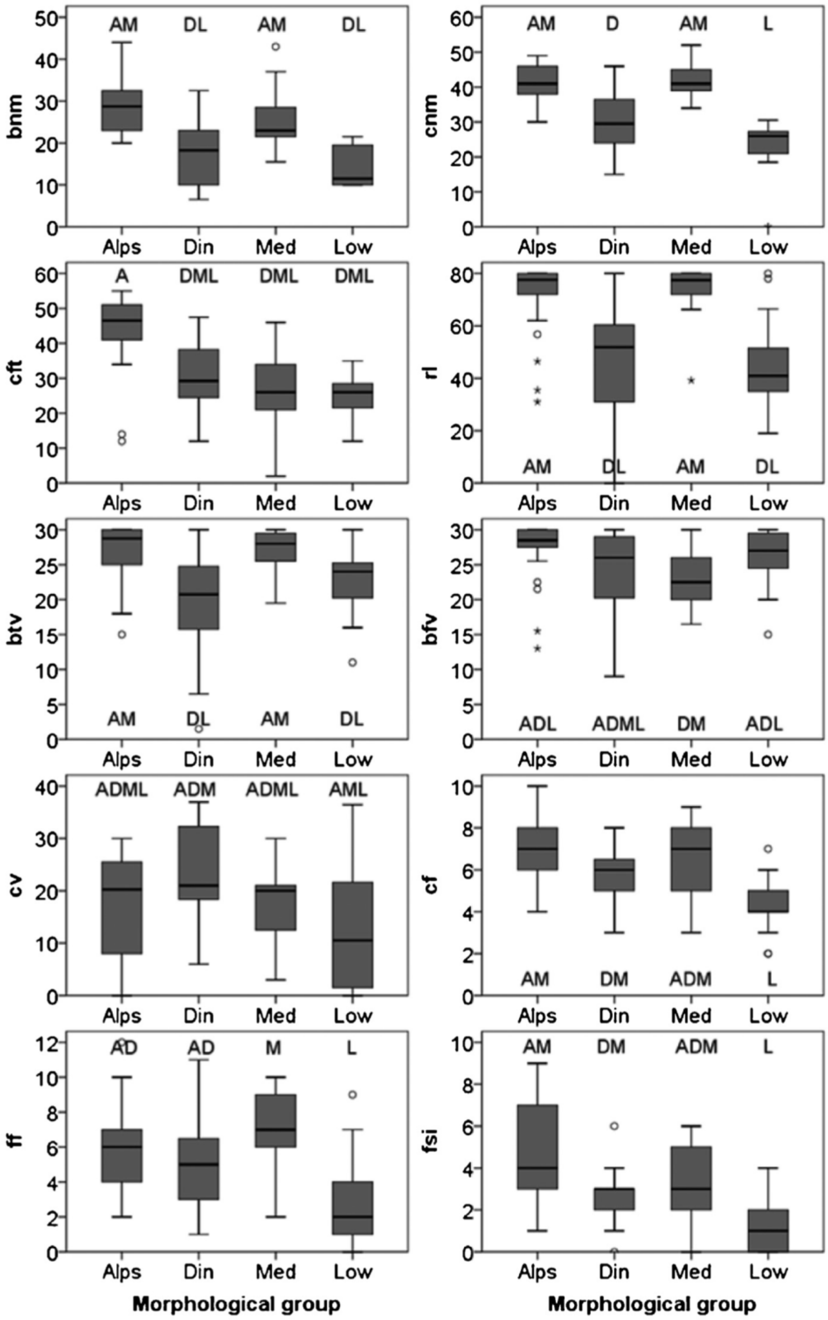


Fig. 5. Distribution of the values for selected RHQ features in four determined morphological groups (Table 2) with significant differences (Mann–Whitney *U*-test, $P < 0.05$) marked by capital letters (A – Alps, D – Din, M – Med, L – Low); for morphological group codes see Table 2; bnm – predominant natural bank material, cnm – predominant channel substrate, cft – predominant flow, rl – land use within 5 m, btv – banktop vegetation structure, bfv – bankface vegetation structure, cv – channel vegetation types, cf – flow types along 500 m, ff – channel and bank features along 500 m, fsi – features of special interest along 500 m.

groups Dinaric and Pannonian Lowland for seven RHQ features and the group Submediterranean for five RHQ features. For the group Alps significantly the highest value was observed for predominant flow, and for the group Submediterranean for channel and bank features along 500 m. The least difference among the morphological groups was observed for the predominant flow, where only the group Alps differed significantly from the other three groups, and for channel vegetation types, where the only significant difference was observed between the groups Dinaric and Pannonian Lowland.

4. Discussion

In this study, we defined the guiding image based on the morphological parameters of rivers derived from the SIHM method for the four major regions (Fig. 6 and Table 6). Since the dataset is represented mostly by sites on smaller rivers (10–100 km^2), the extrapolation to larger rivers should be carefully done. The top–down approach resulted in significant differences among river habitat features of the alpine, lowland, mediterranean and karst

Table 5
The confidence interval (95%) with lower (2.5%) and upper (97.5%) value for median of RHQ features for each morphological group (Table 2) using bootstrapping procedure; for RHQ feature codes see Table 1.

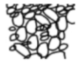
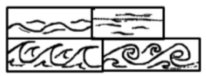
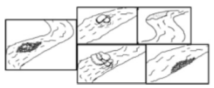
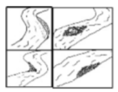
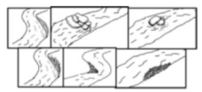
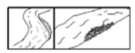
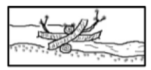
RHQ feature code	Alps		Din		Med		Low	
	2.5%	97.5%	2.5%	97.5%	2.5%	97.5%	2.5%	97.5%
bnm	25	32	10	22	22	29	10	19
cnm	40	44	24	36	39	45	21	27
cft	43	49	26	38	21	34	23	28
rl	76	80	41	60	72	80	37	51
btv	27	29	16	24	27	30	21	25
bfv	28	30	21	29	20	26	25	30
cv	11	25	19	31	13	21	2	21
cf	6	8	5	7	5	8	4	5
ff	5	7	3	6	6	9	1	4
fsi	3	6	2	3	2	5	0	2

region. Using the whole dataset the major gradient among reference sites was observed for morphological characteristics that are in tight relation to water flow and sediment dynamics. Water flow is recognized as the channel forming force, influencing channel substrate characteristics and features (Poff et al., 1997; Allan and Castillo, 2007). It is generally accepted that distinct differences exist between alpine or mountainous rivers and lowland rivers (Szoszkiewicz et al., 2006; Harnischmacher, 2007; Repnik Mah et al., 2010), primarily caused by differences in the topological setting of drainage network. Moreover, the topology and geology of the area also shape the bank material, which in V-shaped valleys of mountainous rivers contributes a large share to channel substrate due to episodic mass-movement. The findings of this study confirmed these differences between the alpine rivers and the lowland rivers in all investigated parameters connected to water flow and substrate. In alpine rivers, the main channel and bank substrate are cobbles, the predominant flow is represented by unbroken standing waves, there are 3–5 flow types regularly present and special features, such as bars, eroding cliffs, exposed boulders or riffles and pools appear on a frequent basis. In natural river reaches of the lowland region, bank material is usually represented by earth, the channel characteristics are gravel substrate and rippled or smooth flow with only little flow diversity and a few special features.

The separation of the ecoregion Dinaric western Balkan to sub-ecoregions belonging to Dinaric karst region and Mediterranean region showed interesting pattern in morphological characteristics. The mediterranean rivers showed similarities to the alpine rivers, and the karst rivers to the lowland rivers. Concerning the morphological nature of the mediterranean rivers in comparison to other regions only a few studies exist (Szoszkiewicz et al., 2006; Feio et al., 2014), but up to our knowledge there are none for karst rivers. Szoszkiewicz et al. (2006) found considerable differences in river habitat features that distinguish the Mediterranean region from alpine or lowland. The mediterranean rivers in our study differed in some features from all other rivers (channel and bank features along 500 m), but showed often similarity to the alpine rivers, e.g. in channel substrate and bank material composition and flow diversity. The probable cause might be the similar character of the alpine rivers and the mediterranean rivers regarding particularly high discharge variability, strongly dependent on season. The difference in the values of predominant flow indicates the torrential discharge of mediterranean rivers. The mediterranean river types are often intermittent, having constant water flow only seasonally (Boix et al., 2010; Pace et al., 2013; Feio et al., 2014). The RHS surveys are carried out in low flow season (which in the mediterranean rivers could be 'no flow' season), which might be the reason for the observed distinction from the alpine rivers. The occasional presence of high discharge is obvious also through the higher value of channel and bank features along 500 m (which include eroding banks) and lower value of bankface vegetation structure. The results considering the karst rivers revealed

Fig. 6. Examples of guiding images of rivers in the four investigated regions; A – alpine, B – mediterranean, C – karst, D – lowland (photographs from personal collection).

Table 6
Guiding image of four morphological groups with range, median and pictogram for the selected RHQ features; for the description of the pictograms see Appendix D.

Feature		Morphological group							
		Alps		Dinaric		Submediterranean		Pannonian Lowland	
Predominant natural bank material	Range Median	20–44 29 – cobbles		7–33 18 – gravel/ sand		16–43 23 – gravel/ sand		10–22 12 – earth	
Predominant channel substrate	Range Median	30–49 41 – cobbles		15–46 30 – gravel/ pebbles		34–52 41 – cobbles		0–31 26 – gravel predominating/ pebbles	
Predominant flow	Range Median	12–55 47 – unbroken standing waves		12–48 29 – rippled		2–46 26 – rippled		12–35 26 – rippled	
Land use within 5 m	Range Median	31–80 78 – broadleaf/ mixed woodland		0–80 52 – scrub and shrubs/tall herbs		39–80 78 – broadleaf/ mixed woodland		19–80 41 – rough unimproved pasture	
Banktop vegetation structure	Range Median	15–30 29 – complex		2–30 21 – simple		20–30 28 – complex		11–30 24 – simple	
Bankface vegetation structure	Range Median	13–30 29 – complex		9–30 26 – complex		17–30 23 – simple		15–30 27 – complex	
Channel vegetation types	Range Median	0–30 20 – amphibious/ mosses		6–37 21 – amphibious/ mosses		3–30 20 – amphibious/ mosses		0–36 11 – amphibious/ none	
Flow types along 500 m[a]	Range Median	4–10 7		3–8 6		3–9 7		2–7 4	
Channel and bank features along 500 m[a]	Range Median	2–12 6		1–11 5		2–10 7		0–9 2	
Features of special interest along 500 m[a]	Range Median	1–9 4		0–6 3		0–6 3		0–4 1	

[a] Diversity of feature's categories.

more stable conditions with smaller fractions of bank material (mostly sand) and channel substrate (mostly gravel) and the rippled predominant flow. The Dinaric karst region in this study includes many river types with the karst spring influence (Urbanič, 2011) that exerts slow discharge changes. Hence, the morphological characteristics might be similar to lowland rivers with smaller catchments (e.g. <1000 km^2), where energy of low flow is not sufficient for moving larger substrate fractions (Poff et al., 1997).

The second, also important gradient among investigated sites was observed for morphological characteristics regarding riparian and channel vegetation features. The highest values for riparian land use and vegetation structure on top of the river banks were observed for the alpine and mediterranean rivers, where the values indicate the presence of mostly broadleaved forest with complex vegetation structure. On the other hand the lower values for the karst or lowland rivers reveal simpler riparian vegetation structure with shrubs, occasional forest and meadows. The question arises whether the latter truly represents the state of morphological features that could be applied as a guiding image. The reference sites were selected on the basis of morphological modification included in the RHM and HLM indices. Since the structure of riparian vegetation mainly represents habitat quality feature due to SIHM method, it was not regarded as a criterion for selection in this study. The historical data suggest that the natural riparian vegetation across the investigated area is mostly a broadleaved forest, also in lowland and karst regions, therefore the lower value of selected features is a sign of human activity. The agricultural incentive in the past and in some places in the present is to remove all riparian vegetation for larger cultivable area. This trend concerns all regions. However, the reference sites of the alpine rivers are mostly in V-shaped valleys, difficult for people to access and modify. The same also holds true for some sites of the mediterranean rivers, whereas the riparian area of other sites was historically cultivated and then reforested because of land abandonment in last decades (Keesstra et al., 2005). The guiding image of riparian vegetation should therefore follow other criteria and not only the state of the reference sites, defined by the absence of humanly made structures. The similar concern follows for channel vegetation types, where the highest values were observed for the karst rivers, although not significantly different from the alpine or mediterranean rivers. The guiding image on the in-stream vegetation state is even more complex, since the presence and type depends not only on hydraulic forces and channel substrate, but also on the presence of riparian vegetation with shading and the nutrients (Julian et al., 2011; Feld, 2013). Moreover, channel vegetation is not only a consequence of morphological river characteristics, but can also act as ecosystem engineer by trapping fine sediment for long enough to induce landform development and river channel change (Gurnell et al., 2010).

Two main morphological gradients were defined among morphological parameters of the selected reference sites, which are a consequence of different hydromorphological processes; water flow, sediment and bank dynamics in one hand, and vegetation and large wood dynamics on the other (Jalón et al., 2013). Several scientists argue that addressing the local 'state of the art' hydromorphological status is not enough for sustainable river management, but should be based on the processes behind (Kondolf et al., 2006; Vaughan et al., 2009; Globevnik and Mikoš, 2009; Rinaldi et al., 2013b). However, of utmost importance for river management, either development of guidelines for river restoration, protection of the non-impacted reaches or for spatial planning, is the link to river ecosystem functioning. The connection between the river forming processes and aquatic biota has not been optimally established yet. Most ecological studies have related morphological features to aquatic assemblages, but without considering geomorphological processes, and most geomorphological studies have linked the processes with hydromorphological forms but with little ecological understanding (Jalón et al., 2013). It is therefore more appropriate to develop guiding images on parameters linked to aquatic assemblages and investigate more the processes influencing those parameters naturally or as a consequence of anthropogenic changes.

In conclusion, the definition of the guiding images based on our study follows main morphological gradients that showed good relation to benthic assemblages (Petkovska and Urbanič, 2015). The water flow, channel and bank substrate and present morphological structures, they all differ regionally. The alpine rivers are represented by cobbles on banks and on the channel bottom, unbroken standing waves and chaotic flow as predominant flow type but also by high diversity of flow types and large number of channel and bank features along 500 m (e.g. eroding banks, bars). In mediterranean rivers cobbles also represent the predominant channel substrate, but the flow is rippled and banks are mostly covered with a mixture of gravel and sand. There is also a variety of flow types and features along 500 m. Karst and lowland rivers are similar in channel substrate, where gravel and pebbles are dominating and rippled flow is predominant. However, karst rivers have large bank material (gravel/sand) when compared to earth in lowland rivers, and higher diversity of flow types and features along 500 m. The guiding image for riparian features, however, based only on our study, is probably misleading. With the consideration of historical data, the pristine image of those features is common for rivers of all regions, e.g. broadleaved forest with complex vegetation structure.

Although the rivers of Europe have been greatly damaged in the past and the pristine reaches hardly exist (Nijboer et al., 2004), in a large share of several Slovenian rivers the human influence might still be called minimal. In our study the guiding images are based on the today's river conditions in the absence of significant human disturbance, which is probably the best possibility for their development. However, due to the moderate amount of data gathered from the ecological status-assessment system development programs, only the major regional units were considered in the study. The variability of some considered parameters within the morphological groups suggests further investigation and eventual division to smaller groups, considering other relevant large scale parameters (e.g. river size class or karst spring influence; Pavlin et al., 2011; Petkovska and Urbanič, 2015). The diverse geographical area of Slovenia offers a great potential for investigating the linkages between natural river forming processes, habitat characteristics and aquatic biota. In river management it is important to define what the guiding images for different river types are and where can be found, not only for mending what was broken, but also for sustainable development of still preserved rivers.

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Appendix A.

Weights for different categories of features recorded in Slovenian hydromorphological assessment method (modified after Tavzes and Urbanič, 2009) (see Tables A1–A3).

Table A1
River habitat quality features (with feature codes).

Predominant natural bank material (bnm)	Value
Bedrock	5
Boulder	4
Cobble	3
Gravel/sand	2
Earth	1
Clay	0
Bank features (bf)	Value
None	0
Eroding cliff	0.5
Stable cliff	1
Unvegetated point bar	2.5
Vegetated point bar	3.5
Unvegetated side bar	2
Vegetated side bar	3
Natural berm	4
Predominant channel substrate (cnm)	Value
Bedrock	6
Boulder	5
Cobble	4
Gravel/pebble (predominating)	3.5
Gravel/pebble	3
Gravel (predominating)/pebble	2.5
Sand	2
Silt/mud	1
Clay	0
Predominant flow (cft)	Value
Freefall	7
Chute	6
Broken standing waves	5.5
Unbroken standing waves	5
Chaotic flow	4
Rippled	3
Upwelling	2.5
Smooth flow	2
No perceptible flow	1
No flow (dry)	0
Channel features (ct)	Value
None	0
Exposed boulders	1
Unvegetated mid-channel bar	3
Vegetated mid-channel bar	4
Mature island	5
Vegetated rock	2
Exposed bedrock	1.5
Land use (rl and lu)	Value
Broadleaf/mixed woodland (semi- natural)	8
Broadleaf/mixed plantation	7.5
Coniferous woodland (semi-natural)	7
Coniferous plantation	6.5
Orchard	3
Scrub and shrubs	5.5
Tall herb/rank vegetation	5
Rough unimproved pasture	4
Improved/semi-improved grassland	2
Tilled land	1
Wetland	4.5
Suburban/urban development	0
Irrigated land	1
Parkland or gardens	3
Banktop and bankface vegetation structure (btv and bfv)	Value
Bare	0
Uniform	1
Simple	2
Complex	3
Channel vegetation types (cv)	Value
None or not visible	0
Liverworts/mosses/lichens	3
Emergent broad-leaved herbs	4
Emergent reeds/sedges/rushes/grasses	4
Floating-leaved (rooted)	1
Free-floating	0.5
Amphibious	1.5
Submerged broad- leaved	5
Submerged fine-leaved	5
Submerged linear- leaved	5
Filamentous algae	2
Unmodified bank profiles (bn)	Value
None	0
Vertical/undercut	0.5
Vertical with toe	1
Steep (>45º)	2
Gentle	3
Composite	4
Natural berm	5
Extent of trees (rt)	Value
None	0
Isolated/scattered	1
Regularly spaced/single	2
Occasional clumps	3
Semi-continuous	4
Continuous	5

Appendix B.

A river habitat quality index (RHQ) considers five river habitat quality variables and its value is calculated according to Eq. (B1):

$$RHQ = Sc_{bf} + Sc_{cf} + Sc_{rf} + Sc_{lu} + Sc_{f} \quad (B1)$$

where RHQ – river habitat quality index; Sc_{bf} – score for bank features; Sc_{cf} – score for channel features; Sc_{rf} – score for riparian features; Sc_{lu} – score for land use within 50 m; Sc_{f} – score for features of interest along 500 m of the river.

Scores of the river habitat quality variables are calculated using following equations:

For bank features the score is calculated using Eq. (B2):

$$Sc_{bf} = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n}(a_{bji} \times f_{bji}) + \sum_{k=1}^{l}(a_{bnk} \times e_{bnk})/s}{2} + \sum_{h=1}^{3} e_{bh} \quad (B2)$$

where Sc_{bf} – score for bank features; a_{bji} – value appointed to a ith category of a jth bank feature (bnm, bf, btv, bfv); a_{bnk} – value appointed to a kth category of the feature unmodified bank profiles (bn); f_{bji} – frequency of a ith category of a jth bank feature (bnm, bf, btv, bfv); e_{bnk} – extent of a kth category of the feature unmodified bank profiles (bn); e_{bh} – extent of a hth bank feature (bbr, bur, bft); n – number of categories of the jth bank feature (bnm, bf, btv, bfv); m – number of the jth features; l – number of categories of the feature unmodified bank profiles (bn); s – number of the present categories of the feature unmodified bank profiles (bn); for explanation of feature codes see Appendix A.

Since some features are surveyed on both river banks, the final score of each such feature is devided by 2.

For channel features the score is calculated using Eq. (B3):

$$Sc_{cf} = \sum_{l=1}^{o}\sum_{i=1}^{n}(a_{cli} \times f_{cli}) + \sum_{m=1}^{10}\frac{1}{r}\sum_{k=1}^{s}(a_{cvk} \times e_{cvk}) + \sum_{j=1}^{p} e_{cfj} + \sum_{h=1}^{2} e_{ch} \quad (B3)$$

where Sc_{cf} – score for channel features; a_{cli} – value appointed to a ith category of a lth channel feature (cnm, cft, ct); a_{cvk} – value appointed to a kth category of the feature channel vegetation types (cv); f_{cli} – frequency of a ith category of a lth channel feature (cnm,

Table A2
River habitat modification features (with feature codes).

Predominant artificial bank material (bam)	Value
Concrete	6
Wood piling	3
Gabion	4
Brick/laid stone	5
Rip-rap	2
Builders waste	0.5
Bank modifications (bm)	Value
None	0
Resectioned (reprofiled)	3
Reinforced	4
Poached	2
Poached bare	2.5
Embankment	1
Artificial channel material (cam)	Value
Artificial channel material	1
Artificial features (dam/weir – sd, bridge – sb, ford – sf, deflector – sde)	Value
Minor	1
Intermediate	2
Major	3
Channel modifications (cm)	Value
None	0
Culverted	5
Resectioned	2
Reinforced	3
Dam/weir/sluice	4
Ford	1
Artificial/modified bank profiles (ba)	Value
None	0
Resectioned (reprofiled)	1.5
Reinforced – whole	5
Reinforced – top only	2.5
Reinforced – toe only	4
Artificial two stage	1.5
Poached bank	2
Embanked	3
Set-back embankment	0.5

cft, ct); e_{cvk} – extent of a kth category of the feature channel vegetation types (cv); e_{cfj} – extent of a jth category of the feature flow types along 500 m (cf); e_{ch} – extent of a hth channel feature (cd, ccv); n – number of categories of the lth feature; o – number of the lth features; p – number of categories of the feature flow types along 500 m (cf); r – sum of extent values e_{cvk} for spot-check m;

Table A3
Features that are weighted according to their extent; 1 – present in 1–33 % of length, 2 – present in >33 % of length; * – 1 if present in >33% of length.

River habitat quality features
Channel vegetation types (cv)
Land use within 50 m (lu)
Unmodified bank profiles (bn)
Artificial/modified bank profiles (ba)
Shading of the channel (rs)
Overhanging boughs (rob)
Exposed bankside roots (bbr)
Underwater tree roots (bur)
Fallen trees (bft)
Coarse woody debris (cd)
Flow types along 500 m (cf)
Channel and bank features along 500 m (ff)
Features of special interest along 500 m (fsi)
Channel choked with vegetation (ccv)*
River habitat modification features
Channel realignment (cmr)
Water impoundment by weir/dam (cmi)

s – number of categories of the feature channel vegetation types (cv); for explanation of feature codes see Appendix A.

For riparian features the score is calculated using Eq. (B4):

$$Sc_{rf} = \frac{\sum_{i=1}^{n}(a_{rli} \times f_{rli}) + \sum_{j=1}^{m} a_{rij}}{2} + \sum_{h=1}^{2} e_{rh} \quad \text{(B4)}$$

where Sc_{rf} – score for riparian features; a_{rli} – value appointed to a ith category of the feature land use within 5 m (rl); a_{rtj} – value appointed to a jth category of the feature extent of trees (rt); e_{rh} – extent of a hth riparian feature (rs, rob); f_{rli} – frequency of a ith category of the feature land use within 5 m (rl); n – number of categories of the feature land use within 5 m (rl); m – number of categories of the feature extent of trees (rt); for explanation of feature codes see Appendix A.

For land use within 50 m of the channel the score is calculated using Eq. (B5):

$$Sc_{lu} = \frac{1}{2}\frac{\sum_{i=1}^{m} e_{lui} \times a_{lui}}{m} \quad \text{(B5)}$$

where Sc_{lu} – score for land use within 50 m; a_{lui} – value appointed to a ith category of the feature land use within 50 m (lu); e_{lui} – extent of a ith category of the feature land use within 50 m (lu); m – number of the present categories of the feature land use within 50 m (lu); for explanation of feature codes see Appendix A.

For features of interest along 500 m of the river the score is calculated using Eq. (B6):

$$Sc_{f} = \sum_{j=1}^{m}\sum_{i=1}^{n} e_{fji} \quad \text{(B6)}$$

where Sc_f – score for features of interest along 500 m of the river; e_{fji} – extent of a ith category of a jth feature of interest along 500 m of the river (ff, fsi); n – number of categories of the jth feature of interest along 500 m of the river (ff, fsi); m – number of jth features; for explanation of feature codes see Appendix A.

Appendix C.

A river habitat modification quality index (RHM) considers bank and channel modifications and its value is calculated according to Eq. (C1):

$$RHM = Sc_{bmo} + Sc_{cmo} \quad \text{(C1)}$$

where RHM – river habitat modification index; Sc_{bmo} – score for bank modifications; Sc_{cmo} – score for channel modifications.

Scores of the river habitat modification variables are calculated using following equations:

For bank modifications the score is calculated using Eq. (C2):

$$Sc_{bmo} = \frac{\sum_{j=1}^{0}\sum_{i=1}^{n}\left(a_{bji} \times f_{bji}\right) + \sum_{k=1}^{m}(a_{bak} \times e_{bak})/s}{2} \quad \text{(C2)}$$

where Sc_{bmo} – score for bank modifications; a_{bji} – value appointed to a ith category of a jth bank modification feature (bam, bm); a_{bak} – value appointed to a kth category of the feature artificial/modified bank profiles (ba); f_{bji} – frequency of a ith category of a jth bank modification feature (bam, bm); e_{bak} – extent of a kth category of the feature artificial/modified bank profiles (ba); m – number of categories of the feature artificial/modified bank profiles (ba); n – number of categories of the jth bank modification feature (bam, bm); o – number of the jth features; s – number of present categories of the feature artificial/modified bank profiles (ba); for explanation of feature codes see Appendix A.

Since some features are surveyed on both river banks, the final score of each such feature is devided by 2.

For channel modifications the score is calculated using Eq. (C3):

$$Sc_{cmo} = \sum_{j=1}^{m}\sum_{i=1}^{n}(a_{cji} \times f_{cji}) + \sum_{k=1}^{o} s_k + \sum_{h=1}^{2} e_{cmh} \tag{C3}$$

where Sc_{cmo} – score for channel modifications; a_{cji} – value appointed to a ith category of a jth channel modification feature (cam, cm); f_{cji} – frequency of a ith category of a jth channel modification feature (cam, cm); s_k – value of the category of a kth channel modification feature (artificial features; sd, sb, sf, sde); e_{cmh} – extent of a hth channel modification feature (cmr, cmi); n – number of categories of the jth channel modification feature (cam, cm); m – number of the jth features; o – number of artificial features types; for explanation of feature codes see Appendix A.

For the calculation of Sc_{cmo} only the value of the category of artificial features present is considered, and not also the frequency of artificial features.

Appendix D.

See Table D1.

Table D1
The description of pictograms in Table 6.

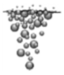
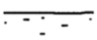
Pictogram	Description
Substrate	
	Cobbles
	Gravel/sand
	Earth
	Gravel predominating/pebbles
Flow types	
	Broken standing waves
	Unbroken standing waves
	Upwelling
	Rippled Smooth flow
	No perceptible flow
Vegetation	
	Broadleaf/mixed woodland
	Scrub and shrubs/tall herbs
	Rough unimproved pasture
	Complex
	Simple
Channel vegetation type	
	Amphibious/mosses
	Amphibious/none
Channel and bank features along 500 m	
	Unvegetated mid-channel bar
	Unvegetated point bar
	Unvegetated side bar
	Unvegetated sand deposit
	Exposed bedrock
	Exposed boulders
	Eroding cliff
	Stable cliff
Features of special interest along 500 m	
	Natural cascade

Table D1 (*Continued*)

Pictogram	Description
	Riffle
	Pool
	Very large boulders
	Debris dam

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Slika 11. Motiv z mesta vzorčenja Savinja, ribnik Vrbje

Figure 11. A theme from sampling site Savinja, ribnik Vrbje

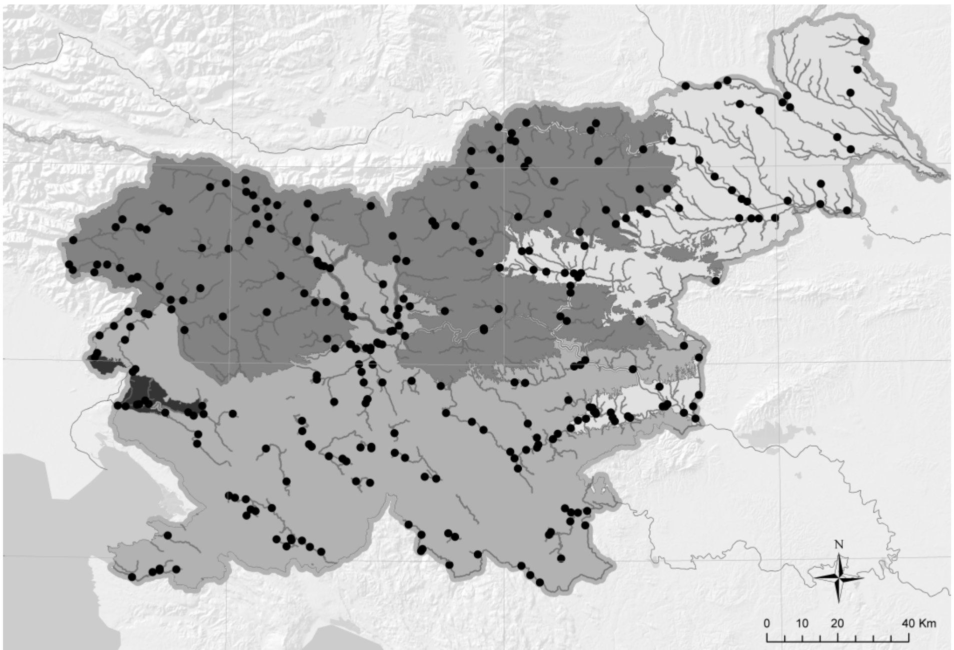
2.2 OSTALO POVEZOVALNO ZNANSTVENO DELO

2.2.1 Metode

2.2.1.1 Izbor mest raziskav

2.2.1.1.1 Mesta vzorčenja bentoških nevretenčarjev

V analizah smo uporabili podatke o številčnosti in taksonomski sestavi združb bentoških nevretenčarjev s 302 mest vzorčenja na tekočih vodah oz. vodotokih Slovenije (Slika 12). Podatki so bili pridobljeni med leti 2005 in 2011 v okviru projektov za razvoj metodologij vrednotenja ekološkega stanja rek v Sloveniji (Inštitut za vode Republike Slovenije) in projektov za izvajanje monitoringa kakovosti površinskih voda v Sloveniji (Agencija Republike Slovenije za okolje). Uporabili smo podatke z mest vzorčenja na vodotokih z velikostjo prispevne površine vsaj 10 km^2 ter v vseh štirih ekoregijah celinskih voda v Sloveniji: Alpe (93 mest), Dinaridi (129 mest), Panonska nižina (73 mest) in Padska nižina (7 mest). Pri izboru mest smo upoštevali vpliv obremenitve vodotokov na mestih vzorčenja. Ker nas je zanimala predvsem povezanost združb bentoških nevretenčarjev s kakovostjo in spremenjenostjo hidromorfoloških značilnosti vodotokov, smo izbrali le mesta vzorčenja, na katerih je bil vpliv drugih obremenitev majhen (za vpliv organskega onesnaženja in hranil smo ugotovili vsaj dobro stanje po veljavni metodologiji vrednotenja ekološkega stanja rek v Sloveniji; Pravilnik …, 2009).

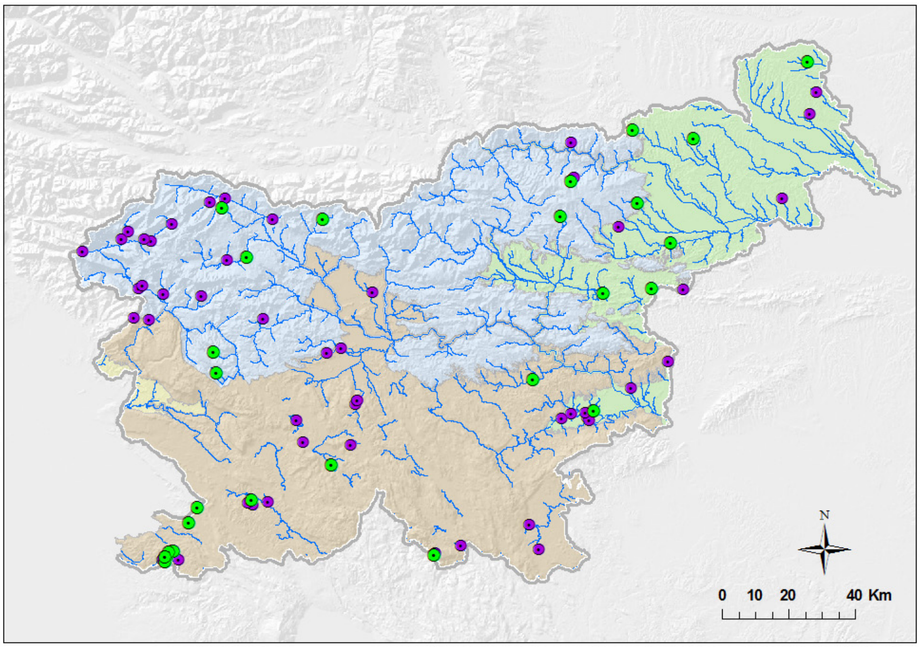


Slika 12. Mesta vzorčenja na vodotokih (302 mesti).

Figure 12. River sampling sites (302 sites).

2.2.1.1.2 Mesta popisov hidromorfoloških značilnosti

Podatke o hidromorfoloških značilnostih smo pridobili na vseh 302 mestih vzorčenja bentoških nevretenčarjev po Slovenskem hidromorfološkem sistemu (SIHM) v obdobju med leti 2002 in 2013. Za določitev značilnih hidromorfoloških razmer za vodotoke v Sloveniji smo izmed že obravnavanih mest izbrali odseke, ki odražajo naravno ali malo spremenjeno stanje hidromorfoloških značilnosti po sistemu SIHM: 51 popisnih odsekov na mestih, kjer so bili vzorčenih bentoški nevretenčarji ter še 27 popisnih odsekov, kjer vzorcev bentoških nevretenčarjev nismo imeli (Slika 13). Podrobneje so kriteriji izbora značilnih mest opisani v poglavju: *Raznolikost vodilnih slik ekosistemov tekočih voda, določenih na podlagi ekološko pomembnih lastnosti rečnih habitatov za alpsko, mediteransko, nižinsko in kraško regijo (poglavje 2.1.3).*



Slika 13. Mesta popisnih odsekov za namen določitve značilnih hidromorfoloških razmer za vodotoke v Sloveniji; vijolično – mesta, uporabljena tudi v analizi povezave z bentoškimi nevretenčarji, zeleno – mesta, uporabljena le v tem delu analize

Figure 13. Sampling sites for determination of reference hydromorphological conditions for Slovenian rivers; purple – sites, also investigated in relation to benthic invertebrate assemblages, green – sites, only used in this part of the analysis

2.2.1.2 VZORČENJE IN LABORATORIJSKA OBDELAVA BENTOŠKIH NEVRETENČARJEV

Vzorci bentoških nevretenčarjev so bili pridobljeni in obdelani v laboratoriju po standardni metodi za vrednotenje ekološkega stanja rek v Sloveniji (Urbanič in sod., 2005; Pravilnik …, 2009). Vzorčenje bentoških nevretenčarjev je potekalo v obdobju nizkih do srednje visokih vodostajev, večinoma med majem in septembrom, z izjemo nekaterih velikih vodotokov, ki imajo nizke vodostaje pozimi, ter presihajočih vodotokov, ki v poletnih mesecih nimajo (dovolj) vode. Z vsakega mesta vzorčenja je bil uporabljen le po en vzorec bentoških nevretenčarjev v obdobju. Vzorec je sestavljalo 20 enot vzorčenja, nabranih z ročno mrežo z okvirjem 0,25 m x 0,25 m (angl. *kick sampling*), skupno torej nabranih na 1,25 m^2 velikem območju. Enote vzorčenja so bile razporejene glede na sorazmerni delež mikrohabitatnih tipov vodotoka, kateri so določeni s kombinacijo pokrovnosti dna struge z organskim in anorganskim substratom ter tipa vodnega toka. Na terenu ali v laboratoriju se je celoten vzorec razdelil na 4 podvzorce po predpisani metodi (Urbanič in sod., 2005; Petkovska in Urbanič, 2010) ter bentoške nevretenčarje iz ene četrtine vzorca shranilo v 96 % etanolu. Po predpisanih določevalnih ključih se je vse bentoške nevretenčarje določilo do taksonomske stopnje, Pravilnik …, 2009), potrebne za vrednotenje ekološkega stanja rek v Sloveniji (Urbanič in sod., 2005; Petkovska in Urbanič, 2010; Pavlin in sod., 2011), večinoma do vrste ali rodu.

2.2.1.3 OKOLJSKE SPREMENLJIVKE

Za vsako mesto vzorčenja smo pridobili podatke o izbranih okoljskih spremenljivkah, za katere smo domnevali, da so pomembne pri raziskavi povezav med morfološkimi značilnostmi in združbami bentoških nevretenčarjev v vodotokih. Za opis naravnih regionalnih dejavnikov smo uporabili spremenljivke tipologije vodotokov v Sloveniji (Urbanič, 2011), (preglednica 1). Mesta vzorčenja smo razvrstili v spremenljivke pripadnost ekoregiji (Alpe, Dinaridi, Panonska nižina, Padska nižina). Po spremenljivkah tipologije vodotokov v Sloveniji smo določili tudi prisotnost vpliva naravnega presihanja, prisotnost vpliva kraškega izvira ter velikostni razred vodotoka. Z uporabo DMV5 (digitalnega modela višin 5 x 5 m) smo za vsako mesto določili še nadmorsko višino in padec struge.

Podatke za morfološke spremenljivke smo dobili na podlagi terenskih popisov po Slovenskem hidromorfološkem sistemu (SIHM). Podatke smo pridobili na 500 m odsekih po metodologiji, ki je bila razvita za vrednotenje ekološkega stanja rek na podlagi hidromorfoloških elementov kakovosti v Sloveniji (Tavzes in Urbanič, 2009; Urbanič in sod., 2013a). Na podlagi podatkov, pridobljenih s popisi RHS, smo po sistemu SIHM izračunali 33 morfoloških spremenljivk (Preglednica 1), 22 spremenljivk kakovosti habitata (RHQ) in 11 spremenljivk spremenjenosti habitata (RHM). Po sistemu SIHM smo izračunali tudi vrednosti indeksa spremenjenosti habitatov (RHM) ter indeksa hidrološke spremenjenosti (HLM) za vse popisne odseke. Pri izračunu indeksa HLM smo upoštevali pregrade, pridobljene s pregledom digitalnih ortofoto posnetkov na spletni aplikaciji Atlas okolja (Atlas okolja, 2013), podatke o velikih pregradah v evidenci IzVRS (Uredba o načrtu …, 2011) ter podatke slojev 'koncesije za rabo vode' ter 'vodna dovoljenja' spletne aplikacije Atlas okolja (Atlas okolja, 2013).

Preglednica 1. Okoljske spremenljivke z oznakami, enotami, uporabljenimi transformacijskimi enačbami in razvrščenostjo v skupine ter osnovno statistiko za štiri obravnavane podatkovne nize. RHQ – spremenljivke kakovosti habitata, RHM – spremenljivke spremenjenosti habitata.

Table 1. Environmental variables with basic statistics for four datasets. RHQ – variables of habitat quality, RHM – variables of habitat modification.

					Mediana (razpon)*			
Okoljska spremenljivka	**Oznaka**	**Enota**	**Transformacija**	**Skupina**	**Slovenija**	**Alpe**	**Dinaridi**	**Panonska nižina**
Regija: »Nižinska«	ER3.11	-	-	tipologija	80	-	-	-
Ekoregija: Alpe	ER4	-	-	tipologija	93	-	-	-
Ekoregija: Dinaridi	ER5	-	-	tipologija	129	-	-	-
Velikostni razred vodotoka	Size_cl	razredi (1-4)	-	tipologija	2 (1-4)	1 (1-4)	1 (1-4)	3 (1-4)
Vpliv kraškega izvira	Kspring	-	-	tipologija	60	21	39	-
Presihanje	Intermit	-	-	tipologija	15	-	15	-
Nadmorska višina*	Alt	m	ln (x+1)	tipologija	283 (1-896)	395 (157-896)	285 (1-745)	208 (132-354)
Padec struge*	Slope	‰	ln (x+1)	tipologija	4,5 (0,0-261,0)	13,9 (0,0-261,0)	4,0 (0,0-89,7)	1,7 (0,0-12,9)
Naravni material brega	bnm	-	-	RHQ	16,0 (0,0-44,0)	20,5 (0,0-42,5)	14,0 (0,0-44,0)	12,0 (0,0-34,5)
Značilnosti brega	bf	-	-	RHQ	1,5 (0,0-23,0)	2,5 (0,0-15,8)	1,5 (0,0-16,5)	0,5 (0,0-23,0)
Naravni substrat struge	cnm	-	-	RHQ	33,5 (0,0-52,0)	37,0 (26,0-49,0)	30,0 (0,0-52,0)	30,0 (0,0-51,5)
Tipi tokov na popisnih točkah	cft	-	-	RHQ	32,5 (2,0-55,0)	40,5 (10,0-55,0)	29,0 (2,0-51,0)	30,0 (10,0-53,0)
Značilnosti struge	ct	-	-	RHQ	1,0 (0,0-47,0)	2,5 (0,0-18,0)	1,0 (0,0-27,0)	0,0 (0,0-47,0)
Raba zemljišča v 5 m pasu	rl	-	-	RHQ	46,0 (0,0-80,0)	55,0 (15,0-80,0)	44,0 (0,0-80,0)	38,0 (7,5-80,0)
Struktura vegetacije vrha brega	btv	-	-	RHQ	21,5 (5,5-30,0)	23,0 (9,5-30,0)	20,5 (5,5-30,0)	20,5 (7,0-30,0)
Struktura vegetacije površine brega	bfv	-	-	RHQ	26,5 (4,0-30,0)	27,5 (10,5-30,0)	26,0 (10,0-30,0)	25,0 (4,0-30,0)
Tipi vegetacije v strugi	cv	-	-	RHQ	19,2 (0,0-43,6)	16,0 (0,0-36,5)	21,4 (0,0-43,6)	16,8 (0,0-43,3)
Raba zemljišča v 50 m pasu	lu	-	-	RHQ	2,5 (0,6-8,0)	2,8 (1,3-8,0)	2,4 (0,8-8,0)	2,2 (0,6-8,0)
Naravni profili bregov	bn	-	-	RHQ	1,5 (0,0-3,5)	1,7 (0,0-3,0)	1,5 (0,0-3,0)	1,4 (0,0-3,5)
Sklenjenost krošenj	rt	-	-	RHQ	4,5 (0,0-5,0)	5,0 (0,0-5,0)	4,0 (0,0-5,0)	4,0 (0,0-5,0)
Osenčenje struge	rs	-	-	RHQ	1 (0-2)	1 (0-2)	2 (0-2)	1 (0-2)
Nad vodo viseče veje	rob	-	-	RHQ	1 (0-2)	1 (0-2)	1 (0-2)	1 (0-2)
Izpostavljene velike korenine ob bregu	bbr	-	-	RHQ	1 (0-2)	1 (0-2)	1 (0-2)	1 (0-2)
Podvodne drevesne korenine	bur	-	-	RHQ	1 (0-2)	0 (0-2)	1 (0-2)	1 (0-2)
Padla drevesa	bft	-	-	RHQ	1 (0-2)	1 (0-2)	1 (0-2)	1 (0-2)

Nadaljevanje.

Continued.

Nadaljevanje preglednice 1.

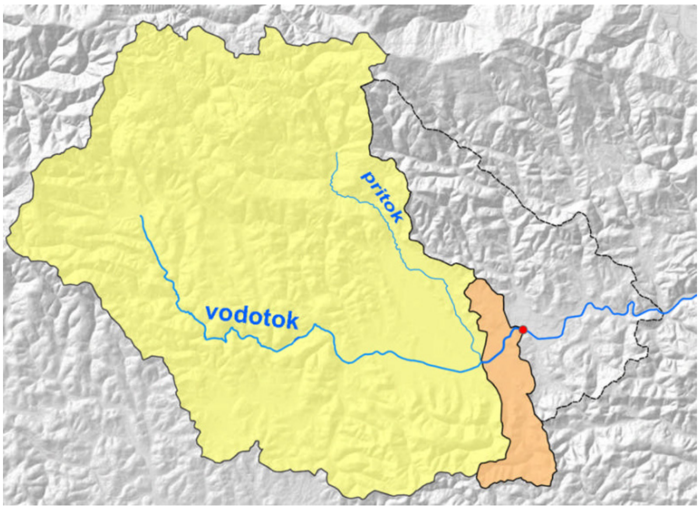
Table 1 continued.

Okoljska spremenljivka	Oznaka	Enota	Transformacija	Skupina	Mediana (razpon)* Slovenija	Alpe	Dinaridi	Panonska nižina
Veliko leseno plavje	cd	-	-	RHQ	1 (0-2)	1 (0-2)	1 (0-2)	1 (0-2)
Tipi tokov vzdolž 500 m	cf	-	-	RHQ	5 (2-9)	6 (2-8)	5 (2-9)	4 (2-8)
Značilnosti vzdolž 500 m	ff	-	-	RHQ	3 (0-11)	4 (0-11)	3 (0-11)	2 (0-7)
Pomembne značilnosti vzdolž 500 m	fsi	-	-	RHQ	1 (0-8)	2 (0-8)	1 (0-8)	1 (0-5)
Zamašenost struge z vegetacijo**	ccv	-	-	RHQ	0 (0-1)**	0 (0-1)**	0 (0-1)**	0 (0-0)**
Umetni material brega	bam	-	-	RHM	2,5 (0,0-60,0)	2,8 (0,0-36,0)	1,3 (0,0-60,0)	4 (0,0-50,0)
Spremembe brega	bm	-	-	RHM	4,5 (0,0-70,0)	4,0 (0,0-42,0)	4,0 (0,0-70,0)	8,0 (0,0-70,0)
Umetni substrat struge**	cam	-	-	RHM	0 (0-10)**	0 (0-3)**	0 (0-10)**	0 (0-3)**
Spremembe struge	cm	-	-	RHM	0 (0-50)	0 (0-9)	0 (0-50)	0 (0-20)**
Umetni profili bregov	ba	-	-	RHM	2,0 (0,0-5,0)	2,0 (0,0-5,0)	1,8 (0,0-5,0)	2,2 (0,0-5,0)
Jezovi	sd	-	-	RHM	0 (0-5)	0 (0-5)	0 (0-5)	0 (0-3)
Mostovi	sb	-	-	RHM	0 (0-5)	1 (0-5)	0 (0-5)	0 (0-4)
Pregazi**	sf	-	-	RHM	0 (0-2)**	0 (0-2)**	0 (0-2)	0 (0-0)**
Jezbice**	sde	-	-	RHM	0 (0-3)**	0 (0-2)**	0 (0-3)**	0 (0-0)**
Izravnava struge	cmr	-	-	RHM	0 (0-2)	0 (0-2)**	0 (0-2)	0 (0-2)
Zastoj vode zaradi jezu	cmi	-	-	RHM	0 (0-2)	0 (0-2)	0 (0-2)	0 (0-2)
Urbane površine (NPP)	URB_SC	%	arcsin√x	Raba tal	0 (0-100)	0 (0-73)	0 (0-100)	4 (0-84)
Intenzivno kmetijstvo (NPP)	I-AG_SC	%	arcsin√x	Raba tal	16 (0-100)	0 (0-100)	15 (0-84)	42 (0-92)
Ekstenzivno kmetijstvo (NPP)	NI-AG_SC	%	arcsin√x	Raba tal	10 (0-100)	12 (0-100)	9 (0-100)	9 (0-76)
Naravne površine (NPP)	NAT_SC	%	arcsin√x	Raba tal	58 (0-100)	69 (0-100)	62 (0-100)	32 (0-92)
Urbane površine (SPP)	URB_C	%	arcsin√x	Raba tal	1 (0-41)	0 (0-7)	1 (0-41)	3 (0-6)
Intenzivno kmetijstvo (SPP)	I-AG_C	%	arcsin√x	Raba tal	10 (0-58)	1 (0-27)	13 (0-44)	19 (2-58)
Ekstenzivno kmetijstvo (SPP)	NI-AG_C	%	arcsin√x	Raba tal	12 (0-55)	9 (0-55)	13 (0-45)	12 (4-42)
Naravne površine (SPP)	NAT_C	%	arcsin√x	Raba tal	72 (1-100)	86 (17-100)	71 (1-100)	64 (24-94)

* - pri nemih spremenljivkah skupine tipologija (brez enote) navajamo število vzorcev, ki smo jih pri binarnem kodiranju označili z »1«; ** - izločene spremenljivke zaradi nizke pogostosti pojavljanja.

* - for dummy variables number of sites coded as »1« is given; ** - variables excluded from further analysis due to low occurrence frequency.

V četrtem delu raziskave smo uporabili spremenljivke rabe tal. Za ugotavljanje povezave spremenljivk rabe tal z drugimi okoljskimi spremenljivkami ter združbami bentoških nevretenčarjev smo uporabili dve velikostni ravni območja prispevnih površin. Vsakemu mestu vzorčenja smo določili območje skupnih prispevnih površin (SPP) in območje neposrednih prispevnih površin (NPP). SPP smo določili kot območje celotne prispevne površine vodotoka od mesta vzorčenja gorvodno do izvira (Slika 14). NPP smo določili od mesta vzorčenja gorvodno do sotočja s pomembnejšim (stranskim) pritokom, ki najbolj neposredno vpliva na mesto vzorčenja. Območja NPP in SPP smo določili na podlagi kartografskega sloja hidrogeografskih območij (HGO, IV. red natančnosti, Monitoring kakovosti …, 2007). Na obeh velikostnih ravneh smo za vsako mesto vzorčenja določili rabo tal iz kartografskega sloja pokrovnosti tal Corine Land Cover (Corine …, 2007). Za vsako območje smo izračunali štiri okoljske spremenljivke rabe tal in jih izrazili kot deleže: naravnih površin (CLC razredi 3, 4 in 5), urbanih površin (CLC razred 1), površin z ekstenzivno kmetijsko rabo (CLC kategorije 2.3.1, 2.4.3 in 2.4.4) in površin z intenzivno kmetijsko rabo (CLC kategorije 2.1, 2.2, 2.4.1 in 2.4.2). Območja prispevnih površin in rabo tal na njih smo določili s programom Arc GIS 9.3 (Hiller, 2007).



Slika 14. Skica območij skupnih prispevnih površin (rumeno in oranžno) in neposrednih prispevnih površin (oranžno) mesta vzorčenja (rdeča točka) vodotoka (Pavlin, 2012: 44).

Figure 14. A sketch of a catchment area (orange and yellow) and subcatchment area (orange) of a river-sampling site (marked in red) (Pavlin, 2012: 44).

V zadnjem delu raziskave smo preverili še povezanost kombinacij že prej analiziranih morfoloških spremenljivk z združbami bentoških nevretenčarjev. Kombinacije smo ustvarili s seštevanjem posameznih spremenljivk (Preglednica 2). Uporabili smo kombinacije posameznih spremenljivk, kot so predvidene v sklopu metode SIHM ter novo ustvarjene kombinacije.

Preglednica 2. Kombinacije morfoloških spremenljivk, uporabljene v analizi, z oznakami in izračunom. Za oznake posameznih spremenljivk glej preglednico 1.

Table 2. The combinations of morphological variables with their codes and calculation. For individual variable's codes see Table 1.

Kombinacija spremenljivk	**Oznaka**	**Izračun**
Lastnosti bregov*	Sc_bf1	bnm+bf+btv+bfv+bn+bbr+bur+bft
Lastnosti struge*	Sc_cf1	cnm+cft+ct+cv+cd+cf+ccv
Lastnosti obrežnega predela*	Sc_rf1	rl+rt+rs+rob
Značilnosti vzdolž 500 m*	Sc_f1	fsi+ff
Spremembe bregov*	Sc_bmo1	bam+bm+ba
Spremembe struge*	Sc_cmo1	cam+cm+sd+sb+sf+sde+cmr+cmi
Lastnosti in spremembe bregov	Sc_bank1	Sc_bf1+Sc_bmo1
Lastnosti in spremembe struge	Sc_chan1	Sc_cf1+Sc_cmo1
Drevesne značilnosti	tree1	rt+rs+rob+bbr+bur+bft+cd
Drevesne značilnosti, struktura vegetacije in raba tal na bregu	trees1	tree1+rl+btv+bfv
Vsa vegetacija	treesV1	trees1+cv+ccv
Značilnosti struge prevladujoče	chan_11	cnm+cft+ct
Značilnosti struge prevladujoče in pestrost	chan_21	chan_11+cf+ff
Značilnosti struge vzdolž 500 m	chan_31	chan_21+fsi
Značilnosti brega prevladujoče ožje	bank_11	bnm+bf
Značilnosti brega prevladujoče širše	bank_21	bank_11+bn
Značilnosti brega prevladujoče širše in pestrost	bank_31	bank_21+ff
Umetne strukture	A_st_1	sd+sb+sf+sde
Raba tal	landuse1	lu+rl

* - uporabljene v metodi SIHM

* - used in SIHM method

2.2.1.4 STATISTIČNE ANALIZE

2.2.1.4.1 Analiza povezanosti spremenljivk rabe tal in drugih skupin okoljskih spremenljivk z združbami bentoških nevretenčarjev

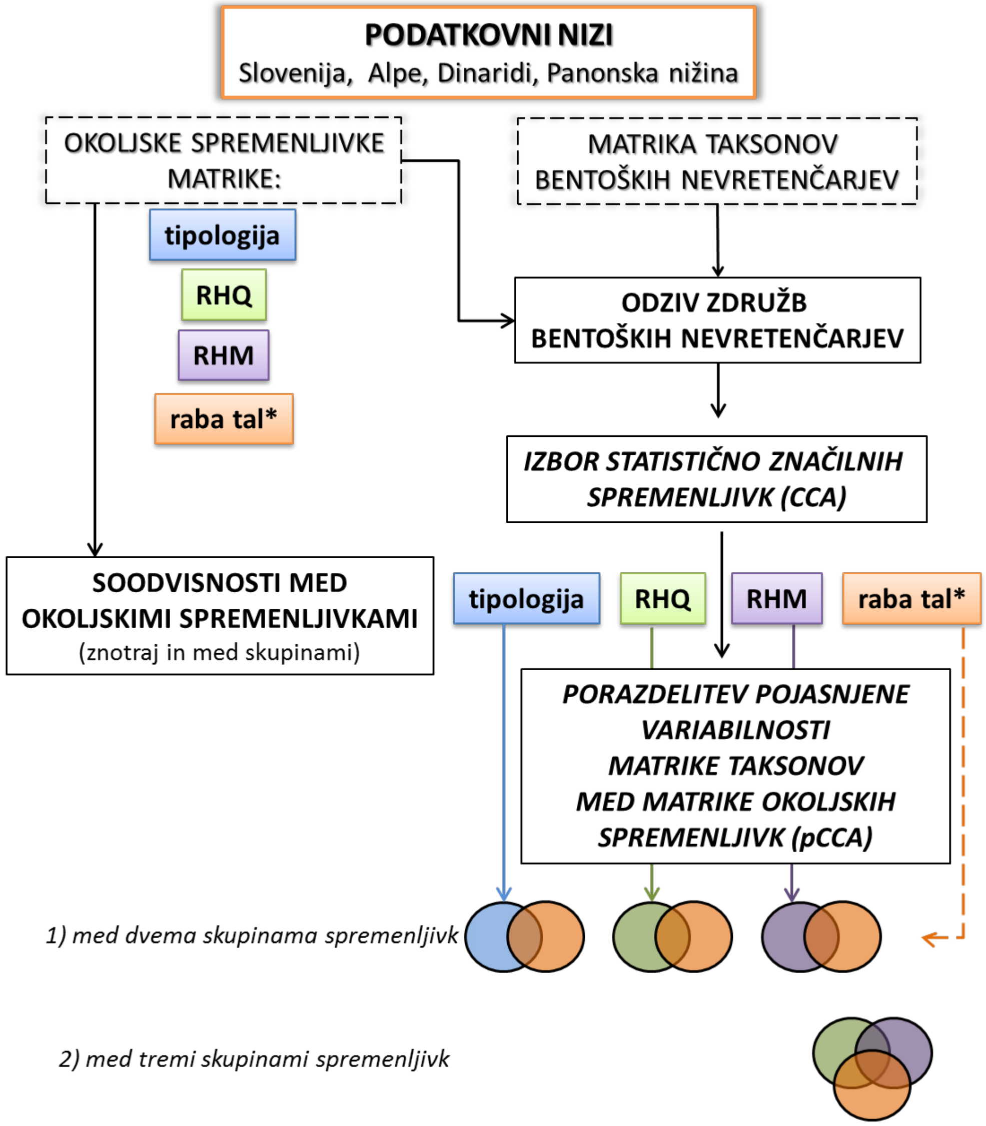
Pri analizi povezanosti spremenljivk rabe tal ter drugih skupin okoljskih spremenljivk z združbami bentoških nevretenčarjev smo uporabili enako zaporedje statističnih analiz kot v prvem delu raziskave, ko smo raziskovali povezanost med skupinami okoljskih spremenljivk tipologija, RHQ in RHM z združbami bentoških nevretenčarjev. Uporabili smo enake podatkovne nize: Slovenija (302 mest vzorčenja), ekoregija Alpe (93 mest vzorčenja), ekoregija Dinaridi (129 mest vzorčenja) in ekoregija Panonska nižina (73 mest vzorčenja). Za vsak posamezni niz podatkov smo uredili matriko taksonov bentoških nevretenčarjev in matrike okoljskih spremenljivk (tipologija, RHQ in RHM). Poleg tega smo uporabili še matriko okoljskih spremenljivk raba tal (Preglednica 1). Vsem okoljskim spremenljivkam brez spremenljivk skupine rabe tal smo že ocenili razpon vrednosti ter delež ničelnih podatkov (pogostost pojavljanja) ter pri skupinah RHQ in RHM uporabili le spremenljivke, zabeležene pri več kot 10 % mest vzorčenja. Po enakem kriteriju, ki je veljal za spremenljivke skupin RHQ in RHM, nismo izločili nobene spremenljivke skupine raba tal. Soodvisnosti med vrednostmi okoljskih spremenljivk smo za vse štiri podatkovne nize določili na podlagi izračuna neparametričnega koeficienta korelacije rangov (Spearmanov korelacijski koeficient, r_{Sp}) s programskim paketom SPSS (IBM ..., 2012).

Za ugotavljanje povezav med skupinami okoljskih spremenljivk in variabilnostjo združb bentoških nevretenčarjev (variabilnostjo taksonomske sestave in številčnosti taksonov) smo uporabili gradientne metode (ter Braak in Prentice, 1988). Z gradientnimi metodami na podlagi matrike taksonov in matrik(e) okoljskih spremenljivk poiščemo tak okoljski gradient, ki najbolje pojasnjuje variabilnost matrike taksonov (ter Braak, 1987, ter Braak in Prentice, 1988). Pred analizami z gradientnimi metodami smo okoljske spremenljivke pretvorili s primernimi transformacijskimi enačbami (Legendre in Legendre, 1998; Lepš in Šmilauer, 2003), (preglednica 1). Vrednosti okoljskih spremenljivk skupine raba tal smo določili v deležih, katerih vsota na posameznem mestu vzorčenja znaša 100 %, zato smo jih pretvorili s funkcijo $\arcsin\sqrt{x}$. S tem smo zmanjšali vpliv zelo številčnih oziroma dominantnih taksonov na rezultate analiz (Clarke in Warwick, 2001; Jongman in sod., 2005).

Matriko taksonov smo že v prvem delu za vsak podatkovni niz analizirali z indirektno gradientno metodo - korespondenčno analizo z odstranjenim trendom (angl. Detrended Correspondence Analysis, DCA, Hill in Gauch, 1980), da bi lahko izbrali primerno direktno gradientno metodo za naše analize. Primarni gradienti analize DCA so bili vedno daljši od dveh standardnih deviacij, zato smo izbrali metodo, ki predpostavlja unimodalen odziv taksonov na okoljske gradiente. Za ugotavljanje odnosov med združbami bentoških nevretenčarjev ter matrikami okoljskih spremenljivk smo uporabili kanonično korespondenčno analizo (CCA) (ter Braak in Prentice, 1988) in parcialno kanonično korespondenčno analizo (pCCA) (Borcard in sod., 1992). Za preveritev povezave spremenljivk skupine raba tal z drugimi skupinami okoljskih spremenljivk ter združbami bentoških nevretenčarjev smo najprej s CCA ocenili pojasnjevalno sposobnost variabilnosti združb bentoških nevretenčarjev za spremenljivke rabe tal v primerjavi z ostalimi okoljskimi spremenljivkami. Nato smo s CCA po metodi izbiranja spremenljivk z vključevanjem značilnih spremenljivk za vse podatkovne nize izbrali statistično značilne spremenljivke iz skupine raba tal (za skupine okoljskih spremenljivk tipologija, RHQ in RHM smo uporabili že izbrane značilne spremenljivke; slika 15). Ob določanju statistično značilnih spremenljivk smo uporabili permutacijski test Monte Carlo (999 naključnih neomejenih permutacij) ter pri testiranju upoštevali Bonferronijevo korekcijo ($\alpha = 0{,}05/n$; n je število testiranj). Nato smo uporabili metodo pCCA za določitev pojasnjene variabilnosti matrike taksonov s spremenljivkami ene matrike okoljskih spremenljivk, medtem ko smo vpliv spremenljivk drugih matrik okoljskih spremenljivk odstranili. Z analizo pCCA smo pojasnjeno variabilnost matrike taksonov razdelili na t. i. presečni del in disjunktni del. Disjunktni del pojasnjene variabilnosti matrike taksonov smo statistično značilno ($p < 0,05$) pojasnili s posamezno od obravnavanih skupin okoljskih spremenljivk, presečni del pojasnjene variabilnosti pa z dvema ali več obravnavanimi skupinami okoljskih spremenljivk. Z metodo pCCA smo za vsak podatkovni niz variabilnost matrike taksonov porazdelili med:

- dve skupini okoljskih spremenljivk: a) raba tal in tipologija, b) raba tal in RHQ in c) raba tal in RHM (Slika 15);
- tri skupine okoljskih spremenljivk: raba tal, RHQ in RHM.

Za analize z direktnimi in indirektnimi ordinacijskimi metodami smo uporabili programski paket CANOCO 5 (ter Braak in Šmilauer, 2012); vedno smo uporabili podatke o vseh prisotnih taksonih ter izbrali možnost »downweighting of rare species«, s katero smo zmanjšali vpliv redkih taksonov na rezultate analiz (Lepš in Šmilauer, 2003).



Slika 15. Koraki analiznega postopka povezav med skupinami okoljskih spremenljivk in združbami bentoških nevretenčarjev. CCA - kanonična korespondenčna analiza, pCCA parcialna kanonična korespondenčna analiza; * - nova matrika spremenljivk glede na prvi del analiz. Za skupine spremenljivk glej preglednico 1.

Figure 15. Analytical procedure in the analyses of relationships among environmental variable groups and benthic invertebrate assemblages. CCA - Canonical Correspondence Analysis; pCCA – partial Canonical Correspondence Analysis; * - new variable matrix regarding the first part of analyses. For variable groups see Table 1.

2.2.1.4.2 Analiza povezanosti kombinacij morfoloških spremenljivk z združbami bentoških nevretenčarjev

Primerjali smo povezanost združb bentoških nevretenčarjev s posameznimi morfološkimi spremenljivkami in njihovimi kombinacijami. Na podlagi predhodnih analiz smo se odločili preveriti povezanost s kombinacijami spremenljivk le na regionalni ravni, torej na treh podatkovnih nizih (Alpe, Dinaridi in Panonska nižina). Analizo smo izvedli z metodo CCA s programskim paketom CANOCO 5; vedno smo uporabili podatke o vseh prisotnih taksonih ter izbrali možnost »downweighting of rare species«. Primerjavo med pojasnjenimi deleži variabilnosti združb bentoških nevretenčarjev, ki smo jih pojasnili s posameznimi spremenljivkami ali kombinacijami spremenljivk, smo s pomočjo programskega paketa SPSS (IBM ..., 2012) izvedli z izrisom grafikonov kvartilov ter statistično značilnost razlik preverili z neparametričnim Mann-Whitney testom (2 skupini) ali Kruskal-Wallis testom (3 skupine).

2.2.2 Rezultati

2.2.2.1 Povezanost spremenljivk rabe tal ter drugih skupin okoljskih spremenljivk z združbami bentoških nevretenčarjev

2.2.2.1.1 Korelacije med okoljskimi spremenljivkami

Med okoljskimi spremenljivkami skupine raba tal in ostalimi skupinami okoljskih spremenljivk smo ugotovili več statistično značilnih soodvisnosti ($p < 0{,}05$, preglednica 3-6). Močne soodvisnosti ($r_{Sp} > 0{,}7$) spremenljivk rabe tal smo ugotovili večinoma le znotraj skupine raba tal, in sicer za vse podatkovne nize. Močno negativno soodvisnost med deležem intenzivnega kmetijstva in naravnih površin v SPP smo ugotovili v vodotokih Slovenije ($r_{Sp} = -0{,}88$), ekoregije Dinaridi ($r_{Sp} = -0{,}81$) in ekoregije Panonska nižina ($r_{Sp} = 0{,}94$). V vodotokih ekoregije Alpe smo ugotovili močno negativno soodvisnost med deležem neintenzivnega kmetijstva in naravnih površin v SPP ter močni pozitivni soodvisnosti med deležem urbanih površin v NPP in v SPP ter med deležem intenzivnega kmetijstva v NPP in v SPP. Izjemoma smo močno soodvisnost ugotovili med spremenljivkami rabe tal in tipologije v vodotokih ekoregije Panonska nižina med velikostnim razredom vodotoka in deležem intenzivnega kmetijstva v SPP in deležem naravnih površin v SPP.

Srednje močne soodvisnosti ($0,5 < r_{Sp} < 0,7$) smo med spremenljivkami rabe tal ugotovili v vseh podatkovnih nizih. Med spremenljivkami rabe tal in spremenljivkami tipologije smo v vodotokih Slovenije ugotovili srednje močno pozitivno soodvisnost med deležem urbanih površin v SPP in velikostnim razredom vodotoka ter negativne soodvisnosti med deležem urbanih površin v SPP in padcem struge ter deležem intenzivnega kmetijstva v SPP in ekoregijo Alpe ali nadmorsko višino. V vodotokih ekoregije Alpe je bil delež urbanih površin v SPP koreliran pozitivno z velikostnim razredom vodotoka in negativno s padcem struge, delež intenzivnega kmetijstva v SPP negativno z nadmorsko višino, delež ekstenzivnega kmetijstva v SPP negativno z vplivom kraškega izvira in delež naravnih površin pozitivno z nadmorsko višino in vplivom kraškega izvira. V vodotokih ekoregije Panonska nižina je bil velikostni razred vodotoka pozitivno koreliran z deležem urbanih površin v SPP, padec struge pa negativno z deležem urbanih površin v SPP. V vodotokih ekoregije Dinaridi smo med spremenljivkami rabe tal in spremenljivkami tipologije ugotovili samo šibke ($r_{Sp} < 0,5$) soodvisnosti (Preglednica 5). Prav tako so bile vse statistično značilne soodvisnosti med spremenljivkami tipologije in rabe tal v NPP šibke v vseh podatkovnih nizih.

Med spremenljivkami rabe tal in spremenljivkami RHQ ali RHM smo v vodotokih Slovenije, ekoregije Alpe in ekoregije Dinaridi ugotovili le šibke soodvisnosti. V vodotokih Panonske nižine smo v analizi s spremenljivkami RHQ ugotovili srednje močne negativne soodvisnosti med deležem urbanih površin v NPP in izpostavljenimi velikimi koreninami ob bregu, deležem urbanih površin v SPP in osenčenjem struge, nad vodo visečimi vejami, izpostavljenimi velikimi koreninami ob bregu, podvodnimi drevesnimi koreninami ter deležem naravnih površin v SPP in osenčenjem struge. Pozitivno pa je bil koreliran delež intenzivnega kmetijstva v SPP z osenčenjem struge. V analizi z RHM spremenljivkami smo ugotovili pozitivno soodvisnost med deležem urbanih površin v SPP ter umetnim materialom brega in umetnimi profili bregov.

Preglednica 3. Statistično značilne korelacije (Spearmanov korelacijski koeficient; $p < 0,05$) med okoljskimi spremenljivkami v vodotokih Slovenije; za pojasnila oznak okoljskih spremenljivk glej Preglednico 1; vrednosti > 0,50 so natisnjene krepko.

Table 3. Statistically significant Spearman's correlations ($p < 0,05$) for each combination of the environmental variables in Slovenian rivers; for environmental variable codes see Table 1; values > 0.50 are in bold.

	URB_SC	**I.AG_SC**	**NI.AG_SC**	**NAT_SC**	**URB_C**	**I.AG_C**	**NI.AG_C**	**NAT_C**
ER3.11	0.20	0.44		-0.37	0.33	0.47	0.12	-0.43
ER4	-0.11	-0.35		0.21	-0.22	**-0.59**	-0.14	0.47
ER5				0.13		0.13		
Size_cl	0.40	0.15		-0.20	**0.55**	0.13		
Kspring	-0.12	-0.20		0.22	-0.15	-0.19	-0.29	0.26
Intermit								
Alt	-0.14	-0.42		0.26	-0.19	**-0.53**		0.40
Slope	-0.34	-0.30		0.31	**-0.52**	-0.43		0.32
bnm	-0.31	-0.29		0.40	-0.40	-0.37	-0.18	0.37
bf	-0.23	-0.15		0.23	-0.23	-0.21		0.22
cnm		-0.31		0.29	-0.15	-0.45	-0.17	0.42
cft		-0.25		0.18		-0.38		0.25
ct	-0.21	-0.20		0.30	-0.18	-0.26	-0.22	0.29
rl	-0.28	-0.22		0.33	-0.21	-0.25	-0.24	0.29
btv	-0.19	-0.19		0.23	-0.13	-0.25	-0.23	0.29
bfv	-0.14			0.17		-0.17	-0.16	0.21
cv								
lu	-0.30	-0.29		0.40	-0.22	-0.31	-0.27	0.36
bn	-0.19			0.14	-0.13	-0.13		0.12
rt	-0.19	-0.21		0.26	-0.21	-0.27	-0.15	0.27
rs	-0.22	0.12	0.16		-0.29	0.17	0.16	-0.23
rob	-0.21		0.15		-0.25	0.15	0.18	-0.19
bbr	-0.21		0.11		-0.20	0.23		-0.17
bur		0.21		-0.12	-0.12	0.29		-0.24
bft	-0.29			0.19	-0.30			
cd	-0.22			0.19	-0.22			
cf	-0.18	-0.31		0.28	-0.24	-0.30		0.23
ff	-0.30	-0.22		0.32	-0.35	-0.26	-0.13	0.25
fsi	-0.35	-0.27		0.32	-0.42	-0.29		0.23
ccv								
bam	0.33			-0.23	0.31		0.13	
bm	0.40	0.16		-0.31	0.36	0.12	0.17	-0.18
cam								
cm	0.12							
ba	0.31			-0.23	0.36			
sd								
sb	0.19			-0.17	0.12			
sf	-0.15							
sde								
cmr	0.21			-0.16	0.16			-0.13
cmi								
URB_SC		0.22		-0.50	**0.59**	0.22	0.17	-0.25
I.AG_SC	0.22			**-0.69**	0.30	**0.62**	0.17	**-0.51**
NI.AG_SC				-0.29			0.30	-0.13

Nadaljevanje.

Continued.

Nadaljevanje preglednice 3.

Table 3 continued.

	URB_SC	**I.AG_SC**	**NI.AG_SC**	**NAT_SC**	**URB_C**	**I.AG_C**	**NI.AG_C**	**NAT_C**
NAT_SC	-0.50	**-0.69**	-0.29		-0.41	**-0.50**	-0.35	**0.53**
URB_C	**0.59**	0.30		-0.41		0.32	0.22	-0.35
I.AG_C	0.22	**0.62**		-0.50	0.32		0.33	**-0.88**
NI.AG_C	0.17	0.17	0.30	-0.35	0.22	0.33		**-0.67**
NAT_C	-0.25	**-0.51**	-0.13	**0.53**	-0.35	**-0.88**	**-0.67**	

Preglednica 4. Statistično značilne korelacije (Spearmanov korelacijski koeficient; p < 0,05) med okoljskimi spremenljivkami v vodotokih ekoregije Alpe; za pojasnila oznak okoljskih spremenljivk glej Preglednico 1; vrednosti > 0,50 so natisnjene krepko.

Table 4. Statistically significant Spearman's correlations (p < 0,05) for each combination of the environmental variables in rivers of the ecoregion Alps; for environmental variable codes see Table 1; values > 0.50 are in bold.

	URB_SC	**I.AG_SC**	**NI.AG_SC**	**NAT_SC**	**URB_C**	**I.AG_C**	**NI.AG_C**	**NAT_C**
Size_cl	0.48	0.33		-0.29	**0.59**	0.28		
Kspring		-0.38		0.36	-0.21	-0.46	**-0.53**	**0.57**
Alt		-0.48		0.40	-0.25	**-0.67**	-0.42	**0.55**
Slope	-0.43	-0.41		0.32	**-0.56**	-0.46		0.24
bnm	-0.38			0.36	-0.40	-0.22		0.25
bf					-0.22			
cnm		-0.29		0.32	-0.22	-0.38	-0.34	0.39
cft		-0.24		0.24		-0.32		
ct			-0.22	0.24	-0.22	-0.23	-0.29	0.31
rl	-0.33	-0.24		0.36	-0.29	-0.23	-0.31	0.34
btv	-0.28	-0.29		0.43	-0.30	-0.31	-0.38	0.42
bfv				0.23			-0.29	0.33
cv								
lu	-0.35	-0.36	-0.21	0.46	-0.39	-0.31	-0.41	0.45
bn	-0.21							
rt	-0.23	-0.24	-0.21	0.29	-0.28	-0.24	-0.23	0.31
rs							0.36	-0.33
rob							0.27	-0.25
bbr						0.21		
bur				-0.21				
bft								
cd								
cf		-0.26		0.21	-0.22	-0.22	-0.22	0.24
ff					-0.28			
fsi	-0.34	-0.24	-0.23	0.35	-0.49	-0.28		0.25
bam	0.38			-0.29	0.34			
bm	0.38			-0.29	0.31			-0.21
cm								
ba	0.24				0.26			
sd								
sb								
cmi								
URB_SC		0.43		-0.50	**0.70**	0.41		-0.25
I.AG_SC	0.43			**-0.61**	**0.53**	**0.81**	0.27	**-0.51**
NI.AG_SC				-0.49			0.39	-0.28
NAT_SC	-0.50	**-0.61**	-0.49		-0.49	**-0.55**	-0.47	**0.58**
URB_C	**0.70**	**0.53**		-0.49		0.46		-0.37
I.AG_C	0.41	**0.81**		**-0.55**	0.46		0.42	**-0.69**
NI.AG_C		0.27	0.39	-0.47		0.42		**-0.92**
NAT_C	-0.25	**-0.51**	-0.28	**0.58**	-0.37	**-0.69**	**-0.92**	

Preglednica 5. Statistično značilne korelacije (Spearmanov korelacijski koeficient; p < 0,05) med okoljskimi spremenljivkami v vodotokih ekoregije Dinaridi; za pojasnila oznak okoljskih spremenljivk glej Preglednico 1; vrednosti > 0,50 so natisnjene krepko.

Table 5. Statistically significant Spearman's correlations (p < 0,05) for each combination of the environmental variables in rivers of the ecoregion Dinaric western Balkan; for environmental variable codes see Table 1; values > 0.50 are in bold.

	URB_SC	I.AG_SC	NI.AG_SC	NAT_SC	URB_C	I.AG_C	NI.AG_C	NAT_C
Size_cl	0.35		-0.19		0.42			
Kspring								
Intermit								
Alt			0.25			-0.19	0.18	
Slope	-0.27			0.29	-0.40	-0.17		
bnm	-0.23	-0.25		0.43	-0.29	-0.19	-0.25	0.30
bf	-0.25			0.25				
cnm	-0.24	-0.25		0.38	-0.32	-0.28		0.32
cft							0.20	
ct	-0.34	-0.19		0.35	-0.26		-0.19	0.25
rl	-0.32	-0.18		0.32	-0.40		-0.21	0.20
btv					-0.19		-0.19	0.21
bfv								
cv					0.20			
lu	-0.40	-0.25	-0.18	0.43	-0.37	-0.17	-0.19	0.24
bn								
rt				0.20	-0.19			
rs	-0.23				-0.21			
rob								
bbr	-0.24		0.19		-0.22			
bur								
bft	-0.33			0.24	-0.28			
cd	-0.22			0.23	-0.21			
cf	-0.25	-0.20		0.25	-0.19			
ff	-0.33	-0.27		0.37	-0.28	-0.19		0.18
fsi	-0.29	-0.18		0.25	-0.30			
bam	0.22			-0.21			0.20	
bm	0.36	0.19		-0.37	0.28		0.26	-0.24
cm				-0.21				
ba	0.34			-0.36	0.30		0.19	
sd								
sb			0.19	-0.26			0.19	
sf		0.18						
cmr	0.37			-0.32	0.22			
cmi								
URB_SC				**-0.53**	**0.65**	0.22	0.23	-0.30
I.AG_SC				**-0.64**	0.22	0.47		-0.36
NI.AG_SC				-0.37			0.42	-0.27
NAT_SC	**-0.53**	**-0.64**	-0.37		-0.47	-0.41	-0.29	0.48
URB_C	**0.65**	0.22		-0.47		0.41	0.37	-0.50
I.AG_C	0.22	0.47		-0.41	0.41		0.27	**-0.81**
NI.AG_C	0.23		0.42	-0.29	0.37	0.27		**-0.69**
NAT_C	-0.30	-0.36	-0.27	0.48	-0.50	**-0.81**	**-0.69**	

Preglednica 6. Statistično značilne korelacije (Spearmanov korelacijski koeficient; p < 0,05) med okoljskimi spremenljivkami v vodotokih ekoregije Panonska nižina; za pojasnila oznak okoljskih spremenljivk glej Preglednico 1; vrednosti > 0,50 so natisnjene krepko.

Table 6. Statistically significant Spearman's correlations (p < 0,05) for each combination of the environmental variables in rivers of the ecoregion Pannonian lowland; for environmental variable codes see Table 1; values > 0.50 are in bold.

	URB_SC	**I.AG_SC**	**NI.AG_SC**	**NAT_SC**	**URB_C**	**I.AG_C**	**NI.AG_C**	**NAT_C**
Size_cl					**0.63**	**-0.71**	-0.25	**0.77**
Alt		-0.32		0.25		-0.38		0.27
Slope	-0.26				**-0.52**	0.39	0.30	-0.48
bnm	-0.29				-0.26			
bf								
cnm	0.31				0.47	-0.35		0.32
cft					0.47	-0.43		0.34
ct								
rl				0.25	0.24			
btv								
bfv	-0.38		0.26					
cv								
lu					0.34	-0.25		0.30
bn	-0.31							
rt	-0.28							
rs	-0.42	0.24	0.27		**-0.64**	**0.56**		**-0.55**
rob	-0.49		0.32		**-0.68**	0.45		-0.42
bbr	**-0.51**		0.29		**-0.63**	0.35		-0.29
bur	-0.30		0.27		**-0.64**	0.45		-0.38
bft	-0.32				-0.50	0.34		
cd	-0.32		0.28		-0.37	0.30		-0.27
cf								
ff								
fsi	-0.36				-0.35	0.28		-0.29
bam	0.45				0.50			
bm	0.47				0.43			
ba	0.36	-0.25			**0.55**	-0.37		0.36
sd						0.24		-0.31
sb	0.38		-0.33					
cmr								
cmi								
URB_SC				-0.32	0.37	-0.23		
I.AG_SC				**-0.63**	-0.33	0.37		-0.33
NI.AG_SC					-0.25			
NAT_SC	-0.32	**-0.63**			0.24	-0.33	-0.29	0.35
URB_C	0.37	-0.33	-0.25	0.24		**-0.55**		0.50
I.AG_C	-0.23	0.37		-0.33	**-0.55**			**-0.94**
NI.AG_C				-0.29				-0.45
NAT_C		-0.33		0.35	0.50	**-0.94**	-0.45	

2.2.2.1.2 Odnosi med okoljskimi spremenljivkami in variabilnostjo združb bentoških nevretenčarjev

Med vodotoki posameznih podatkovnih nizov smo ugotovili različna razmerja med stopnjami variabilnosti združb bentoških nevretenčarjev, ki smo jih pojasnili z istimi okoljskimi spremenljivkami (Preglednica 7). Največ variabilnosti združb bentoških nevretenčarjev smo pojasnili s tipološkimi spremenljivkami ali spremenljivkami RHQ: v vodotokih Slovenije s spremenljivkami ekoregija Alpe, padec struge ter tipi tokov na popisnih točkah, v vodotokih ekoregije Alpe padec struge, v vodotokih ekoregije Dinaridi s spremenljivko naravni substrat struge ter v Panonski nižini s spremenljivko tipi tokov na popisnih točkah. Izmed spremenljivk rabe tal smo večinoma pojasnili več variabilnosti združb bentoških nevretenčarjev s spremenljivkami v SPP kot v NPP. Največ variabilnosti smo pojasnili z deležem intenzivnega kmetijstva v SPP (Slovenija, Dinaridi), deležem naravnih površin v SPP (Alpe) in deležem urbanih površin v SPP (Panonska nižina). Glede na najbolj pojasnjevalne okoljske spremenljivke smo ugotovili visoko pojasnjevalno sposobnost (> 0,7) za spremenljivke rabe tal v SPP v vodotokih ekoregije Alpe, srednjo (>0,5) do visoko pojasnjevalno sposobnost za skoraj vse spremenljivke rabe tal v SPP v vodotokih Slovenije in ekoregije Panonska nižina ter nizko pojasnjevalno sposobnost za spremenljivke rabe tal v SPP v vodotokih ekoregije Dinaridi ter vse spremenljivke rabe tal v NPP v vodotokih Slovenije in posameznih ekoregij.

Od osmih spremenljivk rabe tal smo z metodo izbiranja izbrali tri do štiri spremenljivke, s katerimi smo statistično značilno ($P < 0,05$) pojasnili variabilnost združb bentoških nevretenčarjev v posameznem podatkovnem nizu (Preglednica 7). Po štiri spremenljivke smo izbrali v vodotokih Slovenije, ekoregije Dinaridi in ekoregije Panonska nižina. V vodotokih ekoregije Alpe smo izbrali tri spremenljivke. Vse izbrane spremenljivke rabe tal so bile deleži v SPP.

Preglednica 7. Razmerje med variabilnostjo združb bentoških nevretenčarjev, pojasnjeno s posamezno okoljsko spremenljivko in variabilnostjo združb bentoških nevretenčarjev, pojasnjeno z okoljsko spremenljivko, najbolj pojasnjevalno za združbe v vodotokih posameznih podatkovnih nizov (Slovenija, Alpe, Dinaridi, Panonska nižina). Razmerje je podano za analizo vseh okoljskih spremenljivk skupaj ter po posameznih skupinah okoljskih spremenljivk (skupina). Izbrane okoljske spremenljivke po metodi izbiranja iz vsake skupine okoljskih spremenljivk so označene z zvezdico (*). Morfološke spremenljivke, ki so bile pred analizo izločene, so označene z /.

Table 7. Ratios between the benthic invertebrate assemblage variability explained by each environmental variable and the most explanatory environmental variable in Slovenian rivers and rivers of the ecoregions Alps, Dinaric western Balkan, and Pannonian Lowland. The ratio is given together for all variables and separately for each environmental group. Variables that were forward selected from each variable group are marked with asterics (*). Morphological variables, excluded prior to analysis, are marked with /.

		Slovenija		Alpe		Dinaridi		Panonska nižina	
Okoljska spremenljivka	**Skupina**	**skupaj**	**skupina**	**skupaj**	**skupina**	**skupaj**	**skupina**	**skupaj**	**skupina**
Regija: »Nižinska«	tipologija	0,63	0,63*	-	-	-	-	-	-
Ekoregija: Alpe	tipologija	1,00	1,00*	-	-	-	-	-	-
Ekoregija: Dinaridi	tipologija	0,44	0,44	-	-	-	-	-	-
Velikostni razred vodotoka	tipologija	0,63	0,63*	0,67	0,67*	0,40	0,46*	0,94	1,00*
Vpliv kraškega izvira	tipologija	0,38	0,38*	0,73	0,73*	0,53	0,62*	-	-
Presihanje	tipologija	0,19	0,19*	-	-	0,33	0,38*	-	-
Nadmorska višina*	tipologija	0,44	0,44*	0,73	0,73*	0,20	0,23	0,88	0,94*
Padec struge*	tipologija	1,00	1,00*	1,00	1,00*	0,87	1,00*	0,53	0,56
Naravni material brega	RHQ	0,50	0,50*	0,40	0,60	0,47	0,47	0,29	0,29
Značilnosti brega	RHQ	0,25	0,25	0,33	0,50*	0,40	0,40	0,29	0,29
Naravni substrat struge	RHQ	0,88	0,88*	0,53	0,80	1,00	1,00*	0,76	0,76
Tipi tokov na popisnih točkah	RHQ	1,00	1,00*	0,67	1,00*	0,93	0,93*	1,00	1,00*
Značilnosti struge	RHQ	0,13	0,13	0,27	0,40	0,33	0,33	0,24	0,24
Raba zemljišča v 5 m pasu	RHQ	0,25	0,25	0,40	0,60	0,33	0,33	0,53	0,53
Struktura vegetacije vrha brega	RHQ	0,19	0,19	0,40	0,60	0,27	0,27*	0,35	0,35
Struktura vegetacije površine brega	RHQ	0,13	0,13*	0,27	0,40	0,20	0,20*	0,29	0,29
Tipi vegetacije v strugi	RHQ	0,38	0,38*	0,27	0,40	0,53	0,53*	0,65	0,65*
Raba zemljišča v 50 m pasu	RHQ	0,25	0,25*	0,47	0,70	0,40	0,40	0,47	0,47
Naravni profili bregov	RHQ	0,13	0,13	0,27	0,40*	0,20	0,20	0,24	0,24
Sklenjenost krošenj	RHQ	0,19	0,19	0,33	0,50	0,27	0,27	0,35	0,35

Nadaljevanje.

Continued.

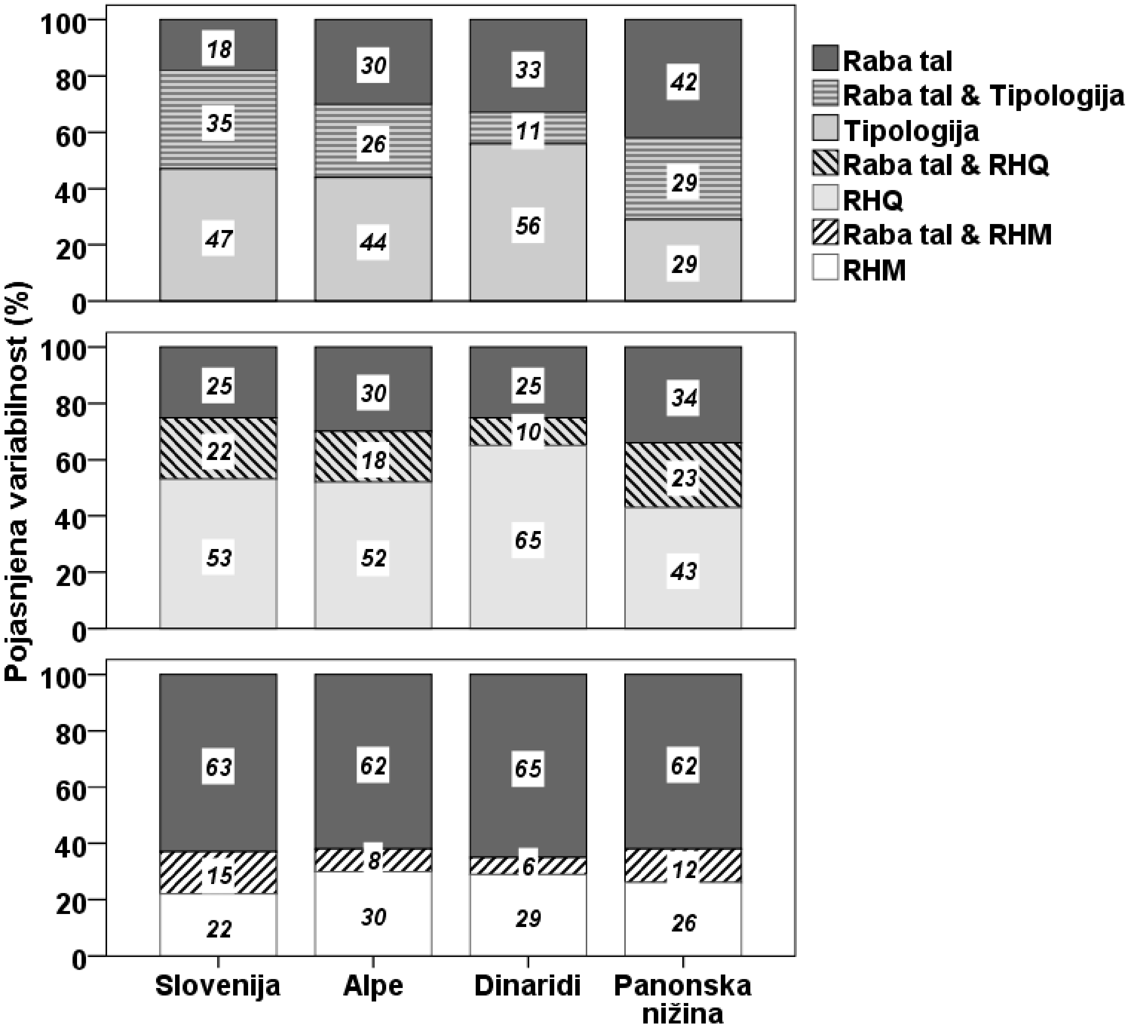
Nadaljevanje preglednice 7.

Table 7 continued.

		Slovenija		Alpe		Dinaridi		Panonska nižina	
Okoljska spremenljivka	**Skupina**	**skupaj**	**skupina**	**skupaj**	**skupina**	**skupaj**	**skupina**	**skupaj**	**skupina**
Osenčenje struge	RHQ	0,25	0,25*	0,27	0,40*	0,40	0,40	0,65	0,65*
Nad vodo viseče veje	RHQ	0,25	0,25	0,27	0,40	0,40	0,40	0,53	0,53
Izpostavljene velike korenine ob bregu	RHQ	0,25	0,25*	0,20	0,30*	0,27	0,27	0,53	0,53
Podvodne drevesne korenine	RHQ	0,31	0,31*	0,13	0,20	0,27	0,27	0,76	0,76*
Padla drevesa	RHQ	0,19	0,19	0,20	0,30	0,40	0,40*	0,47	0,47
Veliko leseno plavje	RHQ	0,13	0,13	0,27	0,40	0,27	0,27	0,29	0,29
Tipi tokov vzdolž 500 m	RHQ	0,56	0,56*	0,53	0,80*	0,53	0,53	0,29	0,29
Značilnosti vzdolž 500 m	RHQ	0,44	0,44*	0,33	0,50	0,67	0,67	0,35	0,35
Pomembne značilnosti vzdolž 500 m	RHQ	0,56	0,56*	0,67	1,00*	0,47	0,47	0,29	0,29
Zamašenost struge z vegetacijo	RHQ	/	/	/	/	/	/	/	/
Umetni material brega	RHM	0,13	0,50*	0,27	0,80	0,20	0,60	0,47	1,00*
Spremembe brega	RHM	0,19	0,75*	0,33	1,00*	0,20	0,60	0,29	0,63
Umetni substrat struge	RHM	/	/	/	/	/	/	/	/
Spremembe struge	RHM	0,13	0,50	0,13	0,40	0,20	0,60	/	/
Umetni profili bregov	RHM	0,19	0,75*	0,33	1,00	0,33	1,00*	0,47	1,00*
Jezovi	RHM	0,06	0,25*	0,20	0,60*	0,20	0,60	0,24	0,50
Mostovi	RHM	0,06	0,25	0,20	0,60	0,20	0,60	0,29	0,63*
Pregazi	RHM	/	/	/	/	0,27	0,80	/	/
Jezbice	RHM	/	/	/	/	/	/	/	/
Izravnava struge	RHM	0,13	0,50	/	/	0,13	0,40	0,24	0,50
Zastoj vode zaradi jezu	RHM	0,25	1,00*	0,33	1,00*	0,27	0,80*	0,29	0,63
Urbane površine (NPP)	Raba tal	0,24	0,27	0,39	0,43	0,27	0,71	0,39	0,44
Intenzivno kmetijstvo (NPP)	Raba tal	0,46	0,52	0,45	0,50	0,23	0,62	0,44	0,50
Ekstenzivno kmetijstvo (NPP)	Raba tal	0,06	0,06	0,13	0,15	0,16	0,43	0,26	0,30
Naravne površine (NPP)	Raba tal	0,39	0,44	0,51	0,57	0,34	0,90	0,28	0,31
Urbane površine (SPP)	Raba tal	0,52	0,58*	0,75	0,83*	0,34	0,90*	0,89	1,00*
Intenzivno kmetijstvo (SPP)	Raba tal	0,89	1,00*	0,76	0,85*	0,38	1,00*	0,79	0,89*
Ekstenzivno kmetijstvo (SPP)	Raba tal	0,30	0,33*	0,76	0,85	0,21	0,57*	0,34	0,39*
Naravne površine (SPP)	Raba tal	0,69	0,77*	0,90	1,00*	0,29	0,76*	0,62	0,70*

2.2.2.1.3 Porazdelitev variabilnosti združb bentoških nevretenčarjev med spremenljivke rabe tal in ostale skupine spremenljivk

Ugotavljali smo, kolikšen del variabilnosti združb bentoških nevretenčarjev lahko pojasnimo samo s spremenljivkami rabe tal v primerjavi s spremenljivkami drugih skupin (tipologija, RHQ in RHM) ter kolikšen del skupno s spremenljivkami rabe tal in spremenljivkami vsake od drugih skupin. Disjunktni deleži so bili pojasnjeni le s spremenljivkami posamezne skupine, presečni pa s spremenljivkami dveh skupin. Disjunktni deleži, pojasnjeni s spremenljivkami rabe tal, so se razlikovali glede na drugo skupino okoljskih spremenljivk ter glede na obravnavani podatkovni niz (Slika 16). S spremenljivkami rabe tal pojasnjeni disjunktni deleži so bili 18-42 % pri analizi s spremenljivkami tipologije, 25-34 % pri analizi s spremenljivkami RHQ in 62-65 % pri analizi s spremenljivkami RHM. Presečni deleži pojasnjene variabilnosti združb bentoških nevretenčarjev s skupino spremenljivk rabe tal so bili skoraj v vseh primerih nižji od disjunktnih deležev skupine spremenljivk rabe tal. Presečni deleži so bili najvišji (11-35 %) pri analizi s spremenljivkami tipologije, 10-23 % pri analizi s spremenljivkami RHQ in zelo nizki (6-15 %) pri analizi s spremenljivkami RHM. Najvišje presečne deleže smo opazili v vodotokih Slovenije in ekoregije Panonska nižina, najnižje pa v vodotokih ekoregije Dinaridi.

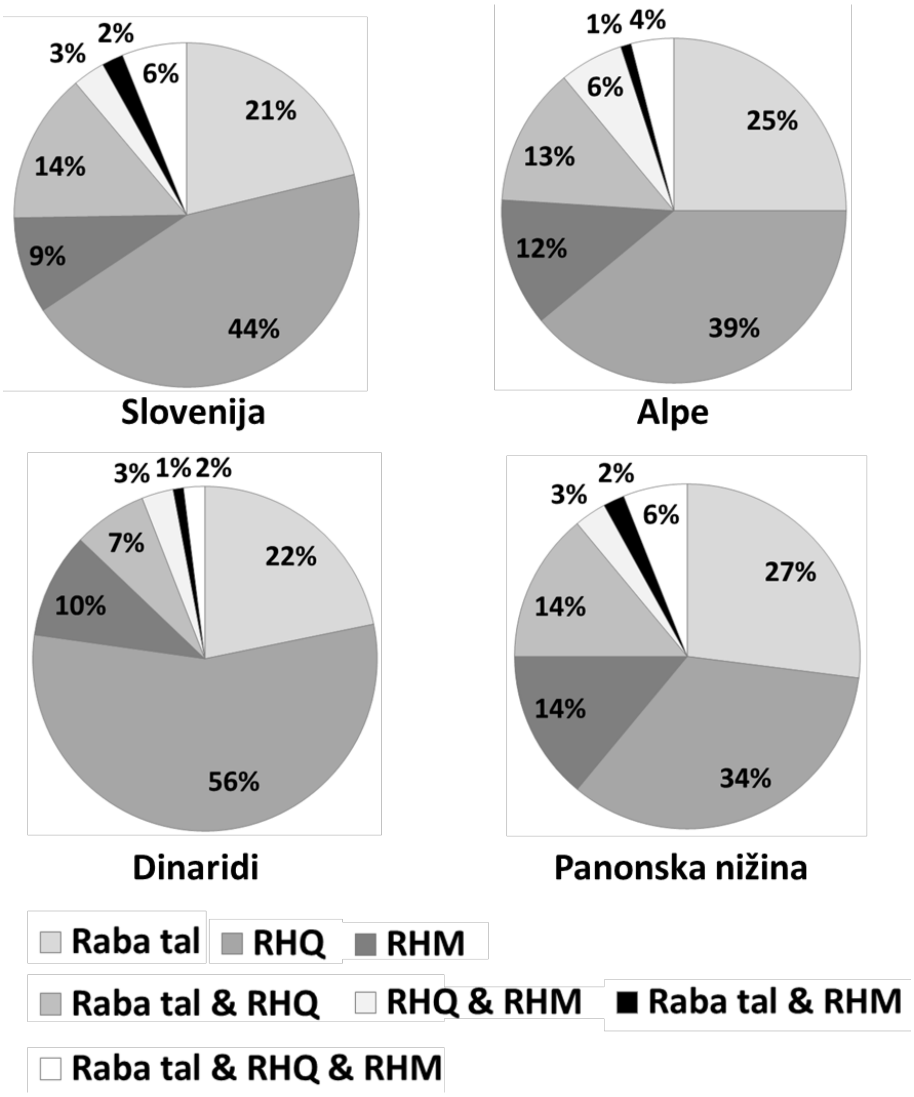


Slika 16. Porazdelitev variabilnosti združb bentoških nevretenčarjev v vodotokih posameznih podatkovnih nizov (Slovenija, Alpe, Dinaridi, Panonska nižina) med spremenljivke skupine raba tal ter spremenljivke skupin Tipologija, RHQ in RHM. Disjunktni in presečni deleži so podani kot odstotek pojasnjene variabilnosti.

Figure 16. Benthic invertebrate assemblages' variability in Slovenian rivers and rivers of the ecoregions Alps, Dinaric western Balkan, and Pannonian Lowland, partitioned between variables of the land use group and the groups typology, RHQ and RHM. Each groups' common and unique contributions are presented.

2.2.2.1.4 Porazdelitev variabilnosti združb bentoških nevretenčarjev med spremenljivke skupin raba tal, RHQ in RHM

Ugotavljali smo porazdelitev disjunktnih in presečnih deležev pojasnjene variabilnosti združb bentoških nevretenčarjev med skupine spremenljivk raba tal, RHQ in RHM (Slika 17). Disjunktni deleži so bili pojasnjeni le s spremenljivkami posamezne skupine, presečni pa s spremenljivkami dveh ali treh skupin. V vseh podatkovnih nizih smo ugotovili podobno razporeditev disjunktnih deležev obravnavanih skupin spremenljivk. Največje disjunktne deleže smo ugotovili za spremenljivke RHQ (34-56 %), srednje za spremenljivke rabe tal (21-27 %) in najnižje za spremenljivke RHM (9-14 %). Delež variabilnosti združb bentoških nevretenčarjev, ki smo ga pojasnili samo s spremenljivkami RHQ in RHM, ne pa tudi rabe tal, je bil največji v vodotokih ekoregije Dinaridi (69 %) in najnižji v vodotokih ekoregije Panonska nižina (51 %). Presečni delež, ki smo ga hkrati pojasnili z vsemi skupinami spremenljivk, je bil največji v vodotokih Slovenije in ekoregije Panonska nižina (6 %) in najnižji v vodotokih ekoregije Dinaridi (2 %).



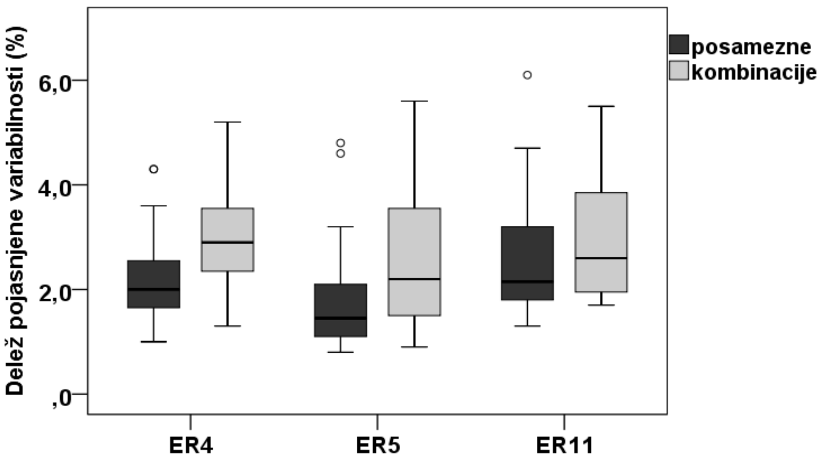
Slika 17. Presečni in disjunktni deli pojasnjene variabilnosti združb bentoških nevretenčarjev v vodotokih posameznih podatkovnih nizov (Slovenija, Alpe, Dinaridi, Panonska nižina). Variabilnost združb bentoških nevretenčarjev smo pojasnili in porazdelili med tri skupine okoljskih spremenljivk: Raba tal, RHQ in RHM.

Figure 17. Common and unique contributions to the explained benthic invertebrate assemblage variability in Slovenian rivers and rivers of the ecoregions Alps, Dinaric western Balkan, and Pannonian Lowland. The assemblage variability was divided among three groups of environmental variables: land use, RHQ and RHM.

2.2.2.2 Povezanost kombinacij morfoloških spremenljivk z združbami bentoških nevretenčarjev

Delež pojasnjene variabilnosti združb bentoških nevretenčarjev s kombinacijami morfoloških spremenljivk je bil statistično značilno višji od deleža, ki smo ga pojasnili s posameznimi spremenljivkami (Slika 18), v vodotokih ekoregije Alpe (U^8 = 152; P = 0,013) in ekoregije Dinaridi (U^5 = 178,5; P = 0,029), ne pa tudi ekoregije Panonska nižina (U^5 = 212,5; P = 0,245). Delež pojasnjene variabilnosti vseh kombinacij spremenljivk se med vodotoki različnih ekoregij ni razlikoval (Kruskal-Wallis χ^2 = 1,218; P = 0,544), delež pojasnjene variabilnosti vseh posameznih spremenljivk pa je bil statistično značilno različen med vodotoki ekoregije Alpe in Dinaridi (U^5 = 264; P = 0,015) in ekoregije Dinaridi in Panonska nižina (U^5 = 195,5; P < 0,001), medtem ko se med vodotoki ekoregije Alpe in Panonska nižina ni razlikoval (U^5 = 319,5; P = 0,234). Med kombinacijami morfoloških spremenljivk smo največ variabilnosti v vseh treh ekoregijah pojasnili s tremi spremenljivkami značilnosti struge (Preglednica 8). S kombinacijami morfoloških spremenljivk smo večinoma pojasnili več variabilnosti kot s posameznimi morfološkimi spremenljivkami, le v vodotokih ekoregije Panonska nižina smo ugotovili najvišji delež pojasnjene variabilnosti pri posamezni spremenljivki Tipi tokov na popisnih točkah (6,1 %), višji od tistega pri najbolj pojasnjevalni kombinaciji spremenljivk (Značilnosti struge prevladujoče, 5,5 %). V vodotokih ekoregije Alpe in Dinaridi smo največ variabilnosti pojasnili s kombinacijo spremenljivk Značilnosti struge vzdolž 500 m (5,4 % in 5,6 %).

[8] Mann-Whitney U-test.



Slika 18. Razporeditev deležev pojasnjene variabilnosti (%) združb bentoških nevretenčarjev za posamezne morfološke spremenljivke in njihove kombinacije za tri podatkovne nize (ER4 – ekoregija Alpe, ER5 – ekoregija Dinaridi, ER11 – ekoregija Panonska nižina).

Figure 18. The distribution of portion of the benthic invertebrate assemblage variability (%), explained by individual morphological variables and their combinations, for three datasets (ER4 - ecoregion Alps, ER5 – ecoregion Dinaric western Balkan, ER11 – ecoregion Pannonian lowland).

Preglednica 8. Delež pojasnjene variabilnosti (%) združb bentoških nevretenčarjev za posamezne morfološke spremenljivke in njihove kombinacije (obravnava) za tri podatkovne nize. Morfološke spremenljivke, ki so bile pred analizo izločene, so označene z /.

Table 8. Portion of the benthic invertebrate assemblage variability (%), explained by individual morphological variables and their combinations, for three datasets. Morphological variables, excluded prior to analysis, are marked with /.

Morfološka spremenljivka	Obravnava	Delež pojasnjene variabilnosti (%)		
		Alpe	Dinaridi	Panonska nižina
Naravni material brega	posamezna	2,9	2,4	1,7
Značilnosti brega	posamezna	2,2	2,1	1,8
Naravni substrat struge	posamezna	3,6	4,8	4,6
Tipi tokov na popisnih točkah	posamezna	4,3	4,6	6,1
Značilnosti struge	posamezna	2,0	1,6	1,3
Raba zemljišča v 5 m pasu	posamezna	2,6	1,5	3,2
Struktura vegetacije vrha brega	posamezna	2,5	1,4	2,2
Struktura vegetacije površine brega	posamezna	1,8	1,1	1,9
Tipi vegetacije v strugi	posamezna	1,8	2,5	4,1
Raba zemljišča v 50 m pasu	posamezna	3,1	1,8	2,7
Naravni profili bregov	posamezna	1,7	0,8	1,5
Sklenjenost krošenj	posamezna	2,0	1,4	2,2
Osenčenje struge	posamezna	2,0	1,8	4,1
Nad vodo viseče veje	posamezna	1,6	1,8	3,4
Izpostavljene velike korenine ob bregu	posamezna	1,4	1,3	3,2
Podvodne drevesne korenine	posamezna	1,1	1,2	4,7
Padla drevesa	posamezna	1,2	1,8	3,0
Veliko leseno plavje	posamezna	1,8	1,4	1,9
Tipi tokov vzdolž 500 m	posamezna	3,5	2,4	1,8
Značilnosti vzdolž 500 m	posamezna	2,1	3,2	2,1
Pomembne značilnosti vzdolž 500 m	posamezna	4,3	2,1	1,9
Zamašenost struge z vegetacijo	posamezna	/	/	/
Umetni material brega	posamezna	1,7	1,0	2,7
Spremembe brega	posamezna	2,4	1,1	1,6
Umetni substrat struge	posamezna	/	/	/
Spremembe struge	posamezna	1,0	0,8	/
Umetni profili bregov	posamezna	2,0	1,7	2,8
Jezovi	posamezna	1,3	0,9	1,5
Mostovi	posamezna	1,5	1,0	2,0
Pregazi	posamezna	/	1,2	/
Jezbice	posamezna	/	/	/
Izravnava struge	posamezna	/	0,8	1,5
Zastoj vode zaradi jezu	posamezna	2,4	1,4	1,8
Lastnosti bregov	kombinacija	2,9	2,2	1,7
Lastnosti struge	kombinacija	4,0	4,1	4,7
Lastnosti obrežnega predela	kombinacija	2,7	1,6	3,1

Nadaljevanje.

Continued.

Nadaljevanje preglednice 8.

Table 8 continued.

Morfološka spremenljivka	**Obravnava**	**Delež pojasnjene variabilnosti (%)**		
		Alpe	**Dinaridi**	**Panonska nižina**
Značilnosti vzdolž 500 m	kombinacija	2,9	3,2	2,2
Spremembe bregov	kombinacija	2,1	1,1	2,0
Spremembe struge	kombinacija	1,6	0,9	2,0
Lastnosti in spremembe bregov	kombinacija	1,3	1,5	3,1
Lastnosti in spremembe struge	kombinacija	4,0	3,9	4,5
Drevesne značilnosti	kombinacija	1,8	1,9	3,2
Drevesne značilnosti, struktura vegetacije in raba tal na bregu	kombinacija	2,6	1,5	2,6
Vsa vegetacija	kombinacija	2,6	1,2	1,9
Značilnosti struge prevladujoče	kombinacija	5,0	5,4	5,5
Značilnosti struge prevladujoče in pestrost	kombinacija	5,0	5,6	5,1
Značilnosti struge vzdolž 500 m	kombinacija	5,2	5,6	5,0
Značilnosti brega prevladujoče ožje	kombinacija	3,1	2,9	1,8
Značilnosti brega prevladujoče širše	kombinacija	3,1	2,9	1,7
Značilnosti brega prevladujoče širše in pestrost	kombinacija	3,1	3,2	1,8
Umetne strukture	kombinacija	1,4	1,1	2,0
Raba tal	kombinacija	2,7	1,6	3,2

Slika 19. Motiv z mesta vzorčenja Kokra, Kranj

Figure 19. A theme from sampling site Kokra, Kranj

3 RAZPRAVA IN SKLEPI

3.1 RAZPRAVA

3.1.1 Povezava regionalnih pokrajinskih značilnosti z morfološkimi značilnostmi tekočih voda na lokalni ravni

Prisotnost in oblika morfoloških značilnosti tekočih voda oz. vodotokov na lokalni ravni sta odvisna od regionalnih pokrajinskih značilnosti - značilnosti višjih ravni (Frissel in sod., 1986; Poff, 1997). Z regionalnimi pokrajinskimi značilnostmi (tipološke spremenljivke) smo v vodotokih Slovenije pojasnili relativno majhen delež variabilnosti značilnosti kakovosti habitata na lokalni ravni (spremenljivke RHQ). Največji delež variabilnosti smo pojasnili s padcem struge, velikega pa tudi z velikostnim razredom vodotoka in pripadnostjo ekoregiji Alpe. Padec struge je že prepoznano posredno pomemben pri izoblikovanju morfoloških značilnosti struge (Allan, 2004), kar smo potrdili še z značilno soodvisnostjo med padcem in večino spremenljivk RHQ. Večji padec struge je večinoma prisoten v alpskih vodotokih in je povezan z močno energetskimi pretoki (Szoszkiewicz in sod., 2006). Tavzes in Urbanič (2009) sta za slovenske vodotoke, ki pripadajo ekoregiji Alpe, ugotovila tipične značilnosti kakovosti habitata alpskih vodotokov, zato je potrditev pomembnosti spremenljivke pripadnost ekoregiji Alpe v naši raziskavi pričakovana. Pomembnost velikostnega razreda vodotoka lahko povežemo delno s spremenjenostjo kakovosti rečnih habitatov, saj smo ugotovili negativno soodvisnost s spremenljivkami RHQ.

Glede na ugotovljeno povezanost med tipološkimi spremenljivkami in spremenljivkami RHQ smo pričakovali tudi povezavo s spremenljivkami sprememb habitata na lokalni ravni (spremenljivke RHM). Alpska območja z ozkimi in odmaknjenimi dolinami so v splošnem manj primerna za poselitev in bi zato pričakovali manj antropogenih sprememb. Vendar odmaknjenost postaja zanimiva za različne dejavnosti (npr. turizem, hidroelektrarne), za katere so lahko veliki pretoki in posledično nestabilnost struge alpskih vodotokov ovira. Zato so prisotne različne spremembe morfoloških značilnosti zaradi ureditev, utrditev bregov, mostov ter prečnih objektov (Bona in sod., 2008; Tavzes in Urbanič, 2009; Wyżga in sod., 2011). Nižinski vodotoki imajo večinoma širše obrežne pasove, povezane z velikimi poplavnimi ravnicami. Razvoj različnih dejavnosti na poplavnih ravnicah in v obrežnem pasu je vodil v zelo pogoste morfološke spremembe rečnih habitatov (Pedersen, 2009; Pedersen in Friberg, 2009), npr. zaradi izravnav ali poglobitev. Morfološke spremembe vodotokov torej pričakujemo neodvisno od regije, kar smo potrdili z ugotovljenim skoraj zanemarljivim deležem variabilnosti spremenljivk RHM, ki smo ga pojasnili s tipološkimi spremenljivkami. Kljub nizkem pojasnjenem deležu smo variabilnost spremenljivk RHM značilno pojasnili s padcem in velikostnim razredom vodotoka. Medtem ko je padec struge slovenskih vodotokov precej regionalno pogojen, pa velikostni razred vodotokov ni odvisen od regije. V hribovitih in nižinskih predelih namreč najdemo majhne vodotoke skupaj z izvirnimi predeli ter tudi večje vodotoke z izlivi. Z analizo soodvisnosti smo ugotovili povezanost med velikostnim razredom vodotokov in spremembami bregov. Vzrok je lahko večja antropogena aktivnost ob velikih vodotokih ter tako posledično družben pogled na velike vodotoke kot bolj ogrožajoče, z več vidne erozije in poplavnimi dogodki, kar se večinoma rešuje z ureditvami in utrditvami bregov.

3.1.2 Povezanost morfoloških značilnosti tekočih voda z združbami bentoških nevretenčarjev

Na podlagi podatkov tekočih voda v Sloveniji ter podatkov po posameznih ekoregijah smo preverili povezanost posameznih morfoloških značilnosti po metodi SIHM z združbami bentoških nevretenčarjev. Več variabilnosti združb bentoških nevretenčarjev smo v vodotokih Slovenije in posameznih ekoregij pojasnili z značilnostmi kakovosti rečnih habitatov (spremenljivke RHQ) kot z značilnostmi spremenjenosti rečnih habitatov (spremenljivke RHM). Med spremenljivkami RHQ smo enega največjih deležev pojasnjene variabilnosti združb bentoških nevretenčarjev ugotovili za spremenljivki prevladujoč tok in substrat struge, dejavnika, ki ju pogosto omenjajo kot pomembna za združbe vodnih organizmov (Richards in sod., 1993; Lammert in Allan, 1999; Sandin, 2003; Sandin in Johnson, 2004, Syrovátka in sod., 2009). Prevladujoč tok ima pomemben vpliv na substrat struge (Statzner in Higler, 1986; Poff in sod., 1997), vendar so redke raziskave, ki so obravnavale učinke obeh značilnosti, vodnega toka in substrata, pokazale delno različno povezanost z združbami bentoških nevretenčarjev (Urbanič in sod., 2005; Friberg in sod., 2009a; Sandin, 2009; Wyżga in sod., 2011). V raziskavi smo ugotovili le srednje dobro soodvisnost med obema spremenljivkama, poleg tega smo v vodotokih ekoregije Dinaridi potrdili pomembno, a različno povezanost obeh spremenljivk z združbami bentoških nevretenčarjev, saj sta bili kljub zelo majhni razliki v deležu pojasnjene variabilnosti obe spremenljivki izbrani v postopku izbiranja spremenljivk. Možen vzrok za različnost vpliva obeh spremenljivk je povezanost vodnega toka z združbami bentoških nevretenčarjev ne le preko zgradbe substrata, ampak tudi preko vpliva na vsebnost kisika in dostopnost hrane, poleg tega pa na organizme deluje neposredno s fizično silo. Zgradba substrata v strugi je poleg vodnega toka odraz tudi drugih dejavnikov (Wyzga in sod., 2011). Različni objekti lahko preprečujejo vzdolžno premeščanje sedimenta (Kondolf, 1997), upravljanje z obrežnim pasom pa lahko zmanjšuje ali pospešuje erozijo bregov ter vnos finega substrata iz prispevnega območja (Allan, 2004).

Značilnosti obrežne vegetacije pogosto vplivajo na habitatsko pestrost ter posledično zgradbo in delovanje združb vodnih organizmov (Cummins in sod., 1989; Bis in sod., 2000; Sandin, 2009). Po metodi SIHM so značilnosti obrežne vegetacije opisane z več spremenljivkami. V vodotokih Slovenije smo z vsemi spremenljivkami obrežne vegetacije pojasnili značilen a zelo majhen delež variabilnosti združb bentoških nevretenčarjev v primerjavi z najbolj pojasnjevalnimi spremenljivkami RHQ. Tudi z analizo po ekoregijah smo za spremenljivke obrežne vegetacije ugotovili manjši delež pojasnjene variabilnosti kot za najbolj pojasnjevalne spremenljivke RHQ. Spremenljivka senčenje se je izkazala kot pomembna v vodotokih vseh ekoregij, najbolj v vodotokih Panonske nižine in najmanj v vodotokih ekoregije Alpe. S senčenjem je povezana dostopnost svetlobe in temperatura vode (Hynes, 1970; Webb in sod., 2008; Julian in sod., 2011), posledično rast primarnih producentov (Schiller in sod., 2007; Bernot in sod., 2010), vsebnost kisika v vodi ter razgradnja organskih snovi (Odum, 1956; Lagrue in sod., 2011) ter tako zgradba habitatov in združb bentoških nevretenčarjev (Melody in Richardson, 2004; Haidekker in Hering, 2007). V vodotokih ekoregije Alpe so prisotni močni vodni tokovi, ki pogojujejo temperaturo vode ter hkrati omejujejo pritrjanje in rast primarnih producentov. Poleg tega je veliko alpskih vodotokov osenčenih večji del dneva že zaradi oblike doline (V) tudi brez obrežne vegetacije. Zato ima v alpskih vodotokih odstopanje v dostopnosti svetlobe na podlagi obrežne vegetacije manj vpliva na zgradbo habitata in posledično združbe bentoških nevretenčarjev kot v nižinskih vodotokih.

Med vodotoki različnih ekoregij smo ugotovili nekaj značilnih razlik med pomembnimi spremenljivkami RHQ. V vodotokih Panonske nižine so pomembne spremenljivke vegetacije (tipi vegetacije v strugi, podvodne korenine, izpostavljene korenine na bregu), saj v nižinskih vodotokih povečujejo habitatsko pestrost ob bregu ali v strugi ter nudijo zatočišča vodnim organizmom (Harrison in sod., 2004; Sandin in Johnson, 2004; Pinto in sod., 2006). V vodotokih ekoregije Alpe sta pomembni spremenljivki naravni material bregov in značilnosti bregov, kar v alpskih vodotokih povečuje habitatsko pestrost ter med sušami ali zelo visokimi pretoki služi kot zatočišče. Pomembne značilnosti vodotokov ekoregije Dinaridi so kombinacija tistih v alpskih in nižinskih vodotokih. Ugotovili smo namreč pomembnost tipov vegetacije v strugi tako kot v vodotokih Panonske nižine ter značilnosti bregov in struge tako kot v vodotokih Alp.

Glede na pomembnost spremenljivk RHQ ugotavljamo, da so združbe bentoških nevretenčarjev bolj povezane z vodnim tokom in substratom struge in bregov kot z vegetacijo v obrežnem pasu in v strugi, vendar med regijami obstajajo razlike in tudi izjeme, ki jih je treba upoštevati pri upravljanju z vodami. Trenutno je največkrat uporabljen pristop pri obnovah prav vzpostavitev obrežne vegetacije, ki ima lahko omejeno učinkovitost ob spremenjeni dinamiki vodnega toka in substrata (Greenwood in sod., 2012).

Antropogene spremembe rečnih habitatov so po metodi SIHM opisane s spremenljivkami RHM. Za vse spremenljivke RHM smo ugotovili vsaj za polovico manjši delež pojasnjene variabilnosti združb bentoških nevretenčarjev v primerjavi s spremenljivkami RHQ, še največjega v vodotokih Panonske nižine. Možno razlago bi lahko iskali v načinu popisa na terenu, saj lahko spremenljivke RHQ skoraj vedno uvrstimo v eno od možnih prisotnih kategorij, medtem ko so spremenljivke RHM redkeje razvrščene v kategorije, ki kažejo na njihovo prisotnost (Raven in sod., 1997; Tavzes in Urbanič, 2009). Vendar tudi za pogosteje prisotne spremenljivke RHM nismo ugotovili večjega deleža pojasnjene variabilnosti. Drugi možni vzrok je prilagojenost združb bentoških nevretenčarjev na habitatske razmere pred človekovim vplivom, ki so najverjetneje odvisne od regionalnih pokrajinskih dejavnikov, zato se lahko različno odzivajo na morfološke spremembe, ki pa so regionalno neodvisne. V vodotokih Slovenije je bila najpomembnejša spremenljivka zastoj vode zaradi jezu, ki je primarno povezana s hidrološkimi spremembami, vendar vključuje tudi spremembe značilnosti vodnega toka in odvisnih spremenljivk, kot npr. povečanje količine drobnega substrata (Kondolf, 1997; Poff in sod., 1997; Tavzes in Urbanič, 2009; Mueller in sod., 2011; Stefanidis in Stefanidis, 2012). Opažanja ustrezajo ugotovitvam Marzina in sod. (2012), da predstavlja prisotnost zajezitve enega glavnih dejavnikov obremenitev za oblikovanje združb rib in bentoških nevretenčarjev na ravni odseka. Z analizo po ekoregijah smo prav tako ugotovili, da je zastoj vode zaradi jezu ena izmed bolj pomembnih spremenljivk RHM, s čimer smo potrdili pomembnost hidroloških sprememb poleg morfoloških tudi na regionalni ravni.

V različnih evropskih raziskavah so kot najbolj tipično spremembo rečnih habitatov izpostavili izravnave in utrditve bregov vodotokov (Feld, 2004; Szoszkiewicz in sod., 2006). Že za vodotoke Slovenije, še bolj pa po ekoregijah smo kot najpomembnejše ugotovili spremenljivke RHM, povezane z bregovi: umetni profili bregov v vodotokih vseh ekoregij, v vodotokih Alp poleg te spremenljivke še sprememba bregov, v vodotokih Panonske nižine pa umetni material bregov. Naše ugotovitve se ujemajo z rezultati raziskave Erba in sod. (2006), kjer so ugotovili dobro soodvisnost med metrikami združb bentoških nevretenčarjev in kategorijami sprememb bregov (izravnave in utrditve). Utrditve in izravnave lahko vodijo v povečanje pretokov ter redkejšo prisotnost struktur zaradi usedanja substrata ob bregu in v strugi ter tako zmanjšanje habitatske pestrosti (Bona in sod., 2008). Vzrok za pomembnost umetnega materiala bregov v nižinskih vodotokih je v velikem odstopanju od naravnih razmer, saj na bregovih nižinskih vodotokov večinoma najdemo pesek ali zemljo (Szoszkiewicz in sod., 2006). Uporaba kamnometa za utrditve, torej večjih kamnov, poveča habitatsko pestrost, ki je lahko v tem primeru večja kot v razmerah brez antropogenega vpliva. Zaradi večje habitatske pestrosti se lahko poveča pestrost združbe bentoških nevretenčarjev zaradi novih taksonov, prisotnih na račun lokalno nenaravnega substrata (Townsend in Hildrew, 1994). Podobno si razlagamo ugotovljeno pomembnost mostov kot motnje v nižinskih vodotokih, saj velikokrat ob njihovi gradnji značilno spremenijo tudi bregove, poleg tega pa različni gradbeni material obleži v strugi in deluje kot spremenjen habitat. Ugotovitve na podlagi nižinskih vodotokov nakazujejo, da višja habitatska pestrost in pestrost združbe bentoških nevretenčarjev ni nujno odraz nespremenjenosti vodotokov.

3.1.3 Skupna povezanost regionalnih pokrajinskih dejavnikov in morfoloških značilnosti tekočih voda na lokalni ravni z združbami bentoških nevretenčarjev

Habitatske značilnosti na lokalni ravni tekočih voda oz. vodotokov so lahko odvisne od regionalnih pokrajinskih dejavnikov (višjih ravni), zato je pogosto njihova povezanost z združbami vodnih organizmov manj jasna (Richards in sod., 1997; Cortes in sod., 2009). Hierarhična organiziranost dejavnikov več ravni je pogosto obravnavana v raziskavah o povezanosti naravnih značilnosti in antropogenih sprememb z združbami rečnih organizmov, kjer je izpostavljena večja pomembnost dejavnikov višjih ravni (Roth in sod., 1996; Lammert in Allan, 1999) ali nižjih ravni (Ormerod in sod., 1993; Richards in sod., 1993; Heino in sod., 2004). Ugotovili smo podobno pojasnjevalno moč najboljših spremenljivk RHQ (lokalna raven) in najboljših tipoloških spremenljivk (višja raven) tako za vodotoke Slovenije kot vodotoke posameznih ekoregij z izjemo vodotokov ekoregije Alpe, kjer je bil delež pojasnjene variabilnosti z najboljšo tipološko spremenljivko (padec struge) kar za tretjino višji od deleža najboljših spremenljivk RHQ (prevladujoč tok, pomembne značilnosti vzdolž 500 m). Zelo podobne deleže variabilnosti smo pojasnili tudi posamezno s spremenljivkami obeh skupin (tipologija in RHQ) ter tako še dodatno potrdili ugotovitve nekaterih avtorjev, da so pomembne spremenljivke obeh ravni (Brosse in sod., 2003; Sandin, 2003; Johnson in sod., 2007). Presečni delež pojasnjene variabilnosti z obema skupinama spremenljivk je bil pomemben, a precej manjši od deležev, ki smo jih pojasnili s posamezno skupino. Z upoštevanjem tudi deleža pojasnjene variabilnosti spremenljivk RHQ s tipološkimi spremenljivkami ugotavljamo, da dejavniki višjih ravni do neke mere oblikujejo procese na nižjih ravneh ter da posledične morfološke značilnosti vplivajo na združbe tekočih voda, kar so potrdile tudi druge raziskave (Richards in sod., 1997; Verdonschot, 2006; Li in sod., 2012, Marzin in sod., 2012). Za razliko od omenjenih raziskav je v slovenskih vodotokih velik delež zgradbe združb bentoških nevretenčarjev odvisen od značilnosti kakovosti habitata ne glede na regionalne pokrajinske dejavnike.

Nasprotno od skupine spremenljivk RHQ smo samo s skupino spremenljivk RHM pojasnili zelo nizek delež variabilnosti združb bentoških nevretenčarjev v vodotokih Slovenije in posameznih ekoregij, prav tako pa tudi zelo nizek presečni delež s tipološkimi spremenljivkami. Vzrok je lahko v veliki pestrosti naravnih značilnosti vodotokov na obravnavanih ravneh ter hkrati regionalno neodvisna prisotnost različnih morfoloških sprememb. Kot smo že omenili pri analizi posameznih spremenljivk, so združbe bentoških nevretenčarjev prilagojene na habitatske razmere pred človekovim vplivom, zato se lahko različno odzivajo na enake morfološke spremembe v odvisnosti od regionalnih značilnosti. Delno smo hipotezo potrdili z večjim disjunktnim deležem pojasnjene variabilnosti v vodotokih posameznih ekoregij kot v vodotokih Slovenije.

3.1.4 Vodilna slika rečnih habitatov

Na podlagi morfoloških spremenljivk po metodi SIHM, ki smo jih prepoznali kot pomembne za zgradbo združb bentoških nevretenčarjev ali pri vrednotenju hidromorfološkega stanja tekočih voda, smo za štiri izmed glavnih evropskih regij določili vodilno sliko oz. potencialno naravno stanje habitatov tekočih voda oz. vodotokov. Ugotovili smo značilne razlike med rečnimi habitati alpske, nižinske, mediteranske in kraške regije. Največji okoljski gradient med referenčnimi mesti smo ugotovili za morfološke značilnosti, povezane z dinamiko vodnega toka in plavin. Vodni tok oblikuje strugo vodotoka in vpliva na značilnosti substrata ter prisotnost in obliko morfoloških tvorb (Poff in sod., 1997; Allan in Castillo, 2007). Razlike med alpskimi in nižinskimi vodotoki se pojavljajo predvsem zaradi razlik v topoloških značilnostih prispevnega območja (Szoszkiewicz in sod., 2006; Harnischmacher, 2007; Repnik Mah in sod., 2010). Topologija z geologijo prispevnega območja vpliva tudi na substrat bregov, posledica česar je v ozkih dolinah alpskih vodotokov velik delež substrata bregov v strugi zaradi vnašanja s plazovi. Z raziskavo smo potrdili razlike med alpskimi in nižinskimi vodotoki v vseh morfoloških spremenljivkah, ki so povezane z vodnim tokom in substratom. Za alpske vodotoke so značilni veliki kamni kot substrat struge in bregov, prevladujoči tip toka so nelomljeni stoječi valovi, pogosto je prisotnih 3-5 različnih tipov tokov ter pojavljanje morfoloških tvorb kot so brzice in tolmuni, prodišča, izpodjedeni bregovi in izpostavljene skale v strugi. Za nižinske vodotoke smo ugotovili, da je za substrat bregov značilna zemlja, substrat struge je gramoz, prevladujoč tok je rahlo valovanje ali gladki tok, prisotnih tipov tokov ter različnih morfoloških tvorb pa je zelo malo. Podobno so za nižinske vodotoke ugotovili tudi Szoszkiewicz in sod. (2006), da jih zaznamuje gladki tok ter gramoz, medtem ko so za alpske vodotoke najbolj pogosto ugotovili močne tokove in skale v strugi, vendar njihova analiza ni bila izvedena samo na neobremenjenih odsekih vodotokov.

Na podlagi določenih subekoregij po tipologiji vodotokov v Sloveniji (Urbanič, 2008b) smo vodotoke ekoregije Dinaridi razvrstili v dve morfološki skupini: mediteransko in kraško regijo. Med mediteranskimi in kraškimi vodotoki smo ugotovili značilne razlike, mediteranski vodotoki so bili v veliko spremenljivkah podobni alpskim, kraški pa nižinskim. V raziskavah, kjer so primerjali morfološke značilnosti mediteranskih vodotokov z vodotoki ostalih regij (Szoszkiewicz in sod., 2006; Feio in sod., 2014), so ugotovili značilne razlike v značilnostih rečnih habitatov v Mediteranski regiji v primerjavi z alpsko ali nižinsko. Podobnih raziskav za kraške vodotoke nismo našli. Mediteranski vodotoki se v nekaterih spremenljivkah značilno razlikujejo od ostalih obravnavanih regij (npr. značilnosti vzdolž 500 m), v precej spremenljivkah pa so podobni alpskim vodotokom (substrat struge in bregov, pestrost vodnega toka). Možen vzrok je podobno pester pretok alpskih in mediteranskih vodotokov zaradi močnega sezonskega značaja. Razlika v vrednostih spremenljivke prevladujoči vodni tok lahko nakazuje celo bolj hudourniški značaj mediteranskih vodotokov v primerjavi z alpskimi. Mediteranski tipi vodotokov so pogosto presihajoči in imajo vodo le v določenem obdobju (Boix in sod., 2010; Urbanič, 2011; Pace in sod., 2013; Feio in sod., 2014). Popisi po metodi SIHM se izvajajo v obdobju nizkih vodostajev, kar je lahko za mediteranske vodotoke tudi že v delno presihajočem obdobju, ko je na določenem delu struga že suha. Ob popisu stoječe vode v strugi ali suhe struge dobimo lahko nižje vrednosti spremenljivke prevladujoči vodni tok kot če je na celem odseku prisoten površinski tok vode. Občasna prisotnost močnih pretokov se odraža v višjih vrednostih spremenljivke značilnosti struge in bregov vzdolž 500 m, saj vključuje tudi izpodjedanje bregov, ter v nižjih vrednostih strukture vegetacije na površini brega, saj jo visoke vode periodično odnašajo. Za kraške vodotoke smo v primerjavi z alpskimi in mediteranskimi ugotovili bolj stabilne razmere z manjšim substratom bregov (večinoma pesek) in struge (večinoma gramoz) ter prevladujočim tokom rahlo valovanje, podobno kot smo opazili tudi za nižinske vodotoke. V morfološko skupino kraških vodotokov je vključenih veliko tipov vodotokov z vplivom kraškega izvira (Urbanič, 2011), zaradi katerega so spremembe pretoka večinoma počasne. Zato so lahko morfološke značilnosti kraških vodotokov podobne tistim v malih nižinskih vodotokih (< 1000 km^2), kjer je pretok prešibek za premikanje večjega substrata (Poff in sod., 1997). Kljub temu smo za kraške vodotoke ugotovili večjo pestrost tokov in značilnosti bregov in struge vzdolž 500 m kot za nižinske.

Drugi okoljski gradient, po katerem se ločijo referenčna mesta, so značilnosti obrežne in vodne vegetacije. Najvišje vrednosti vegetacije vrh brega, ki predstavljajo najbolj kompleksno vegetacijo, smo prepoznali pri alpskih in mediteranskih vodotokih, kjer vrednosti kažejo na prisotnost listopadnega ali mešanega gozda s kompleksno strukturo vegetacije. Za kraške in nižinske vodotoke smo ugotovili nižje vrednosti, torej bolj enostavno strukturo vegetacije z grmovjem, občasnim pojavljanjem gozda ter travniki. Ob rezultatih raziskave se postavlja vprašanje, ali te usmeritve res predstavljajo naravno stanje obrežne vegetacije. Referenčna mesta smo namreč izbrali na podlagi morfoloških sprememb, ki so vključene v indeksa RHM in HLM, nismo pa določili kriterijev na podlagi spremenljivk kakovosti rečnih habitatov, kamor spada tudi obrežna vegetacija. Po zgodovinskih podatkih je v obrežnem pasu večinoma prisoten listopadni gozd v vseh regijah, tudi ob kraških in nižinskih vodotokih, zato predpostavljamo, da so nižje vrednosti spremenljivk obrežne vegetacije posledica človekovega delovanja. Z namenom povečanja kmetijskih obdelovalnih površin se je v preteklosti in ponekod še v današnjem času spodbujalo krčenje obrežne vegetacije. Trend je bil sicer prisoten v vseh regijah, vendar se je zaradi strmih pobočij in nedostopnosti manj izrazil v alpskih vodotokih. Podobno kot za alpske vodotoke velja tudi za nekatere mediteranske vodotoke, na drugih vodotokih pa je bilo prisotno krčenje obrežne vegetacije zaradi kmetijskih praks v preteklosti, z opuščanjem kmetijstva pa so se površine kasneje zarasle (Keesstra in sod., 2005). Za vodilno sliko značilnosti obrežne vegetacije torej priporočamo upoštevanje tudi drugih kriterijev in ne le stanja na referenčnih mestih brez pomembnih antropogenih tvorb. Podobna dilema je pri spremenljivki tipi vegetacije v strugi, kjer smo opazili najvišje vrednosti v kraških vodotokih, vendar se niso značilno razlikovale od vrednosti v alpskih in mediteranskih vodotokih. Vodilno sliko vegetacije v strugi je še težje določiti, saj je njeno pojavljanje odvisno tako od hidravličnih sil in substrata struge kot tudi od senčenja ter koncentracije hranil (Suren in Riis, 2010; Julian in sod., 2011; Feld, 2013).

Vodilno sliko smo določili na podlagi današnjih razmer rečnih habitatov v odsotnosti človekovih vplivov, torej po prostorskem pristopu, ki je eden od boljših. Na slovenskih vodotokih je uporabljen pristop možen, saj je velik delež odsekov vodotokov še vedno pod minimalnim človekovim vplivom (Urbanič in Peterlin, 2007). Za katerikoli del upravljanja z vodami, naj bo to razvoj usmeritev za obnove, varovanje ali pa trajnostni razvoj še nespremenjenih odsekov, je najbolj pomembno razumevanje povezave z delovanjem ekosistema tekočih voda. Zato smo analize osnovali na morfoloških spremenljivkah, ki so povezane z združbami vodnih organizmov. Omejitev je predstavljala količina podatkov, ki smo jih lahko zbrali iz programov razvoja sistemov vrednotenja ekološkega stanja, tako da smo bili primorani se omejiti le na velike regije. Poleg tega so bili podatki z referenčnih mest v velikem deležu z mest na malih rekah (10-100 km^2), zato je pri prenosu rezultatov na večje vodotoke potrebna pazljivost. Na podlagi ugotovljene pestrosti nekaterih morfoloških značilnosti znotraj določenih morfoloških skupin predlagamo nadaljnje raziskave z možnimi delitvami teh skupin ob upoštevanju pomembnih dejavnikov višjih ravni (npr. velikostni razred vodotoka ali vpliv kraškega izvira; Pavlin in sod., 2011; Petkovska in Urbanič, 2014).

3.1.5 Primerjava povezanosti združb bentoških nevretenčarjev s hidromorfološkimi spremenljivkami različnih prostorskih ravni

Raba tal je povezana z različnimi obremenitvami ekosistemov tekočih voda oz. vodotokov na več ravneh (Allan, 2004; Matthaei in sod., 2010). Spremembo rabe tal lahko obravnavamo tudi kot hidromorfološko spremenljivko, saj je povezana s spremembo rečnih habitatov neposredno preko npr. izravnav, poglabljanja ali utrditev (Giller in Malmqvist, 1998; Bona in sod., 2008; Verdonschot, 2009) ter posredno zaradi sprememb v hidrološkem režimu in vnosu sedimenta (Towsend in sod., 2004; Poff in sod., 2006).

Spremembe rabe tal so povezane z značilnostmi površja (npr. padec struge, nadmorska višina) (Allan, 2004; Pedersen, 2009), v alpskih vodotokih z ožjimi dolinami je raba tal večinoma še vedno naravna (Buffagni in sod., 2009), medtem ko imajo nižinski vodotoki obsežne poplavne ravnice, ki se z manjšanjem padca večajo in postajajo tako bolj primerne za antropogeno rabo (Johnson in sod., 2006). V Sloveniji so tako razmere za poselitev in kmetovanje bolj primerne v Panonski nižini kot v Alpah (Petek, 2004). V vodotokih Slovenije smo ugotovili značilno manjšo prisotnost intenzivnega kmetijstva v ekoregiji Alpe kot v ekoregijah Dinaridi in Panonska nižina ter zmanjševanje z nadmorsko višino. Poleg tega smo po pričakovanjih ugotovili večjo prisotnost urbanih površin s povečevanjem prispevnega območja ter manjšanjem padca tako za vodotoki Slovenije kot tudi v vodotokih Alp in Panonske nižine.

V različnih raziskavah so izpostavili povezanost med hidromorfološkimi spremenljivkami višjih in nižjih prostorskih ravni (Richards in Host, 1994; Allan in sod., 1997; Diana in sod., 2006; Poff in sod., 2006; Buffagni in sod., 2009; Kail in sod., 2009). Najpogosteje obravnavane prostorske ravni so skupno prispevno območje, območje ob vodotokih do izvira ter območje ob vodotokih na določenem odseku (Allan, 2004). V raziskavo smo vključili spremenljivke rabe tal na ravni skupnega prispevnega območja (SPP) in neposrednega prispevnega območja (NPP). V vodotokih Slovenije in posameznih ekoregij smo boljše soodvisnosti ugotovili med spremenljivkami značilnosti habitata ter rabo tal v SPP kot v NPP, vendar so bile soodvisnosti v splošnem nizke. Srednje dobre soodvisnosti smo ugotovili le v vodotokih ekoregije Panonska nižina med deležem urbanih površin in površin z intenzivnim kmetijstvom ter značilnostmi obrežne vegetacije in spremembami bregov. Razlike v vplivih rabe tal glede na tip vodotoka so ugotovili tudi Kail in sod. (2009), ki so izpostavili tip velikih vodotokov, kjer je večji delež značilnosti habitata pojasnila raba tal poplavnih ravnic v SPP. Naši rezultati ne potrjujejo ugotovitev drugih avtorjev o pomembnem vplivu rabe tal v neposredni in skupni prispevni površini (Allan in sod., 1997) ali poplavnih ravnic na ravni odseka (Kail in sod., 2009). Najverjetnejša razlaga za ugotovljeno nizko soodvisnost je dejstvo, da je v Sloveniji prisotnih precej vodotokov s spremenjeno rabo tal v NPP ali SPP, vendar z ohranjeno obrežno vegetacijo. Ker imajo značilnosti obrežnega pasu precejšen vpliv na značilnosti rečnih habitatov na lokalni ravni (Nerbonne in Vondracek, 2001; Sponseller in sod., 2001; Stone in sod., 2005; Sandin, 2009), tudi nismo pričakovali dobre soodvisnosti spremenljivk RHQ in RHM z rabo tal v prispevni površini. Harding in sod. (1998) so ugotovili tudi vpliv časovnega zamika antropogenih sprememb. Pogosto so bili rečni habitati zaradi kmetijske rabe v NPP spremenjeni (izravnave, utrditve), opuščanje kmetijske rabe je privedlo do zaraščanja obrežnega pasu (Keesstra in sod., 2005), ostale antropogene spremembe rečnih habitatov pa so ostale in se približujejo naravnim značilnostim z določenim časovnim zamikom. Poleg tega spreminjanje rabe tal v prispevni površini morda še ni vplivalo na značilnosti rečnih habitatov, ki so posredno odvisne od hidrološkega režima ter sedimentacije (Allan, 2004; Kail in sod., 2009).

Delovanje hidromorfoloških spremenljivk na združbe bentoških nevretenčarjev je prepoznano na več prostorskih ravneh; na ravni prispevne površine raba tal, geologija in velikost prispevne površine (Allan, 2004; Death in Collier, 2009), na ravni odseka ali pododseka hidrološki režim, substrat ter obrežna vegetacija (Richards in sod., 1993; Lammert in Allan, 1999; Feld, 2013). Poleg tega spremenljivke različnih prostorskih ravni tudi sovplivajo, zaradi česar se postavlja vprašanje o najpomembnejši ravni za združbe bentoških nevretenčarjev ter tako tudi za upravljanje voda (Sandin, 2009; Wahl in sod., 2013). Za vodotoke Slovenije in posameznih ekoregij smo ugotovili večjo pomembnost spremenljivk RHQ na ravni odseka kot spremenljivk rabe tal v SPP ali NPP. Najmanj variabilnosti združb bentoških nevretenčarjev smo v primerjavi z najbolj pojasnjevalnimi spremenljivkami RHQ pojasnili v vodotokih ekoregije Dinaridi. Kljub temu, da je bil gradient deležev rabe tal v SPP krajši od gradienta v NPP, smo večji delež variabilnosti združb bentoških nevretenčarjev pojasnili s spremenljivkami rabe tal v SPP in s tem potrdili ugotovitve Pavlinove (2012). Raba tal je delno povezana z naravnimi pokrajinskimi značilnostmi (Allan, 2004; Petek, 2004), zato je bil pričakovano ugotovljen največji presečni delež (hkratni vpliv) pojasnjene variabilnosti združb bentoških nevretenčarjev s spremenljivkami rabe tal pri tipoloških spremenljivkah. S spremenljivkami RHQ smo ugotovili manjše presečne deleže, najnižje pa s spremenljivkami RHM. Vplive hidromorfoloških spremenljivk smo lahko vedno dobro ločili med različnimi prostorskimi ravnmi, ugotovili pa smo različen disjunktni delež pojasnjene variabilnosti združb bentoških nevretenčarjev glede na raven raziskave (Slovenija, ekoregije): za spremenljivke rabe tal 21–27 %, za spremenljivke RHQ in RHM pa skupaj 48–66 %. To je v skladu z ugotovitvami Feld in Hering (2007) ter Sandin (2009), kjer so spremenljivke na ravni odseka pojasnile večji del variabilnosti združb bentoških nevretenčarjev kot spremenljivke na ravni prispevne površine ali ravni pododseka. Kljub temu smo velik delež pojasnili s spremenljivkami rabe tal, katerega ne moremo pripisati spremenljivkam RHQ ali RHM, saj smo ugotovili nizke presečne deleže (10–22 %). Ker smo iz izbora mest raziskave predhodno izločili mesta z drugimi obremenitvami glede na slovenski saprobni indeks (SIG3) (Urbanič in sod., 2006), je ugotovljen vpliv rabe tal zaradi vpliva organskega onesnaženja ali onesnaženja s hranili majhen. Neodvisen vpliv rabe tal smo morda ugotovili na račun prisotnosti strupenih snovi, za katere nismo imeli podatkov in lahko vplivajo na sestavo združb bentoških nevretenčarjev (Allan, 2004). Ena od možnih razlag za neodvisen vpliv rabe tal pa je tudi, da se v spremenljivkah RHQ in RHM še niso odrazile vse hidromorfološke spremembe (npr. spremembe v hidrološkem režimu ali sedimentacija), so se pa zaradi neposrednih vplivov že odrazile na zgradbi združb bentoških nevretenčarjev. Pri oblikovanju usmeritev za upravljanje z vodami je treba upoštevati spremenljivke obeh obravnavanih ravni, saj značilno različno pojasnita variabilnost združb bentoških nevretenčarjev in vplivata na stanje voda.

3.1.6 Povezanost kombinacij hidromorfoloških spremenljivk lokalne ravni z združbami bentoških nevretenčarjev

Vrednotenje hidromorfoloških značilnosti tekočih voda oz. vodotokov na lokalni ravni je najbolj pogosto razdeljeno na pasove struge, brega in obrežnega pasu ter poplavnih ravnic (Raven in sod., 2002; Boon in sod., 2010; Wyzga in sod., 2010; Fernandez in sod., 2011). Raziskave povezanosti morfoloških spremenljivk z združbami bentoških nevretenčarjev v večji meri obravnavajo posamezne spremenljivke enega od pasov, npr. substrat v strugi (Radwell in sod., 2007; Sandin, 2009; Wolter in sod., 2013), vegetacija na bregu ali raba tal v obrežnem pasu (Rios in sod., 2006; Sandin, 2009). Rečni habitati so skupek več morfoloških spremenljivk, ki hkrati vplivajo na združbe vodnih organizmov. Zato se v raziskavah za opis gradienta hidromorfoloških značilnosti pogosto uporablja en indeks, ki zajema večino značilnosti habitata (Balestrini in sod., 2004; Stone in sod., 2005; Bona in sod., 2008; Tavzes in Urbanič, 2009; Urbanič, 2014), saj kombinacije spremenljivk povečujejo robustnost – so manj odvisne od naključnih sprememb. Vendar na podlagi vrednosti enega indeksa težko izpeljemo usmeritve za upravljanje. Zelo redke so raziskave različnih kombinacij posameznih morfoloških spremenljivk (npr. Vaughan, 2010; Cortes in sod. 2009), nismo pa zasledili primerjave povezanosti posameznih spremenljivk in njihovih kombinacij z združbami vodnih organizmov. Obe omenjeni raziskavi sta uporabili skupine spremenljivk, ki jih popišemo z metodo RHS, vendar v izračun spremenljivk niso bile vključene uteži glede na povezanost z združbami vodnih organizmov. V naši raziskavi smo preverili kombinacije spremenljivk RHQ in RHM, ki se uporabljajo za izračun indeksov po metodi SIHM ter ostale možne kombinacije ob upoštevanju najpogostejših pasov vodotokov.

S kombinacijami spremenljivk smo po pričakovanjih značilno bolje pojasnili variabilnost združb bentoških nevretenčarjev v primerjavi s posameznimi spremenljivkami v vodotokih ekoregije Alpe in Dinaridi, za razliko od vodotokov Panonske nižine, kjer med posameznimi spremenljivkami in njihovimi kombinacijami nismo opazili značilne razlike. Pri vodotokih Panonske nižine smo opazili najvišji delež pojasnjene variabilnosti s posameznimi spremenljivkami, medtem ko med deleži pojasnjene variabilnosti s kombinacijami spremenljivk med vodotoki različnih ekoregij nismo opazili razlik. Delež pojasnjene variabilnosti s posameznimi spremenljivkami v vodotokih Panonske nižine je bil ravno toliko visok, da nismo opazili značilne razlike z deležem pojasnjene variabilnosti s kombinacijami spremenljivk. Za preveritev te ugotovitve bi bilo smiselno ponoviti analize na bolj obširnem nizu podatkov z drugačnim (daljšim) gradientom spremenljivk.

Pojasnjevalna sposobnost morfoloških spremenljivk je značilna za regijo ali tip vodotoka, zato je težko razviti metodo vrednotenja, ki bo široko uporabna (Cortes in sod., 2009). Kljub razlikam med ekoregijami smo povsod največ variabilnosti združb bentoških nevretenčarjev pojasnili s kombinacijami spremenljivk struge in bistveno manj s kombinacijami spremenljivk brega in obrežnega pasu. Pri upravljanju z vodami na lokalni ravni se je smiselno osredotočiti predvsem na ohranjanje pestrosti značilnosti struge, ki pa se razlikujejo na regionalni ravni. Upoštevati je treba, da so morfološke razmere na lokalni ravni le eden od dejavnikov, ki vplivajo na združbe bentoških nevretenčarjev ter ostale združbe vodnih in obvodnih organizmov. Za doseganje večje učinkovitosti trajnostnega upravljanja z vodami na lokalni ravni je treba upoštevati še druge dejavnike, kot npr. rabo tal v prispevni površini (Lorenz in Feld, 2012), povezanost habitatov (Kondolf in sod., 2006) ter časovni okvir za doseganje ciljev (Spanhoff in Arle, 2007).

3.2 SKLEPI

1. Ugotovljeni vplivi različnih skupin okoljskih spremenljivk na združbe bentoških nevretenčarjev (BN) so odvisni od soodvisnosti med okoljskimi spremenljivkami. Med hidromorfološkimi spremenljivkami skupin različnih prostorskih ravni kot tudi med spremenljivkami skupin naravnih in antropogeno spremenjenih hidromorfoloških značilnosti smo ugotovili večinoma nizke soodvisnosti ($r_{Sp} < 0,5$) tako v vodotokih Slovenije kot po posameznih ekoregijah. S hidromorfološkimi spremenljivkami višjih prostorskih ravni smo pojasnili del variabilnosti hidromorfoloških značilnosti nižjih prostorskih ravni, vendar je bil pojasnjen delež relativno nizek. Zato smo imeli dobro izhodišče za ugotavljanje neodvisnih vplivov posameznih skupin okoljskih spremenljivk na združbe BN.

2. Največji vpliv na združbe BN smo ugotovili za spremenljivki prevladujoč tok in substrat struge. S spremenljivkami naravnih hidromorfoloških značilnosti vodotokov smo pojasnili velik delež variabilnosti združb BN, večinoma precej večji kot s spremenljivkami sprememb hidromorfoloških značilnosti vodotokov. Združbe BN se bolj odzivajo na učinke, ki jih imajo spremembe na lastnosti kakovosti rečnih habitatov kot pa na sam objekt spremembe. V upravljanju z ekosistemi tekočih voda je upoštevanje sprememb rečnih habitatov sicer pomembno, vendar bi se morali bolj posvetiti prav lastnostim kakovosti habitatov.

3. Deleži pojasnjene variabilnosti združb BN s hidromorfološkimi spremenljivkami so se razlikovali med prostorsko ravnijo Slovenije ter ekoregij, pa tudi glede na obravnavano ekoregijo. Poleg spremenljivk prevladujoč tok in substrat struge smo v Alpah ugotovili večjo pomembnost spremenljivk bregov, medtem ko so v Panonski nižini bolj pomembne razmere v strugi, v Dinaridih pa je bila pomembna kombinacija spremenljivk bregov in struge. Prav tako smo ugotovili razlike med ekoregijami v pomembnosti spremenljivk sprememb hidromorfoloških značilnosti vodotokov. V vseh ekoregijah smo kot eno najpomembnejših prepoznali spremenljivko umetni profili bregov, poleg tega smo podobno pojasnjevalno sposobnost ugotovili v Alpah še za spremenljivki zastoj vode zaradi jezu in spremembe bregov, v Panonski nižini pa za spremenljivko umetni material brega. Ugotovitev o pomembnosti spremenljivk za združbe BN v vodotokih ene ekoregije ne moremo prenesti na vodotoke drugih ekoregij.

4. Vplive hidromorfoloških spremenljivk na združbe BN smo lahko vedno dobro ločili med obravnavanima prostorskima ravnema (regionalno in lokalno), saj so bili disjunktni deleži pojasnjene variabilnosti združb BN veliki. Mnogo manjši presečni deleži pojasnjene variabilnosti združb BN pa nakazujejo, da se med vplivi obeh obravnavanih prostorskih ravni ne da ločiti popolnoma. V upravljanju z ekosistemi tekočih voda je treba upoštevati vplive hidromorfoloških spremenljivk obeh obravnavanih prostorskih ravni, saj značilno različno pojasnita variabilnost združb BN.

5. Glede na ugotovljene pomembne hidromorfološke spremenljivke kakovosti rečnih habitatov smo določili vodilno sliko za obravnavane regije: Alpe, Panonska nižina, Submediteran in Dinaridi. Vodilna slika ekosistemov tekočih voda na podlagi ekološko pomembnih hidromorfoloških značilnosti se med regijami razlikuje. Iste hidromorfološke spremenljivke imajo različen prispevek k habitatski pestrosti glede na regijo. Usmeritve za lastnosti rečnih habitatov, ki so tesno povezane z dinamiko vodnega toka in plavin, so primerna osnova za bolj trajnostno in stroškovno učinkovito upravljanje z ekosistemi tekočih voda. Zaradi načina določitve referenčnih mest, kjer so upoštevane le spremenljivke sprememb rečnih habitatov, ne pa tudi spremenljivke kakovosti rečnih habitatov, smo lahko v določenih regijah podcenili vodilno sliko na podlagi kompleksnosti strukture obrežne vegetacije. Zato pri uporabi usmeritev o lastnostih obrežne vegetacije predlagamo tudi kritično presojo zgodovinskih podatkov.

6. Rečni habitati so skupek več morfoloških značilnosti, ki hkrati vplivajo na združbe vodnih organizmov. S kombinacijami spremenljivk hidromorfoloških značilnosti smo večinoma pojasnili večji delež variabilnosti združb BN kot s posameznimi spremenljivkami hidromorfoloških značilnosti. Kljub razlikam med obravnavanimi ekoregijami smo povsod največ variabilnosti združb BN pojasnili s kombinacijami spremenljivk struge in bistveno manj s kombinacijami spremenljivk brega in obrežnega pasu. Pri upravljanju z vodami na lokalni ravni se je smiselno osredotočiti predvsem na ohranjanje pestrosti značilnosti struge, ki pa se razlikujejo na regionalni ravni.

Slika 20. Izgubljanje na terenu

Figure 20. Getting lost in the field

4 POVZETEK (SUMMARY)

4.1 POVZETEK

V zadnjih desetletjih je v upravljanju z ekosistemi tekočih voda več pozornosti namenjeno spremembam hidromorfoloških značilnosti. Za vzpostavitev trajnostnega upravljanja z ekosistemi tekočih voda je pomembno dobro poznavanje povezav med naravnimi in spremenjenimi rečnimi habitati ter združbami rečnih organizmov, ki pa je trenutno pomanjkljivo. Med rečnimi organizmi so dobri pokazatelji sprememb rečnih habitatov bentoški nevretenčarji zaradi njihove razširjenosti, relativne omejenosti na raven habitatov ter dovolj dolge življenjske dobe, da se odzovejo na spreminjajoče se razmere. Namen naše raziskave je bil: a) ugotoviti povezanost hidromorfoloških spremenljivk različnih prostorskih ravni v vodotokih Slovenije in po posameznih ekoregijah, b) ugotoviti, kolikšen delež variabilnosti združb bentoških nevretenčarjev lahko pojasnimo z vsako od obravnavanih hidromorfoloških spremenljivk, ter ugotoviti hidromorfološke spremenljivke, ki pomembno vplivajo na združbe bentoških nevretenčarjev v vodotokih Slovenije in po posameznih ekoregijah, c) ugotoviti, kolikšen delež variabilnosti združb bentoških nevretenčarjev lahko pojasnimo s posamezno skupino okoljskih spremenljivk: pokrajinske regionalne značilnosti, raba tal, kakovost rečnih habitatov, spremenjenost rečnih habitatov, ter kolikšen hkrati z več skupinami okoljskih spremenljivk, d) preveriti vpliv posameznih hidromorfoloških spremenljivk na habitatsko pestrost in e) ugotoviti, kolikšen delež variabilnosti združb bentoških nevretenčarjev lahko pojasnimo s kombinacijami hidromorfoloških spremenljivk v primerjavi z deležem variabilnosti, ki ga pojasnimo s posameznimi spremenljivkami.

V analizah smo uporabili podatke o številčnosti in taksonomski sestavi združb bentoških nevretenčarjev s 302 mest vzorčenja v vodotokih Slovenije, pridobljenih med leti 2005 in 2011. Pri izboru mest smo zajeli celoten razpon obremenitve hidromorfološke spremenjenosti, izbrali pa smo le mesta vzorčenja, na katerih je bil vpliv organskega onesnaženja in hranil majhen. Podatke smo razporedili v štiri podatkovne nize glede na območje raziskovanja: Slovenija (302 mest vzorčenja), Alpe (93 mest vzorčenja), Dinaridi (129 mest vzorčenja) in Panonska nižina (73 mest vzorčenja).

Za vsako mesto vzorčenja smo zbrali podatke o 49 okoljskih spremenljivkah, ki smo jih razvrstili v skupine: regionalne pokrajinske značilnosti (tipologija, 8 spremenljivk), raba tal (8 spremenljivk), lastnosti kakovosti rečnih habitatov (RHQ, 22 spremenljivk) in lastnosti spremenjenosti rečnih habitatov (RHM, 11 spremenljivk).

Soodvisnosti med vrednostmi okoljskih spremenljivk smo v vodotokih Slovenije in po posameznih ekoregijah določili na podlagi izračuna neparametričnega koeficienta korelacije rangov (Spearmanov korelacijski koeficient, r_{Sp}). V vodotokih Slovenije smo večinoma ugotovili šibke in le redko srednje močne soodvisnosti (r_{Sp} < 0,7) med okoljskimi spremenljivkami različnih skupin, močne soodvisnosti (r_{Sp} > 0,7) smo ugotovili le med okoljskimi spremenljivkami iste skupine. V vodotokih posameznih ekoregij smo močne soodvisnosti ugotovili le v vodotokih ekoregije Panonska nižina. V vodotokih ekoregije Panonska nižina je bil velikostni razred vodotoka močno negativno soodvisen z deležem intenzivnega kmetijstva v skupni prispevni površini ter pozitivno z deležem naravnih površin v skupni prispevni površini. Soodvisnosti med okoljskimi spremenljivkami različnih skupin v vodotokih ekoregij Alpe in Dinaridi so bile večinoma šibke in redke srednje močne. Ta izhodišča so nam omogočila ugotavljanje neodvisnih vplivov izbranih skupin okoljskih spremenljivk na združbe bentoških nevretenčarjev.

Povezave med združbami bentoških nevretenčarjev in okoljskimi spremenljivkami smo ugotavljali s kanonično korespondenčno analizo (CCA). Izmed posameznih spremenljivk kakovosti rečnih habitatov smo največji delež variabilnosti združb bentoških nevretenčarjev v vodotokih Slovenije in po posameznih ekoregijah pojasnili s spremenljivkama prevladujoč tok in substrat struge. S spremenljivkami RHQ smo večinoma pojasnili precej večje deleže variabilnosti združb bentoških nevretenčarjev kot s spremenljivkami RHM. Združba bentoških nevretenčarjev se manj odziva na sam objekt spremembe kot na učinek te spremembe na lastnosti kakovosti rečnih habitatov. Poleg spremenljivk prevladujoč tok in substrat struge smo v Alpah ugotovili pomembnost spremenljivk bregov, v Panonski nižini razmer v strugi (predvsem spremenljivk vegetacije), medtem ko je v Dinaridih bila pomembna kombinacija obeh - spremenljivk bregov in struge. Razlike med ekoregijami smo ugotovili tudi v pomembnosti spremenljivk lastnosti sprememb rečnih habitatov. V vseh ekoregijah smo kot eno najpomembnejših prepoznali spremenljivko umetni profili bregov, poleg tega smo podobno pojasnjevalno sposobnost ugotovili v Alpah še za spremenljivki zastoj vode zaradi jezu in spremembe bregov, v Panonski nižini pa za spremenljivko umetni material brega.

Porazdelitev pojasnjene variabilnosti združb bentoških nevretenčarjev med skupine okoljskih spremenljivk smo ugotavljali s parcialno kanonično korespondenčno analizo (pCCA). Disjunktni del pojasnjene variabilnosti matrike taksonov smo statistično značilno ($p < 0,05$) pojasnili s posamezno skupino okoljskih spremenljivk, presečni del pojasnjene variabilnosti pa z dvema ali več skupinami okoljskih spremenljivk. V vodotokih Slovenije smo zelo podobne disjunktne deleže variabilnosti pojasnili s tipološkimi spremenljivkami (30 %) in spremenljivkami RHQ (31 %), medtem ko smo pojasnili precej nižje disjunktne deleže s spremenljivkami RHM (8 %). Z analizo po posameznih ekoregijah se je disjunktni delež pojasnjene variabilnosti tipoloških spremenljivk precej zmanjšal (19-31 %) v primerjavi s spremenljivkami RHQ (34-42 %) in spremenljivkami RHM (10-15 %). Presečni deleži pojasnjene variabilnosti so skupaj znašali v vodotokih Slovenije 32 % in po posameznih ekoregijah 22-31 %. Tipološke spremenljivke do neke mere oblikujejo procese na nižjih ravneh in posledično vplivajo na združbe bentoških nevretenčarjev, vendar pa je velik delež zgradbe združbe bentoških nevretenčarjev odvisen od lastnosti kakovosti habitata ne glede na regionalne pokrajinske dejavnike.

S pCCA med spremenljivkami rabe tal in ostalimi skupinami okoljskih spremenljivk smo pričakovano največje presečne deleže pojasnjene variabilnosti združb bentoških nevretenčarjev ugotovili s tipološkimi spremenljivkami. S spremenljivkami RHQ smo ugotovili manjše presečne deleže, najnižje pa s spremenljivkami RHM. S pCCA med skupinami raba tal, RHQ in RHM smo vplive hidromorfoloških spremenljivk lahko vedno dobro ločili med različnimi prostorskimi ravnmi, ugotovili pa smo različen disjunktni delež pojasnjene variabilnosti združb bentoških nevretenčarjev v vodotokih Slovenije in po posameznih ekoregijah: za spremenljivke rabe tal 21–27 %, za spremenljivke RHQ in RHM pa skupaj 48–66 %. Pri oblikovanju usmeritev za upravljanje z vodami je treba upoštevati spremenljivke obeh obravnavanih ravni, saj značilno različno pojasnita variabilnost združb bentoških nevretenčarjev in vplivata na stanje voda.

Na podlagi morfoloških spremenljivk, ki smo jih v predhodnjih analizah prepoznali kot pomembne za zgradbo združb bentoških nevretenčarjev ali pri vrednotenju hidromorfološkega stanja tekočih voda, smo za štiri izmed glavnih evropskih regij določili vodilno sliko oziroma potencialno naravno stanje rečnih habitatov. Za določitev vodilne slike smo izbrali odseke, ki odražajo naravno ali malo spremenjeno stanje morfoloških značilnosti. Ugotovili smo značilne razlike med rečnimi habitati alpske, nižinske, mediteranske in kraške regije. Največji okoljski gradient med referenčnimi mesti smo ugotovili za morfološke značilnosti, povezane z dinamiko vodnega toka in plavin. Največje razlike v teh lastnostih smo ugotovili med alpskimi in nižinskimi vodotoki, po drugi strani pa smo prepoznali podobnosti med mediteranskimi in alpskimi vodotoki ter med kraškimi in nižinskimi vodotoki. Pomemben gradient smo ugotovili tudi na podlagi lastnosti obrežne in vodne vegetacije, za katere smo najvišje vrednosti opazili za alpske in mediteranske vodotoke ter nižje v kraških ali nižinskih vodotokih. Vendar preprostejša zgradba vegetacije, ki jo razberemo iz naših rezultatov, morda ni reprezentativna slika naravnih razmer, zato priporočamo upoštevanje tudi drugih kriterijev (npr. zgodovinskih podatkov) in ne le stanja na referenčnih mestih brez pomembnih antropogenih tvorb. Prepoznane podobnosti in razlike med regijami so lahko vodilo za bolj trajnostno in stroškovno učinkovito upravljanje z ekosistemi tekočih voda.

V zadnjem delu raziskave smo z metodo CCA preverili še povezanost kombinacij že prej analiziranih morfoloških spremenljivk z združbami bentoških nevretenčarjev. Kombinacije smo izračunali na podlagi vsote vrednosti posameznih spremenljivk. Uporabili smo kombinacije posameznih spremenljivk kot so predvidene v sklopu metode Slovenskega hidromorfološkega sistema ter novo ustvarjene kombinacije. S kombinacijami spremenljivk morfoloških značilnosti smo večinoma pojasnili večji delež variabilnosti združb bentoških nevretenčarjev kot s posameznimi spremenljivkami morfoloških značilnosti. Kljub razlikam med obravnavanimi ekoregijami smo povsod največ variabilnosti združb bentoških nevretenčarjev pojasnili s kombinacijami spremenljivk struge in bistveno manj s kombinacijami spremenljivk brega in obrežnega pasu. Pri upravljanju z vodami na lokalni ravni se je smiselno osredotočiti predvsem na ohranjanje pestrosti značilnosti struge, ki pa se razlikujejo na regionalni ravni. Upoštevati je treba, da so morfološke razmere na lokalni ravni le eden od dejavnikov, ki vplivajo na združbe bentoških nevretenčarjev, ter da je za doseganje večje učinkovitosti trajnostnega upravljanja z ekosistemi tekočih voda na lokalni ravni treba upoštevati še druge dejavnike (rabo tal v prispevni površini, povezanost habitatov, časovni okvir za doseganje ciljev).

4.2 SUMMARY

In last decades, hydromorphological degradation of rivers has gained more attention in river management. For the desired sustainable river management the understanding of the relationship between river natural and degraded habitats and river assemblages is crucial but yet insufficient. Among aquatic organisms the benthic invertebrates are good ecological indicators of river habitat alteration, since they are ubiquitous, relatively bound to their habitat and have sufficiently long life-span to integrate ecosystem changes over time. The aims of our investigation were: a) to identify the relationship between hydromorphological variables on different spatial scales for Slovenian rivers and rivers of investigated ecoregions, b) to indentify the relationship between hydromorphological variables and benthic invertebrate assemblages composition and define the variables that are most important in structuring benthic invertebrate assemblages in Slovenian rivers and rivers of investigated ecoregions, c) to define what share of benthic invertebrate assemblages composition can be attributed to distinctive effects among environmental variables' groups (regional natural characteristics, land use, river habitat quality, and river habitat modification) and what to joint effect of more environmental variables' groups, d) to investigate the effect of hydromorphological variables on habitat quality, and e) to identify the relationship between combinations of hydromorphological variables and benthic invertebrate assemblages composition in comparison to that of individual hydromorphological variables.

Data on benthic invertebrate abundance and composition were obtained from 302 sampling sites in the Slovenian rivers between the years 2005 and 2011. The selection of sites cover the gradient from natural to heavily altered morphological conditions, and sites showing another type of stressor (organic pollution or nutrients) were apriori excluded. Data were organized in four datasets, according to the study area: Slovenia (302 sites), the ecoregion Alps (93 sites), the ecoregion Dinaric western Balkan (129 sites) and the ecoregion Pannonian lowland (73 sites).

For each sampling site data on 49 environmental variables were collected. The environmental variables were assigned to four groups: regional natural characteristics (typology, 8 variables), land use (8 variables), river habitat quality variables (RHQ, 22 variables), and river habitat modification variables (RHM, 11 variables).

The correlation between each pair of environmental variables in Slovenian rivers and rivers of investigated ecoregions was determined using Spearman rank correlation coefficient (r_{Sp}). In Slovenian rivers mostly weak and rarely moderate ($r_{Sp} < 0.7$) correlations were observed among environmental variables of different groups, strong correlations ($r_{Sp} > 0.7$) were observed only among environmental variables within groups. Investigating rivers on regional level, only in rivers of Pannonian lowland strong correlations were observed. In

rivers of Pannonian lowland the river size class showed strong negative correlation with the share of intensive agriculture in the catchment and positive with the share of natural area in the catchment. In rivers of ecoregions Alps and Dinaric western Balkan only weak and rarely moderate correlations among environmental variables of different groups were observed. The findings meet the requirements to investigate the unique effects of defined environmental variables' groups on benthic invertebrate assemblages.

The relation of environmental variables on benthic invertebrate assemblages was analyzed using canonical correspondence analysis (CCA). Using individual morphological variables among the highest explanatory power was observed for predominant flow and predominant channel substrate in Slovenian rivers and across all ecoregions. In general, RHQ variables explained higher share of benthic invertebrate assemblages' variability than RHM variables. These results suggest weaker response of benthic invertebrate assemblages to the physical alteration itself, than to the effect that the alteration exerts on habitat quality features. Beside the variables predominant flow and predominant channel substrate, benthic invertebrate assemblages of the Alps were influenced most by bank variables, whereas of the Pannonian lowland by features linked directly to channel conditions (mostly vegetation variables). In Dinaric western Balkan a combination of bank and channel variables influenced the assemblages. The differences among ecoregions were observed also regarding the river habitat modification variables. Artificial bank profiles appeared important across all ecoregions, but besides, in the Alps equal explanatory power was observed for variables water impoundment by weir/dam and bank modifications, and in the Pannonian lowland for variable artificial bank material.

The explained variability of benthic invertebrate assemblages was partialed among groups of environmental variables using partial canonical correspondence analysis (pCCA). The unique effects were statistically significantly ($p < 0.05$) explained by individual variable group, whereas joint effects were explained by two or more variable groups. In Slovenian rivers a similar share of unique effects was explained by tipological variables (30 %) and RHQ variables (31 %) but the explanatory power of RHM group was considerably smaller (8 %). Investigating rivers on regional level, considerably lower share of unique effects of explained variability by tipological variables was observed (19-31 %) in comparison to RHQ variables (34-42 %) and RHM variables (10-15 %). The sum of joint effects of explained variability was in Slovenian rivers 32 % and on regional level 22-31 %. Tipological variables constrain the processes on smaller scales to the certain extent, and consequently influence benthic invertebrate assemblages, but there is a considerable part of benthic invertebrate assemblage variability in Slovenia dependent on habitat quality features irrespective of typological characteristics.

The pCCA analysis between land use variables and other environmental variable groups showed the highest joint effects of explained variability of benthic invertebrate assemblages with tipological variables. Lower joint effects were found with RHQ variables and the lowest with RHM variables. Using pCCA among land use, RHQ and RHM variable groups the effects of hydromorphological variables of different spatial scales were generally well separated. However, the difference was observed for unique effects of explained variability of benthic invertebrate assemblages in Slovenian rivers and among ecoregions: for land use variables 21–27 %, and for RHQ and RHM variables together 48–66 %. When discussing river management options both investigated spatial scales of variables should be considered, since their effect on benthic invertebrate assemblages is significantly different.

Using morphological variables, previously acknowledged as important for structuring benthic invertebrate assemblages or for river hydromorphological assessment, the guiding images (the present-day potential natural state) of river habitats of four major European regions were defined. The definition of guiding images was based on sampling sites with no or negligible alteration of morphological features. Significant differences were observed among river habitats of alpine, lowland, mediterranean and karst region. The major environmental gradient among reference sites was observed for morphological features that are in tight relation to water flow and sediment dynamics. The major differences considering these features were found between the alpine and the lowland rivers, whereas the similarities were observed between the mediterranean and the alpine rivers and between the karst and the lowland rivers. Another important gradient was observed on account of habitat features of riparian and channel vegetation, where the highest values of these features were observed for the alpine and the mediterranean rivers and lower in the karst or the lowland rivers. The simpler riparian vegetation structure suggested by our results might not be the representative picture of natural vegetation, hence also other criteria (e.g. historical data) and not only the state of the reference sites, defined by the absence of humanly made structures, should be considered. The recognized similarities and differences among four regions in river habitat features might serve as guidance for more sustainable and cost-effective river management.

The last part of our investigation covered the relationship between benthic invertebrate assemblages and different combinations of previously used morphological variables using CCA. The combinations were calculated by summing up values of individual variables, some on the basis of variable combinations used in Slovenian hydromorphological system, and some newly created combinations. In general, the combinations of morphological variables explained more variability of benthic invertebrate assemblages than individual morphological variables. Although differences among investigated regions were observed, the largest share of variability of benthic invertebrate assemblages was explained by combinations of channel variables and considerably less by combinations of bank or riparian variables. River management on local level should focus on preservation of channel habitat heterogeneity features, which nevertheless differ on regional level. Moreover, local morphological features are only one of the factors, important for structuring benthic invertebrate assemblages, and hence for more effective and sustainable river management on local level also other factors should be considered (land use in the catchment, the inter-habitat connection, time-table for goal achievement).

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PRILOGE

Priloga A: Dovoljenje založnika za objavo članka The links between morphological parameters and benthic invertebrate assemblages, and general implications for hydromorphological river management, v tiskani in elektronski verziji doktorske disertacije

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Priloga B: Dovoljenje založnika za objavo članka The links between river morphological variables and benthic invertebrate assemblages; comparison among three European ecoregions, v tiskani in elektronski verziji doktorske disertacije

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