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Geomorfološke promjene tekućica: pristupi, rezultati i izazovi istraživanja

Geomorphological change in rivers: research approaches, results and challenges

Iako su rijeke prirodno dinamični sustavi skloni promjenama, smatra se da je u posljednjem stoljeću antropogeni utjecaj na rijeke postao toliko snažan da je uzrokovao dosad nezabilježen intenzitet geomorfoloških promjena korita i naplavnih ravnica. Budući da te promjene nerijetko rezultiraju degradacijom ekoloških uvjeta, ali i povećanim rizicima od poplava, u posljednjih dvadesetak godina dolazi do promjena u pristupu upravljanju rijekama. Sve veći naglasak daje se holističkom pristupu i razumijevanju procesa u riječnom sustavu, za koji su studije geomorfoloških promjena tekućica vrlo važan izvor informacija. Cilj je ovoga preglednog rada prikazati osnovne metode u istraživanju geomorfoloških promjena tekućica, uključujući prostorno-hijerarhijsku delineaciju riječnoga sustava, izvore podataka te najčešće analizirana geomorfološka obilježja i čimbenike promjena. Rezultati dosadašnjih istraživanja prikazani su za analizirane radove koji se bave razdobljem od posljednjih 150 godina. Najvažnije geomorfološke promjene uključuju sužavanje i usijecanje korita te smanjenje složenosti fluvijalnih oblika i procesa zbog kanaliziranja i izgradnje velikoga broja poprečnih građevina koje sprečavaju slobodan protok vode i prijenos sedimenta. Objašnjavanje složenih, kumulativnih utjecaja i predviđanje budućih promjena glavni su izazovi u istraživanjima, a vezani su uz kompleksnost riječnoga sustava, odnosno velik broj čimbenika promjena, veza i interakcija u riječnom sustavu, te nelinearnost geomorfološkoga razvoja tekućica.

Ključne riječi: fluvijalna geomorfologija, promjene korita, izvori podataka, geomorfološki pokazatelji, antropogeni utjecaji

Although rivers are inherently dynamic systems that are susceptible to change, human impact on rivers in the last century is considered to have been so significant that it has caused an unprecedented intensity of geomorphological change in river channels and floodplains. As these changes often lead to deterioration of ecological conditions as well as increased flood risks, the approach to river management has changed over the past twenty years. There is an increasing emphasis on a holistic approach based on the understanding of river system processes, for which studies of geomorphological change in rivers represent a very important source of information. The aim of this review is to present the basic methods used in studies of geomorphological change in rivers, including the spatio-hierarchical delineation of the river system, data sources, and the most commonly analysed geomorphological characteristics and factors of change. The results of previous research are presented for the period of the last 150 years. The most important geomorphological changes include channel narrowing, incision, and reduction in the complexity of fluvial landforms and processes due to channelization and the construction of numerous barriers that disrupt the connectivity in water flow and sediment transport. Explaining the cumulative impacts and predicting future changes are the major research challenges. These challenges are related to the complexity of the river system, i.e. a large number of causal factors, connections, and interactions in the river system, and to the nonlinearity of the evolutionary trajectory of changes in rivers.

Key words: fluvial geomorphology, channel changes, data sources, geomorphological indicators, human impacts

Uvod

Česte promjene reljefnih oblika osnovno su svojstvo fluvijalnih geomorfoloških sustava. Korita rijeka i naplavne ravnice prirodno se mijenjaju pod utjecajem čimbenika koji djeluju unutar korita, poput protoka vode i prijenosa sedimenta, te čimbenika koji djeluju na razini porječja, poput klime i zemljišnoga pokrova (Fryirs i Brierley, 2013; Grabowski i dr., 2014). Određeni tipovi tekućica skloniji su promjenama, odnosno većoj dinamici geomorfoloških procesa. Zbog toga neki autori razlikuju standardnu dinamiku tekućice koja je karakteristična za određeni geomorfološki tip (engl. *river behaviour*) od značajne promjene u geomorfološkim obilježjima koja dovodi do promjene tipa tekućice (engl. *river change*) (Brierley i Fryirs, 2005; Kondolf i Piégay, 2016). Primjerice, bočna erozija i kretanje meandara pripada prirodnoj dinamici rijeka koje aktivno meandriraju. S druge strane, potpuno zarastanje riječnih prudova i njihova stabilizacija mijenja obilježja erozijsko-sedimentacijskih procesa u tekućici te se time mijenja njezin geomorfološki tip. Međutim, treba naglasiti da se navedena razlika među pojmovima ponekad ne može jasno razlučiti u fluvijalnogeomorfološkim radovima. Uzrok tomu možda jest i činjenica da je katkad teško odrediti kad nastupa bitna promjena u geomorfološkim obilježjima rijeke. Riječ „promjena" zato se većinom koristi u širem smislu koji podrazumijeva i promjene koje su dio prirodne dinamike kao i promjenu tipa tekućice prema Brierleyju i Fryirs (2005). U radovima se često koristi i izraz prilagodba korita (engl. *channel adjustment*) (Surian i Rinaldi, 2003; Scorpio i Piégay, 2021). U okviru ovoga rada geomorfološke promjene tekućica stoga se također promatraju u širem smislu iako se veći naglasak stavlja na promjene u geomorfološkim obilježjima kojima se mijenja tip tekućice.

Geomorfološkim promjenama tekućica posvećen je velik broj radova, između ostaloga zahvaljujući činjenici da od kraja 19. stoljeća na brojnim rijekama dolazi do intenzivnih promjena uslijed pojačanoga antropogenog djelovanja (Downs i Piégay, 2019). Zbog kanaliziranja toka, izgradnje brana i nasipa, intenzivne urbanizacije, jaružanja i sl. dolazi do morfoloških promjena korita poput usijecanja, sužavanja i smanjenja heterogenosti reljefnih oblika (Surian i Rinaldi, 2003; Zawiejska i Wyżga, 2010). Takve promjene u morfologiji uzrokuju smanjenje kvalitete ekosustava i gubitak

Introduction

Frequent changes in landforms are a fundamental characteristic of fluvial geomorphological systems. Channels and floodplains naturally change under the influence of intrinsic factors acting within the river channel, such as water and sediment flow, and external factors acting at the catchment scale, such as climate and land cover (Fryirs and Brierley, 2013; Grabowski et al., 2014). Certain river types are more susceptible to change, i.e. to greater dynamics of geomorphological processes. Therefore, some authors distinguish standard river dynamics which are specific for certain geomorphological river types (*river behaviour*) from significant change in geomorphological features which leads to a change in river type (*river change*) (Brierley and Fryirs, 2005; Kondolf and Piégay, 2016). For example, lateral erosion and meander movement are part of the natural dynamics of actively meandering rivers. On the other hand, the complete stabilization of fluvial bars due to the spread of vegetation alters the character of erosional and depositional processes in the river and thus its morphological type. It should be emphasised, however, that the aforementioned difference in terms is not always clearly distinguished in fluvial geomorphological studies. The reason for this may be the fact that it is sometimes difficult to define when a significant change in the geomorphological features of a given river occurs. The word *change* is therefore usually used in a broader sense, which includes both river change and behaviour according to Brierley and Fryirs (2005). The term *channel adjustment* is also frequently used in studies (Surian and Rinaldi, 2003; Scorpio and Piégay, 2021). In this review, geomorphological change in rivers is therefore also considered in a broader sense, although the focus is more on alterations in geomorphological features which lead to a change in river type.

Numerous studies have analysed the geomorphological change in rivers, in part due to the fact that, since the end of the 19th century, many rivers have undergone intense transformations due to increased human activities (Downs and Piégay, 2019). River channelization, construction of dams and embankments, intensive urbanization, dredging, etc., cause morphological channel changes such as incision, narrowing and reduction in the heterogeneity of fluvial landforms (Surian and Rinaldi, 2003; Zawiejska and staništa (Hajdukiewicz i Wyżga, 2019), ali mogu imati i izravne negativne posljedice za stanovništvo poput povećanoga rizika od poplava (Kiss i dr., 2021). Svijest o okolišu i zaštiti voda javlja se od kraja 20. stoljeća, a u posljednjih dvadesetak godina donose se zakonske regulative kojima se nastoji postići ravnoteža između antropogenoga iskorištavanja vodnih resursa i očuvanja i poboljšanja vodenih okoliša (npr. Okvirna direktiva o vodama Europske unije – ODV; Europska komisija, 2000). Također se razvijaju pristupi upravljanju rijekama u cilju prirodnijega funkcioniranja riječnih sustava (Brierley i Fryirs, 2005; Gurnell i dr., 2016) te se pristupa obnovi rijeka (engl. *river restoration*), odnosno ponovnoj uspostavi karakterističnih struktura, procesa i funkcija riječnoga okoliša koji odgovaraju ciljanim „prirodnim" uvjetima i pružaju razne usluge ekosustava poput potpore bioraznolikosti, rekreacije ili upravljanja poplavama (Muhar i dr., 2018).

Analiza promjena tekućica tijekom prošlih razdoblja ističe se kao važan korak u upravljanju i planiranju njihove obnove jer pruža informacije o prošlim stanjima, procesima te stopama promjena u porječju, naplavnoj ravnici i koritu (Grabowski i dr., 2014; Ioana-Toroimac, 2016). Identifikacija i povezivanje morfoloških promjena s mogućim prirodnim i antropogenim uzrocima omogućuje razumijevanje sadašnjega stanja i procesa, kao i procjenu onih budućih (Zawiejska i Wyżga, 2010; Scorpio i dr., 2015). Navedene informacije posebno su bitne u holističkom upravljanju vodama koje sagledava tekućice u njihovu širem prostornom kontekstu (porječje) i koje je prvenstveno temeljeno na poznavanju geomorfoloških, hidroloških i ekoloških procesa u tekućicama (Grabowski i dr., 2014).

Od dosadašnjih preglednih radova o geomorfološkim promjenama tekućica potrebno je navesti kritički pregled osnovnih metoda i rezultata istraživanja Downsa i Piégayja (2019), koji se bavi razdobljem od posljednjih dvjestotinjak godina, s posebnim naglaskom na metode povezivanja uzroka i posljedica promjena i procjenu kumulativnoga antropogenog utjecaja[1] na morfologiju rijeka. Pregled dosadašnjih istraživanja antropogenih utjecaja na riječna korita s

1 Utjecaji (pozitivni ili negativni, izravni i neizravni, dugoročni i kratkoročni) koji proizlaze iz niza aktivnosti u cijelom području ili regiji, pri čemu svaki pojedinačni utjecaj možda nije značajan ako se promatra zasebno (EEA, n.d.).

Wyżga, 2010). Such morphological changes lead to poorer ecosystem quality and habitat loss (Hajdukiewicz and Wyżga, 2019), but may also have direct negative consequences for the population, such as increased flood risk (Kiss et al., 2021). Environmental and water protection awareness have been on the rise since the end of the 20th century, while a legislation to balance human use of rivers with conservation and enhancement of the aquatic environment has been enacted over the past twenty years (e.g. the European Union Water Framework Directive - WFD; European Commission, 2000). Moreover, new approaches to river management are being developed with the goal of making river systems function more naturally (Brierley and Fryirs, 2005; Gurnell et al., 2016). River restoration, i.e. restoring characteristic structures, processes, and functions of the river environment that correspond to the targeted "natural" conditions and provide various ecosystem services such as biodiversity support, recreation, or flood control, is also being addressed (Muhar et al., 2018).

Analysing past changes in rivers is an important step in managing and planning their restoration because it provides information about past conditions, processes, and rates of change in the catchment, floodplain, and channel (Grabowski et al., 2014; Ioana-Toroimac, 2016). Identifying and linking morphological changes to possible natural and human causes enables understanding of current conditions and processes, as well as predicting future processes (Zawiejska and Wyżga, 2010; Scorpio et al., 2015). The aforementioned information is particularly important for holistic water management, which considers rivers in their larger spatial context (catchment) and is based primarily on knowledge of geomorphological, hydrological, and ecological processes in rivers (Grabowski et al., 2014).

Of the previous reviews of geomorphological change in rivers, the critical review of methods and research findings by Downs and Piégay (2019) should be noted, covering the period of the last two hundred years, with emphasis on methods for linking the causes and consequences of change and assessing cumulative human impacts[1] on river morphology. Gregory (2006)

1 The impacts (positive or negative, direct and indirect, long-term and short-term impacts) arising from a range of activities throughout an area or region, where each individual effect may not be significant if taken in isolation (EEA, n.d.).

kritičkim osvrtom na izazove istraživanja napisao je i Gregory (2006). Također je potrebno istaknuti rad Grabowskog i dr. (2014), u kojem je dan detaljan pregled hidroloških i geomorfoloških obilježja tekućica strukturiran s obzirom na prostornu hijerarhiju riječnoga sustava (porječje, krajobrazna jedinica, segment, odsječak), a navedeni su i izvori podataka. Posljedice antropogenoga utjecaja na riječne sustave u sredozemnom slijevu istražila je Hooke (2006), a u Srednjoj Europi Maaß i dr. (2021).

Cilj je ovoga preglednog rada prikazati osnovne pristupe, rezultate i izazove istraživanja geomorfoloških promjena tekućica u svijetu i Hrvatskoj. Predstavljene su metode prostorno-hijerarhijske delineacije riječnoga sustava, izvori podataka u istraživanjima, najčešće analizirana geomorfološka obilježja tekućica i uzroci promjena. Rezultati dosadašnjih istraživanja prikazani su za analizirane radove koji se bave razdobljem od posljednjih 150 godina. U radu je poseban naglasak stavljen na obilježja izvora podataka te rezultate dosadašnjih istraživanja na prostoru Hrvatske. U radu je također predstavljen primjer primjene metoda istraživanja na rijeci Cetini.

Delineacija prostornih jedinica riječnoga sustava

Neovisno o tome odnosi li se istraživanje geomorfoloških promjena tekućice na njezin cijeli tok, ili na samo određeni kraći dio toka, tekućicu je uvijek potrebno staviti u njezin širi prostorni kontekst (Downs i Piégay, 2019). Naime, promjene na određenom dijelu toka nisu samo posljedica lokalnih utjecaja, nego i onih uzvodno. S druge strane, da bi se mogle analizirati različitosti u stopama promjene s obzirom na različite čimbenike i obilježja toka, razumno je podijeliti tekućicu na manje prostorne jedinice. Stoga metodološki okviri, koji su razvijeni u cilju boljega razumijevanja fluvijalnih procesa i upravljanja tekućicama, naglašavaju važnost poznavanja prostorno-hijerarhijske organizacije riječnoga sustava (Brierley i Fryirs, 2005; Grabowski i dr., 2014).

Prema metodološkom okviru projekta REFORM, koji je razvijen za potrebe upravljanja i obnove u skladu s ODV-om (Gurnell i dr., 2016),

also authored a review of previous research on human impact on channels and critically pointed out research challenges. Furthermore, the work of Grabowski et al. (2014) is of note, which gives a detailed overview of the hydrological and geomorphological characteristics of rivers in terms of the spatial hierarchy of a river system (catchment, landscape unit, segment, reach) and also lists data sources. The consequences of human impact on river systems in the Mediterranean region have been studied by Hooke (2006) and in Central Europe by Maaß et al. (2021).

The aim of this review is to present the approaches, results and challenges of research on geomorphological change in rivers worldwide and in Croatia. The methods of spatio-hierarchical delineation of the river system, data sources in research, the most frequently analysed geomorphological features of rivers, and the causes of changes are presented. The results of previous research are presented for the period of the last 150 years. Special attention is given to the characteristics of data sources and the results of previous research in Croatia. Also, an example of the implementation of research methods on the Cetina River is presented.

Delineation of spatial units of the river system

Regardless of whether the study of the geomorphological change in a river refers to its entire course or only to a specific shorter section, it is always necessary to place the river in its larger spatial context (Downs and Piégay, 2019). Indeed, changes in a particular part of a river are not only the result of local influences, but also of influences upstream. On the other hand, it is also useful to divide a river into smaller spatial units to analyse differences in rates of change related to different factors and characteristics of the river. Therefore, methodological frameworks developed to better understand fluvial processes and water management emphasise the importance of knowing the spatio-hierarchical organization of a given river system (Brierley and Fryirs, 2005; Grabowski et al., 2014).

According to the methodological framework of the project REFORM, developed for the purposes of management and restoration in accordance with

Tab. 1. Ključna obilježja prostornih jedinica riječnog sustava s obzirom na različito prostorno i vremensko mjerilo istraživanja (prema Grabowski i dr., 2014; Gurnell i dr., 2016)
Tab. 1 Key characteristics of spatial units of the river system with regard to the different spatial and temporal scale of research (according to Grabowski et al., 2014; Gurnell et al., 2016)

Prostorna jedinica / Spatial unit	**Prostorno i vremensko mjerilo** / Spatial and temporal scale	**Obilježja** / Characteristics
Porječje / Catchment	100 - 100.000 km^2 1000 - 10.000 godina / years	Ukupni unos vode u sustav – režim padalina, Zemljišni pokrov, geološka obilježja, topografija / Water production - rainfall regime Land cover, geology, topography
Krajobrazna jedinica / Lanscape unit	100 - 1000 km^2 100 - 1000 godina / years	Obilježja otjecanja i količina sedimenta, Zemljišni pokrov, topografija, Režim padalina, podzemne vode, stopa erozije tla / Runoff characteristics and sediment production Land cover, topography Rainfall regime, groundwater, soil erosion rate
Segment / Segment	10 - 100 km 10 - 100 godina / years	Obilježja doline – reljefna ograničenost, nagib, širina, Režim otjecanja, donos i režim prijenosa sedimenta, Koridor priobalne vegetacije, Prekidi uzdužne povezanosti toka / Characteristics of the valley – confinement, slope, width, Runoff regime, supply and sediment transport regime, Riparian vegetation corridor, Disruption of longitudinal connectivity
Odsječak / Reach	0,1 - 10 km 10 - 100 godina / years	Tlocrtni oblik i geometrija korita, Prijenos sedimenta, Priobalna i vodena vegetacija, drvni ostaci, Nagib korita, prilagodbe korita (bočno kretanje, usijecanje), Antropogeni utjecaji (hidrotehničke građevine) / Planform and channel geometry, Sediment transport, Riparian and aquatic vegetation, wood production, Channel slope, adjustment (lateral movement, incision), Human imapcts (hydraulic structures)
Geomorfološka jedinica / Geomorphological unit	1 - 100 km 1 - 10 godina / years	Specifičan reljefni oblik, obilježja sedimenta, struktura dubine i brzine toka, vrsta vegetacije / Specific fluvial landform, sediment structure, depth and flow speed structure, type of vegetation
Hidraulička jedinica / Hydraulic unit	0,1 - 10 km 0,1 - 10 godina / years	Dubina i brzina toka, smično naprezanje na dnu korita, granulometrijski sastav / Flow depth and velocity, shear stress at the bottom of the bed, granulometric composition

delineacija prostornih jedinica prvi je korak analize. Nakon delineacije pristupa se prikupljanju dostupnih podataka potrebnih za analizu obilježja pojedinih jedinica (tab. 1). Treći korak uključuje procjene stanja i procesa u prošlosti i danas, rekonstrukciju promjena, interpretaciju njihovih uzroka i procjenu budućih promjena na razini odsječka s obzirom na buduće scenarije (klimatske promjene, načini upravljanja).

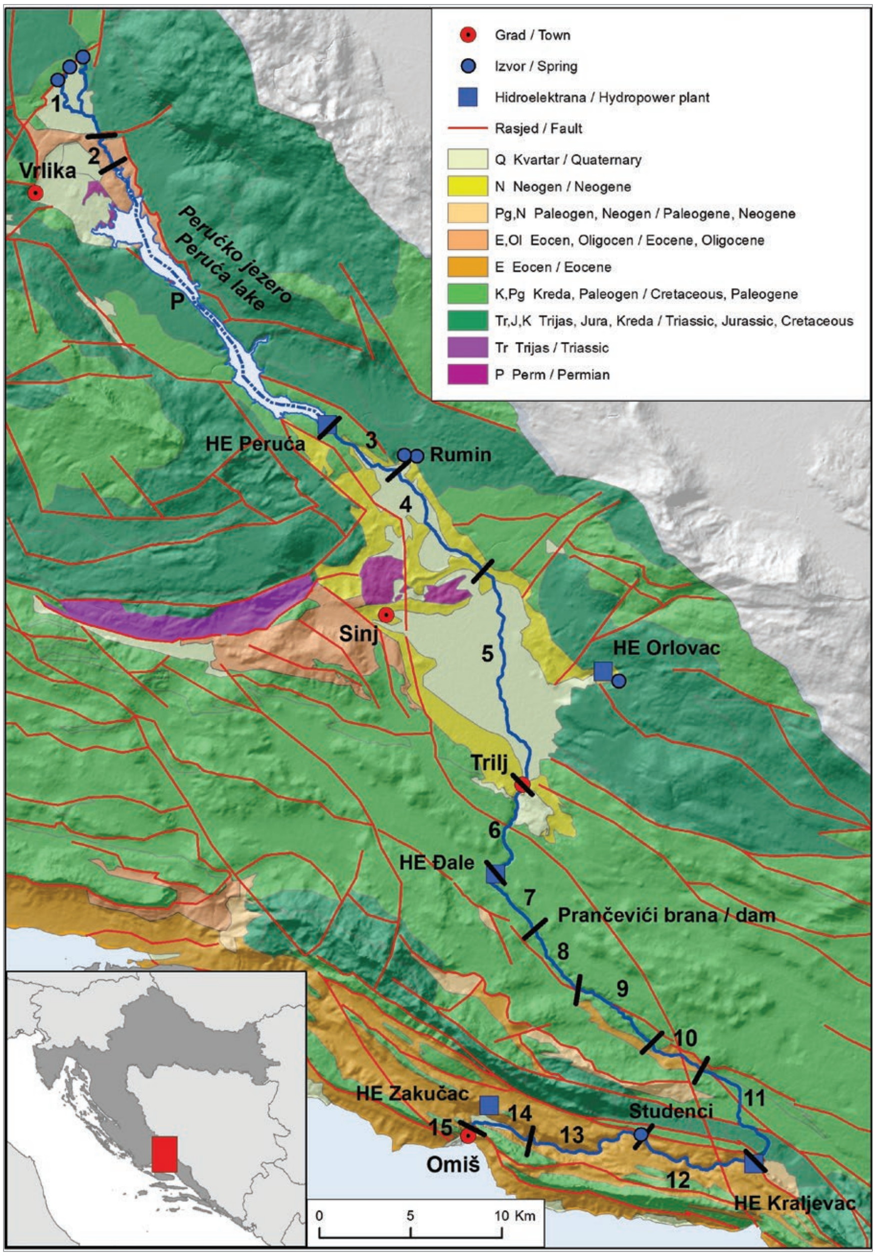
the WFD (Gurnell et al., 2016), the delineation of spatial units is the first step of the analysis. After delineation, available data needed to analyse the characteristics of spatial units is collected (Tab. 1). The third step includes an assessment of past and present conditions and processes, reconstruction of changes, interpretation of their causes, and an assessment of future changes at the reach level according to future scenarios (climate change, management practices).

Porječje se unutar metodološkoga okvira REFORM definira na temelju topografske razvodnice jer je hidrogeološku uglavnom teško detaljno odrediti. Krajobrazna jedinica dio je porječja sa sličnim morfološkim obilježjima krajobraza (topografija, zemljišni pokrov), a segment dio rijeke sa sličnim obilježjima na razini riječne doline (reljefna ograničenost, nagib) te energije i količine toka (Gurnell i dr., 2016). Odsječak se određuje kao morfološki relativno homogen dio rijeke unutar kojega su granični uvjeti dovoljno uniformni, tj. unutar kojega nema bitnih razlika u obilježjima riječne doline, geomorfološkim oblicima korita i naplavne ravnice, obliku korita i tipu sedimenta dna (Brierley i Fryirs, 2005; Rinaldi i dr., 2013). Prema tome, odsječci se određuju (delineiraju) na temelju obilježja morfologije i nagiba korita, veličine sedimenta te prirodnih i umjetnih prepreka u uzdužnoj povezanosti (Gurnell i dr., 2016). Budući da je odsječak osnovna prostorna jedinica analize u fluvijalnogeomorfološkim istraživanjima (Gurnell i dr., 2016; Downs i Piégay, 2019), u ovom je radu predstavljen primjer delineacije toka na hrvatskoj rijeci Cetini (sl. 1). Treba napomenuti da posebno izdvajanje segmenata na rijekama srednje veličine poput navedene nije neophodno, tako da se kriteriji za izdvajanje i obilježja za analizu segmenata mogu primijeniti i na same odsječke (kao što je to npr. u metodološkom okviru *River Styles Framework*, Brierley i Fryirs, 2005).

Rijeka Cetina najdulja je tekućica jadranskoga slijeva koja u potpunosti protječe Hrvatskom (105 km) (Čanjevac i dr., 2022). Krškom topografijom njezina porječja dominiraju karbonatne stijene jurske i kredne starosti, koje obilježava siromaštvo površinskih tokova. Trajni tokovi razvijaju se u poljima u kršu gdje se nalaze vodonepropusne kvartarne naslage. Riječna dolina Cetine obilježena je izmjenom krških polja ili dolinskih proširenja i uskih klanaca (kanjona) (Pavlek i Faivre, 2020). Na Cetini su odsječci određeni na temelju geomorfoloških obilježja (reljefna ograničenost riječne doline, prirodne barijere – slapovi), geoloških obilježja (položaj rasjeda), hidroloških obilježja (pritok Rumin, izvori Studenci) te lokacije brana (HE Peruća, HE Đale, Prančevići), koje čine važan antropogeni prekid u uzdužnoj povezanosti toka

In the methodological framework of REFORM, a catchment is defined based on the topographic watershed, since the hydrogeological watershed is usually difficult to define in detail. A landscape unit is a part of a catchment with similar features (topography, land cover), while a segment is a part of the river with similar river valley features (confinement, slope) and flow energy conditions (Gurnell et al., 2016). A reach is defined as a morphologically relatively homogeneous part of the river, within which the boundary conditions are sufficiently uniform, i.e. within which there are no significant differences in river valley characteristics, channel and floodplain landforms, channel pattern, and bed sediment type (Brierley and Fryirs, 2005; Rinaldi et al., 2013). Therefore, reaches are determined (delineated) based on characteristics of channel morphology and slope, sediment size, and natural and anthropogenic disruptions in longitudinal connectivity (Gurnell et al., 2016). Since a reach is the fundamental spatial unit of analysis in fluvial geomorphology (Gurnell et al., 2016; Downs and Piégay, 2019), this paper presents an example of river delineation using the Cetina River in Croatia (Fig. 1). It should be noted that the separation of segments of medium-sized rivers such as the Cetina is not necessary, so the criteria for separation and characterisation of segments can also be applied to the reaches themselves (such as in the methodological framework of the *River Styles Framework*, Brierley and Fryirs, 2005).

The Cetina River is the longest river of the Adriatic basin that flows entirely through Croatia (105 km) (Čanjevac et al., 2022). The karst topography of its catchment is dominated by Jurassic and Cretaceous carbonate rocks and scarcity of surface flows. Permanent streams are formed in karst poljes where impermeable Quaternary deposits are present. The Cetina River valley is characterized by an alternation of karst poljes or valley widenings and narrow canyons (Pavlek and Faivre, 2020). For the Cetina River, the reaches were determined based on geomorphological features (valley confinement and natural barriers, i.e. waterfalls), geological features (location of faults), hydrological features (Rumin tributary, Studenci springs) and location of dams (the hydropower plants of Peruća, Đale, and Prančevići dam), which represent significant anthropogenic barriers in the longitudinal



Sl. 1. Delineacija odsječaka na primjeru toka rijeke Cetine. Geološke jedinice: Q – aluvijalne, proluvijalne i deluvijalne naslage; N – lapori, vapnenci, konglomerati; Pg, N – vapnenačka breča; E, Ol – konglomerati, vapnenci, breča; E – fliš; K, Pg – vapnenci; Tr, J, K – vapnenci i dolomiti; Tr – klastiti, vapnenci, lapori; P – evaporiti

Fig. 1 Delineation of reaches on the Cetina River. Geological units: Q – alluvial, proluvial and deluvial deposits; N – marls, limestones, conglomerates; Pg, N – limestone breccia; E, Ol – conglomerates, limestones, breccia; E – flysch; K, Pg – limestones; Tr, J, K – limestones and dolomites; Tr – clastites, limestones, marls; P – evaporites

Izvor: modificirano prema Pavlek i Faivre (2020); HGI (2009)

Source: modified from Pavlek and Faivre (2020); CGS (2009)

vode i sedimenta (Pavlek i Faivre, 2020). Moguće je također odrediti nekoliko krajobraznih jedinica porječja koje određuju kompozitni karakter doline Cetine: krška polja u izvorišnom području s kraćim kanjonskim tokom (odsječci 1-2), dolinsko proširenje koje je danas potopljeno pod Perućkim jezerom (P), prostrana krška polja u središnjem dijelu toka (Hrvatačko i Sinjsko, 3-5), kanjonski tok u karbonatima (6-11) te izmjena dolinskih proširenja i kanjona u flišu (12-15) (sl. 1).

connectivity of water flow and sediment transport (Pavlek and Faivre, 2020). In addition, several landscape units of the catchment can be identified, which define the composite character of the Cetina River valley: karst poljes in the headwaters with a shorter canyon section (reaches 1–2), the valley widening under Peruća lake (P), extensive karst poljes in the central part of the river (Hrvatačko and Sinjsko, 3–5), canyon in carbonates (6–11), and alteration of valley widenings and canyons in flysch (12–15) (Fig. 1).

Pristupi istraživanju i izvori podataka

Obilježja tekućica na razini svih prostornih jedinica istražuju se korištenjem raznovrsnih tehnika, koje je prema Grabowskom i dr. (2014) moguće podijeliti u četiri osnovna pristupa na temelju disciplina unutar kojih su razvijeni, izvora podataka kojima se koriste i vremenske skale unutar koje ih se može primijeniti. To su terensko istraživanje, daljinska istraživanja, povijesna istraživanja i paleoistraživanja. U nastavku je dan pregled osnovnih metoda istraživanja i literature za svaki od tih pristupa.

Terenska istraživanja

Terenskim istraživanjem u pravilu se pokriva kraće razdoblje. U terenska istraživanja spadaju geomorfološko kartiranje reljefnih oblika te razne metode procjene (hidro)morfološkoga stanja rijeka poput istraživačkoga okvira *River Styles Framework* (Brierley i Fryirs, 2005) ili metode *Morphological Quality Index* (MQI) koja je razvijena u Italiji (Rinaldi i dr., 2013). U Europskoj uniji Okvirna direktiva o vodama propisuje provođenje hidromorfološkoga monitoringa u cilju procjene ekološkoga stanja vodnih tijela. Hidromorfološkim monitoringom ocjenjuju se tri osnovna elementa: hidrologija, uzdužna povezanost i morfologija (Europska komisija, 2000). Na razini Europske unije ne postoji jedinstvena metodologija hidromorfološkoga monitoringa iako postoje određeni standardi (EN 2004; EN 2010). Države članice uglavnom razvijaju svoje nacionalne metodologije (Beletti i dr., 2015). Hidromorfološki monitoring u Hrvatskoj sustavno se provodi od 2017. godine (Zaharia i dr., 2018). Terenskim metodama geomorfološkoga kartiranja i hidromorfološke procjene relativno se brzo i jednostavno mogu prikupiti informacije o oblicima i procesima u koritu i naplavnoj ravnici, što je važan dio analiza na razini odsječka. Međutim, procjene se često oslanjaju na stručnost procjenitelja te ih nije moguće primjenjivati na većim prostornim jedinicama (Grabowski i dr., 2014).

Terenska istraživanja također uključuju mjerenja geomorfoloških procesa i oblika pomoću alata i mjernih instrumenata. Budući da su dva glavna agensa u fluvijalnoj geomorfologiji protok vode i

Research approaches and data sources

The characteristics of rivers at the scale of all spatial units are studied using various techniques that, according to Grabowski et al. (2014), fall into four basic classes based on the disciplines in which they were developed, the data sources they use, and the time scale at which they can be applied: field research, remote sensing, historical research, and palaeo research. The following is an overview of the basic research methods and literature for each of these approaches.

Field research

Field research usually covers a shorter period of time. It includes geomorphological mapping, and various methods for assessing the (hydro)morphological conditions of rivers, such as the *River Styles Framework* (Brierley and Fryirs, 2005) or the *Morphological Quality Index* (MQI) method developed in Italy (Rinaldi et al., 2013). In the European Union, the Water Framework Directive requires the implementation of hydromorphological monitoring to assess the ecological status of water bodies. Hydromorphological monitoring assesses three basic elements: hydrology, longitudinal connectivity, and morphology (European Commission, 2000). At the European Union level, there is no uniform methodology for hydromorphological monitoring, although certain standards exist (EN 2004; EN 2010). Member states mostly develop their own methodologies (Beletti et al., 2015). Hydromorphological monitoring in Croatia has been carried out systematically since 2017 (Zaharia et al., 2018). Information on channel and floodplain forms and processes, which are important components of reach-level analysis, can be relatively quickly and easily collected by geomorphological mapping and hydromorphological assessment. However, assessments are often dependent on expert knowledge and cannot be applied to larger spatial units (Grabowski et al., 2014).

Field investigations also include measurements of geomorphological processes and landforms using tools and measuring instruments. Since the two main agents in fluvial geomorphology are water and prijenos sedimenta, ukupna proizvodnja sedimenta u porječju te unos i prijenos sedimenta riječnim sustavom važna su tema istraživanja promjena tekućica (Gregory, 2006; Fryirs, 2017). Unos sedimenta u riječni sustav sastoji se od dva glavna elementa: denudacije i erozije riječnih obala i dna. Erozija riječnih obala može se mjeriti pomoću erozijskih šipki (Keesstra i dr., 2009; Henshaw i dr., 2013) ili uzastopnih mjerenja obalne linije pomoću GNSS uređaja (globalni navigacijski satelitski sustav) visoke preciznosti (Zhang i dr., 2019). Denudacija se može mjeriti pomoću sedimentacijskih prostirki (engl. *sedimentation mat*) (Keesstra i dr., 2007). Navedenim metodama dobivaju se ulazni podatci za računalne numeričke modele prijenosa sedimenta poput WATEM/SEDEM-a (Keesstra i dr., 2009). Terenskim mjerenjima također se prikupljaju detaljni podatci o poprečnom presjeku korita, obilježjima protoka vode i strukturi obala i dna, što su važni ulazni podatci za hidrauličke modele (Klösch i dr., 2015; Kidova i dr., 2021). Zbog korozije su krške tekućice bogate otopljenim karbonatima, koji se zatim talože u obliku sedre. Prirast sedre na vapnenačkim pločicama može se mjeriti pomoću mikroerozijskoga metra ili fotogrametrijskih metoda (Marić i dr., 2020). Na terenu se naravno prikupljaju i uzorci za sedimentološke i stratigrafske analize te datiranje, koji će pobliže biti objašnjeni u poglavlju o paleoistraživanjima.

Daljinska istraživanja

Daljinska istraživanja danas su vrlo raširen pristup istraživanju i izvor podataka u geomorfologiji općenito (Smith i Pain, 2009; Mićunović i dr., 2021), a mogu se podijeliti na nekoliko platforma: satelitske misije, aerofotogrametrijske snimke iz zraka (iz zrakoplova ili bespilotnih letjelica) te terestričko snimanje. Na temelju daljinskih istraživanja moguće je prikupiti velik broj podataka za jedinice različitih prostornih mjerila te istražiti mnogobrojna obilježja tekućica, poput tlocrtnoga oblika korita, količine suspendiranoga sedimenta, granulometrijskoga sastava vučenoga sedimenta, precizne topografije korita i sl. (Piégay i dr., 2020).

Zračne snimke u nekim su europskim državama dostupne za razdoblje od početka 20. stoljeća

sediment transport, the total production of sediment in the catchment and the input and transport of sediment through the fluvial system are important topics of river change studies (Gregory, 2006; Fryirs, 2017). Sediment input to the river system consists of two main elements: erosion of hillslopes and erosion of river banks and bed. The extent of bank erosion can be measured using erosion pins (Keesstra et al., 2009; Henshaw et al., 2013) or by repeated measurements of the bankline using high-precision Global Navigation Satellite System (GNSS) instruments (Zhang et al., 2019). Erosion of hillslopes can be measured using sediment mats (Keesstra et al., 2007). The aforementioned methods provide input data for numerical models of sediment transport such as WATEM/SEDEM (Keesstra et al., 2009). Field investigations also include measurements of the channel cross-section, characteristics of flow, and structure of the banks and bed, which are important input data for hydraulic models (Klösch et al., 2015; Kidova et al., 2021). Due to corrosion, karst rivers are rich in dissolved carbonates, which can be deposited in the form of tufa. Tufa growth on limestone tiles can be measured using a micro-erosion meter or photogrammetric methods (Marić et al., 2020). Naturally, in the field, samples are also collected for sedimentological and stratigraphic analyses and dating, which are discussed in more detail in the section on palaeo research.

Remote sensing

Remote sensing is a widely-used research approach and data source in geomorphology in general (Smith and Pain, 2009; Mićunović et al., 2021). It can involve several platforms: satellite missions, aerial imagery (from aircraft or drones), and terrestrial imagery. Based on remote sensing, it is possible to collect a large amount of data for units of various spatial scales and to study numerous characteristics of rivers, such as channel planform, amount of suspended sediment, granulometric composition of bedload, precise channel topography, etc. (Piégay et al., 2020).

In some European countries, aerial images are available for the period from the beginning of the 20th century (Grabowski et al., 2014). In Croatia, (Grabowski i dr., 2014). U Hrvatskoj najstarije dostupno aerofotogrametrijsko snimanje datira iz 1950-ih godina, a danas se snimanje provodi parcijalno, za jednu polovicu države svake dvije godine. Na temelju aerofotogrametrijskih snimanja izrađuju se ortofoto karte (sl. 2). Što se tiče satelitskih podataka, najstarija satelitska misija Landsat lansirana je 1972. godine. Do danas je broj satelitskih misija porastao, kao i njihova prostorna rezolucija (Deur i dr., 2021). Primjerice, satelitska misija WorldView pruža multispektralne snimke s osam kanala u prostornoj rezoluciji od 1.85 m. Međutim, izazovi u korištenju su visoka cijena te potrebno stručno znanje za analizu snimaka. Naime, što je rezolucija snimaka veća, to je i veća cijena. Stoga su besplatno dostupne satelitske misije uglavnom one manje prostorne rezolucije (npr. Sentinel, 10 m), koje iako nisu prikladne u analizi manjih tekućica, čine vrlo vrijedan izvor podataka za one veće (Spada i dr., 2018; Grecu i dr., 2022). Za manje tekućice koriste se bespilotne letjelice (Rivas Casado i dr., 2015) ili zračne snimke snimljene iz zrakoplova (Keesstra i dr., 2005; Hooke i Yorke, 2010), čija prostorna rezolucija iznosi od nekoliko centimetara do uglavnom 1 m (za zračne snimke).

Na satelitskim i zračnim snimkama metodama klasifikacije zemljišnoga pokrova moguće je automatizirati identifikaciju i mjerenje geometrije korita (tlocrtni oblik, širina) te reljefnih oblika u koritu (prud, otok s vegetacijom) (Rivas Casado i dr., 2015; Demarchi i dr., 2016; Spada i dr., 2018). U literaturi je također prošireno korištenje LiDAR-a ili totalne stanice za izradu visokopreciznoga modela terena (Demarchi i dr., 2016; Wiliams i dr., 2020) ili za analizu priobalne vegetacije (Féhérvary i Kiss, 2020). Naime, prednost je LiDAR-a u tome što njegove laserske zrake prolaze kroz vegetaciju te se na taj način jednostavnije i točnije može izraditi model terena, za razliku od optičkoga aerofotogrametrijskog snimanja (riječne obale su često obrasle gustom priobalnom vegetacijom). Daljinska istraživanja također su dragocjena u istraživanjima zemljišnoga pokrova na naplavnoj ravnici ili na razini porječja (Boix-Fayos i dr., 2007).

the oldest available photogrammetric aerial survey dates back to the 1950s, and today a survey is conducted every two years for one half of the country (the other half is surveyed in the adjoining year). Orthophoto maps are produced based on this aerial survey (Fig. 2). As for satellite data, the oldest Landsat satellite mission was launched in 1972. Since then, the number of satellite missions as well as their spatial resolution have substantially increased (Deur et al., 2021). The WorldView satellite mission, for example, provides multispectral imagery with eight channels and a spatial resolution of 1.85 m. However, there is a high cost and the expertise required to analyse the images is considerable. The higher the resolution of the images, the higher the price. Therefore, the satellite missions that are freely available are mostly those with lower spatial resolution (e.g. Sentinel, 10 m), which are not suitable for the analysis of smaller rivers, but are a very valuable source of data for larger ones (Spada et al., 2018; Grecu et al., 2022). For smaller rivers, unmanned aerial vehicles (UAV) (Rivas Casado et al., 2015) or aerial photographs taken from aircraft (Keesstra et al., 2005; Hooke and Yorke, 2010) are used, with spatial resolutions ranging from a few centimetres to (mostly) 1 m (for aerial photographs from an aircraft).

The identification of channels and the measurement of their geometry (planform, width) and the detection of channel landforms (bars, islands with vegetation) on satellite and aerial imagery can be automated using land cover classification methods (Rivas Casado et al., 2015; Demarchi et al., 2016; Spada et al., 2018). The literature also expands on the use of LiDAR or total stations to create high-precision terrain models (Demarchi et al., 2016; Wiliams et al., 2020) or for riparian vegetation analysis (Féhérvary and Kiss, 2020). Indeed, the advantage of LiDAR is that its laser beams penetrate vegetation, and in this way a terrain model can be created more easily and accurately than is the case with optical aerial photogrammetry, because riverbanks are often covered with dense riparian vegetation. Remote sensing is also useful for studying land cover in the floodplain or at the catchment level (Boix-Fayos et al., 2007).

Sl. 2. Prikaz korita Cetine kod Radmanovih mlinica na karti treće vojne izmjere Habsburške Monarhije iz 1883., arhivskoj aerofotogrametrijskoj snimci iz 1951. i suvremenoj ortofoto karti iz 2021.

Fig. 2 The Cetina River channel near Radmanove mlinice on the map of the Third Military Survey of the Habsburg Monarchy from 1883, archival aerial image from 1951 and a contemporary orthophoto map from 2021

Izvori: Austrian Federal Office of Metrology and Surveying (1883); DGU (1951; 2021)

Sources: Austrian Federal Office of Metrology and Surveying (1883); SGA (1951; 2021)

Povijesna istraživanja

Povijesni izvori podataka za istraživanje rijeka prema Grabowskom i dr. (2014) jesu karte, premjeri zemljišta, topografski premjeri rijeka, popisi stanovništva, poljoprivrede i sl., podatci hidroloških ili meteoroloških postaja, stare fotografije, crteži, dokumenti (putopisi, evidencije nekretnina i sl.). Po-

Historical research

According to Grabowski et al. (2014), historical data sources for river research include maps, land surveys, topographic surveys of rivers, censuses of population and agriculture, data from hydrological or meteorological stations, old photographs, drawings, and documents (travel letters, property uzdanost je potonjih podataka varijabilna, međutim za starija razdoblja to su često jedini podatci kojima se raspolaže.

Povijesne i suvremene topografske karte zajedno s podatcima daljinskih istraživanja danas su najznačajniji izvori podataka u istraživanju promjena korita rijeka za razdoblje od posljednjih dvjestotinjak godina (Downs i Piégay, 2019). Međutim, različito vrijeme nastanka te različite kartografske projekcije i mjerila izrade kartografskih izvora utječu na njihovu točnost. Starije karte općenito imaju manju točnost. Primjerice, na području Habsburške Monarhije, pa tako i današnje Hrvatske, najstarija relativno pouzdana karta za istraživanje hidrografskih elemenata jest prva vojna izmjera izrađena u razdoblju od 1764. do 1787. godine. No, s obzirom na veća odstupanja u pozicijskoj točnosti prostornih elemenata te karte nije pogodno koristiti za mjerenja, već samo kao prikaze tadašnjega morfološkog stanja i oblika korita.

Za područje Hrvatske također su vrijedni podatci Franciskanskog katastra, koji je izrađen u razdoblju od 1817. do 1877. godine. U prvoj polovini 19. stoljeća načinjena je izmjera Istre i Dalmacije, a u drugoj polovini Hrvatske i Slavonije (Slukan Altić, 2003). Zahvaljujući krupnijem mjerilu, katastarski su prikazi pozicijski dosta točni, odnosno horizontalna pogreška u georeferenciranju iznosi oko 3 m (Timár i Biszak, 2010). S druge strane, budući da je katastar rađen da bi se omogućilo naplaćivanje poreza, razgraničenje čestica i korištenje zemljišta detaljno je prikazano, ali ne i na područjima od manjega interesa za gospodarsko iskorištavanje. Zbog toga morfološki oblici (prudovi, otoci) unutar korita nisu prikazani odviše vjerno. Međutim, podatci Franciskanskog katastra mogu se koristiti za određivanje širine i duljine korita (iako treba imati na umu da su na katastru uglavnom prikazane granice korita za vrijeme visokih voda) te u analizi bočnoga kretanja rijeke, zahvaljujući zadovoljavajućoj horizontalnoj točnosti.

Karte iz 18., 19. i početka 20. stoljeća za područje Europe mogu se pregledavati i djelomično kupovati preko internetskog portala Arcanum Maps. Za istraživanje područja Hrvatske posebno su važne karte druge i treće vojne izmjere Habsburške Monarhije, na kojima je struktura krajo-

records, etc.). The reliability of the latter data varies, but for older periods they are often the only data available.

Historical and contemporary topographic maps, along with remote sensing data, are the primary data sources for studying channel changes for the last two hundred years (Downs and Piégay, 2019). However, differing dates of creation, as well as various sorts of cartographic projections and criteria for compiling mapped sources, affect their accuracy. Older maps generally have lower accuracy. For example, in the territory of the former Habsburg Monarchy, which included much of present-day Croatia, the oldest relatively reliable map for the study of hydrographic elements is the First Military Survey, created in the period from 1764 to 1787. However, due to the great deviations in the positional accuracy of spatial elements, these maps are not suitable for measurements, rather only as representations of the morphological state and pattern of the channel at that time.

For the territory of contemporary Croatia, the data of the Franciscan cadastre, made in the period from 1817 to 1877, are also valuable. In the first half of the 19th century, Istria and Dalmatia were surveyed, and in the second half Croatia and Slavonia (Slukan Altić, 2003). Thanks to the larger scale, the cadastral representations are quite accurate in terms of location, i.e. the horizontal error in georeferencing is about 3 m (Timár and Biszak, 2010). However, since the cadastre was created for tax collection, the delineation of parcels and land use are shown in detail, but not in areas that were less interesting for economic use at the time. For this reason, fluvial landforms (bars, islands) within the channel are not very accurately represented. However, the data of the Franciscan cadastre can be used to determine channel width and length (noting that the cadastre mainly shows the limits of the bankfull channel) and to analyse the lateral movement of the river, thanks to the satisfactory horizontal accuracy.

Maps from the 18th, 19th and early 20th centuries for Europe can be viewed and in some cases purchased via the online portal Arcanum Maps. Of particular importance for the study of the Croatian regions are the maps of the Second and Third Military Land Surveys of the Habsburg Monarchy, braza poput vodnih tijela te topografije terena vjerno prikazana radi njihove vojne namjene (sl. 2). Timár i dr. (2006) navode da je prosječna horizontalna točnost karata druge vojne izmjere na portalu Arcanum Maps 150-200 m iako naglašavaju da na nekim listovima ta točnost može biti dvostruko bolja te pozivaju korisnike da doprinesu boljem georeferenciranju karata. Prema tome, u literaturi se navodi da točnost karata iz 19. stoljeća, dobivena detaljnim georeferenciranjem isječaka karte koji pokrivaju područje istraživanja, iznosi otprilike 20 m (Scorpio i dr., 2015; Pavlek i Faivre, 2020). Zahvaljujući zadovoljavajućoj horizontalnoj točnosti, topografske karte iz 19. stoljeća često se koriste u istraživanjima povijesnih promjena korita rijeka (Hohensinner i dr. 2021). Naravno, u istraživanju treba imati na umu da primjerenost korištenoga izvora ovisi o veličini analizirane rijeke te o analizama koje se namjeravaju provesti. Primjerice, nije prikladno provoditi analizu bočnoga kretanja ili širine korita rijeke na temelju povijesne karte horizontalne točnosti 20 m ako sama širina korita i njegovo kretanje iznose manje od te vrijednosti.

Topografski premjeri, koji uključuju poprečne i uzdužne profile tekućica, te podatci hidroloških postaja, odnosno poprečni presjeci na njihovoj lokaciji, vrlo su važni i često jedini izvori podataka za istraživanje promjena u razini dna tekućica (Surian i Rinaldi, 2003; Kiss i dr., 2008). Na području današnje Hrvatske prve detaljne hidrotehničke izmjere izvode se tijekom 18. stoljeća kad počinju i prvi važni hidrotehnički radovi. Hidrografske karte uglavnom se izrađuju za veće rijeke poput Dunava, Drave, Save i Mure, za koje se mjerenja kontinuirano provode i danas (Slukan Altić, 2003). Hidrografska mjerenja pogotovo su česta na Dravi jer se radi o dinamičnoj, graničnoj rijeci. U 19. stoljeću obavljene su dvije sustavne hidrografske izmjere (1846. i 1886.), hidrografski atlas rijeke objavljen je 1972., a novi digitalni hidrografski atlas iz 2005. godine sastoji se od topografskoga prikaza, poprečnih i uzdužnih profila te režima nanosa (Prevedan, 2006).

which faithfully depict the structure of the landscape, such as water bodies, and the topography of the terrain thanks to their intended military purpose (Fig. 2). Timár et al. (2006) stated that the average horizontal accuracy of Second Military Land Survey maps on the Arcanum Maps portal is 150–200 m, although they emphasized that this accuracy can be twice as high for certain sheets, and encouraged users to contribute to better georeferencing of the maps. The literature states that the accuracy of 19th century maps obtained by detailed georeferencing of map sections covering the study area is about 20 m (Scorpio et al., 2015; Pavlek and Faivre, 2020). Thanks to their satisfactory horizontal accuracy, 19th century topographic maps are often used to study historical channel changes (Hohensinner et al., 2021). It is important to note, of course, that the suitability of the source used depends on the size of the river being studied and the intended analyses. For example, it is not appropriate to conduct an analysis of lateral shift or channel width based on a historical map with a horizontal accuracy of 20 m, if the width of the channel itself and its displacement are less than 20 m.

Topographic surveys, which include transverse and longitudinal profiles of rivers, and data from hydrological stations, i.e. cross-sections at their location, are very important and often the only data sources for studying changes in bed level (Surian and Rinaldi, 2003; Kiss et al., 2008). In present-day Croatia, the first detailed hydrotechnical measurements were conducted in the 18th century, when the first significant hydrotechnical works began. Hydrographic maps were created mainly for larger rivers such as the Danube, Drava, Sava, and Mura, for which measurements are still carried out continuously today (Slukan Altić, 2003). Hydrographic measurements are especially common on the Drava River, as it is a dynamic boundary river. Two hydrographic surveys were completed in the 19th century (1846 and 1886) and a hydrographic atlas of the river was published in 1972. The new digital hydrographic atlas from 2005 consists of a topographic preview, transverse and longitudinal profiles, and a sediment regime (Prevedan, 2006).

Paleoistraživanja

U paleoistraživanja se ubrajaju sedimentološke i stratigrafske metode te metode datiranja poput radiokarbonskoga, OSL-a (optički stimulirana luminiscencija) i dendrokronologije (Grabowski i dr., 2014). Tim metodama u posebno opremljenim laboratorijima moguće je analizirati morfološku evoluciju tekućica nekoliko tisuća godina u prošlost.

Sedimentološke analize uključuju mjerenje granulometrijskoga sastava (određivanje veličina zrna i njihove raspodjele i masenoga udjela u uzorku) i oblika zrnaca sedimenta (Frančišković-Bilinski i dr., 2012). Geokemijskim analizama određuje se kemijski sastav i svojstva sedimenta, a organske se čestice (ugljen, drvni ostatci) izdvajaju radi radiokarbonskoga datiranja kojim se određuje stratigrafija slojeva sedimenta te istražuje evolucija korita i doline (Faivre i dr., 2019). Primjerice, Keesstra i dr. (2005) su na rijeci Dragonji pomoću metode ^{14}C istražili starost i slijed riječnih terasa te utvrdili faze agradacije riječne doline i faze usijecanja riječnoga korita. Felja i dr. (2015) su na temelju sedimentoloških i paleontoloških istraživanja te radiokarbonskoga datiranja analizirali razvoj donjega dijela riječne doline Mirne tijekom holocena, koja je obilježena postupnim zatrpavanjem nekadašnjega estuarija aluvijalnim sedimentom.

Datiranje optički stimuliranom luminiscencijom (OSL) mjeri vrijeme otkada su zrnca sedimenta bila istaložena i zaštićena od daljnjega izlaganja svjetlu ili toplini. Na taj se način mogu rekonstruirati morfološki stadiji razvoja tekućice identificiranjem smjerova paleotokova i određivanjem morfologije, oblika i starosti paleokorita (Kiss i dr., 2014). S druge strane, dendrokronološke metode koriste se godovima drveća u određivanju starosti vegetacije uz korito i na naplavnoj ravnici (Liébault i Piégay, 2002). Primjenom te metode moguće je istražiti razdoblja akumulacije i stabilizacije prudova, odnosno razvoj i dinamiku riječnih otoka (Kiss i dr., 2011; Kiss i Blanka, 2012).

Palaeo research

Palaeo research includes sedimentological, stratigraphic, and dating methods such as radiocarbon, OSL (optically-stimulated luminescence), and dendrochronology (Grabowski et al., 2014). Using these methods, it is possible to analyse the morphological evolution of rivers several thousand years into the past in specially equipped laboratories.

Sedimentological analyses include measurement of granulometric composition (grain size distribution and mass fraction in the sample) and the shape of sediment grains (Frančišković-Bilinski et al., 2012). Geochemical analyses determine the chemical composition and properties of sediment grains, while organic particles (charcoal, wood debris) are separated for radiocarbon dating, which is used to determine the stratigraphy of sediment layers and to study the evolution of the river channel and valley (Faivre et al., 2019). For example, Keesstra et al. (2005) studied the age and sequence of river terraces on the Dragonja River using the ^{14}C method and established the stages of aggradation of the river valley and channel incision. Based on sedimentological and palaeontological studies and radiocarbon dating, Felja et al. (2015) analysed the evolution of the lower Mirna River valley during the Holocene, which was characterized by the gradual filling of the former estuary with alluvial sediments.

Optically stimulated luminescence (OSL) dating is used to measure the time since sediment grains were deposited and protected from further exposure to light or heat. In this way, the morphological evolutionary stages of the river can be reconstructed by determining the directions of palaeoflows, and determining the morphology, pattern, and age of the palaeochannels (Kiss et al., 2014). Dendrochronological methods, on the other hand, use tree rings to determine the age of vegetation along the channel and in the floodplain (Liébault and Piégay, 2002). This method enables the investigation of periods of bar accumulation and stabilization, or the evolution and dynamics of river islands (Kiss et al., 2011; Kiss and Blanka, 2012).

Pokazatelji promjena i morfološki tipovi korita

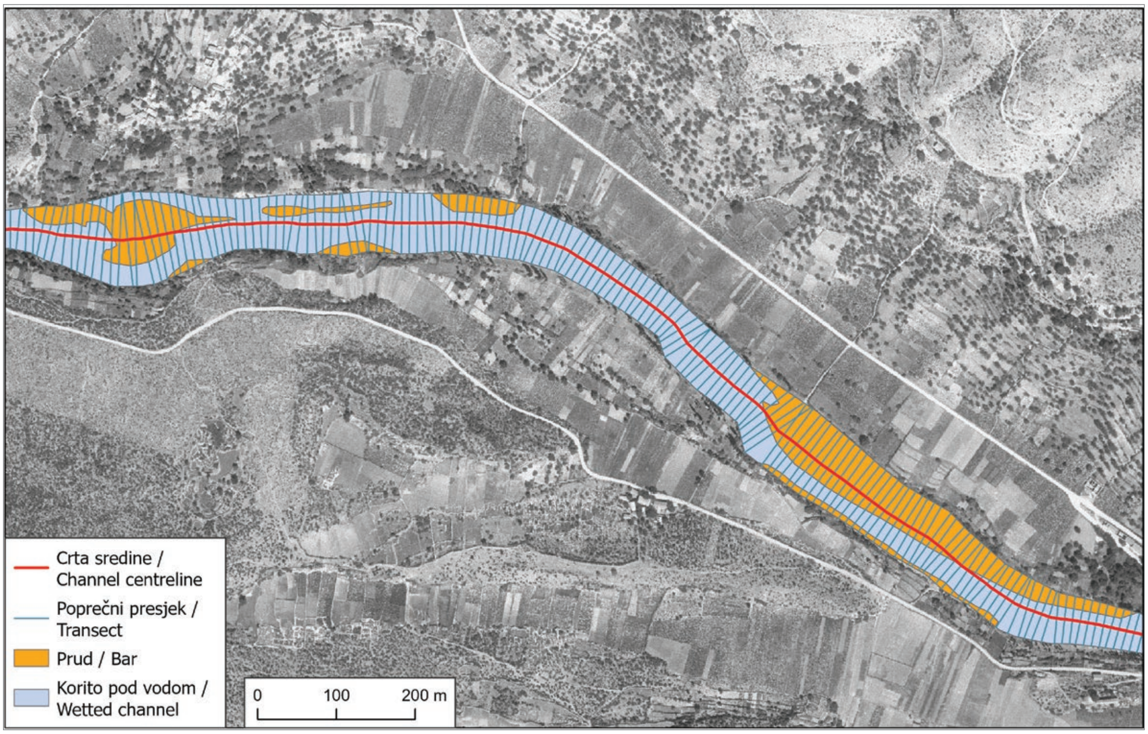
Geomorfološka obilježja tekućica koja se analiziraju u studijama geomorfoloških promjena tekućica prikazana su u tablici 2. Najčešće analizirano obilježje jest širina aktivnoga korita koje se sastoji od korita pod vodom i prudova bez vegetacije (Provansal i dr., 2014; Martínez-Fernández i dr., 2017; Scorpio i Piégay, 2021). Širina aktivnoga korita može se izračunati dijeljenjem njegove površine s duljinom crte sredine ili na temelju prosječne duljine poprečnih presjeka na crtu sredine (sl. 3). Duljina korita također se najčešće mjeri crtom sredine aktivnoga korita (detalji izmjere na primjeru Hrvatske predstavljeni su u radu Čanjevca i dr., 2022). Vrlo moćan alat u analizi tih obilježja jest geografski informacijski sustav u kojem je moguće integrirati podatke iz raznovrsnih izvora na svim prostornim razinama (porječje, naplavna ravnica, riječno korito), ali i automatizirati izdvajanje određenih jedinica i analizu njihovih obilježja (Roux i dr., 2015).

Odabir obilježja koja će se analizirati ovisi o morfološkom tipu tekućice; primjerice bočno kretanje ima smisla analizirati samo kod reljefno neograničenih tekućica, dok se s druge strane pojavnost prudova i otoka može analizirati i kod reljefno ograničenih i kod neograničenih tekućica. Morfološki tip tekućica moguće je odrediti na temelju mnogobrojnih klasifikacija (npr. Nanson i Knighton, 1996; Fryirs i Brierley, 2013) koje iako su raznovrsne, dijele mnoga zajednička obilježja. Morfološki tipovi tekućica prvenstveno se određuju na temelju oblika korita, reljefne ograničenosti i obilježja sedimenta dna (Brierley i Fryirs, 2005; Rinaldi i dr., 2016). Prema klasifikaciji Rinaldija i dr. (2016), koja se koristi u okviru projekta REFORM, oblik korita rijeka prvenstveno se dijeli prema broju rukavaca u poprečnom presjeku. Jednostavni oblik korita sastoji se od jednoga korita, dok se složeni oblik sastoji od više rukavaca od kojega jedan može i ne mora biti glavno korito. Druga razina podjele odnosi se na reljefnu ograničenost korita s obzirom na riječnu dolinu. Reljefno ograničene tekućice teku klancima (kanjonima) (sl. 4A), dok se reljefno neograničene tekućice nalaze u aluvijalnim ravnicama (sl. 4B-F). Jednostavne reljefno neograničene tekućice dalje se

Change indicators and channel morphology types

The geomorphological characteristics which are analysed in studies of geomorphological change in rivers are listed in Table 2. The most commonly analysed characteristic is the width of the active channel, which consists of the wetted channel and the non-vegetated bars (Provansal et al., 2014; Martínez-Fernández et al., 2017; Scorpio and Piégay, 2021). The width of the active channel can be calculated by dividing its area by the centreline length, or based on the average length of transects perpendicular to the centreline (Fig. 3). The length of the channel is also usually measured using the centreline of the active channel (the details of the measurement for the example of Croatian rivers are presented in the study by Čanjevac et al., 2022). A very powerful tool for the analysis of these features is geographic information systems (GIS), where it is possible to integrate data from different sources at all spatial scales (catchment, floodplain, channel), and also to automate the extraction of specific units and the analysis of their characteristics (Roux et al., 2015).

The choice of features to be analysed depends on the morphological type of the river; for example, lateral shift can only be analysed for unconfined rivers, whereas the occurrence of bars and islands for both confined and unconfined rivers. The morphological type of a river can be determined using numerous and varied classifications (e.g. Nanson and Knighton, 1996; Fryirs and Brierley, 2013) that share many common characteristics. Morphological river types are primarily determined based on channel planform, valley confinement and bed sediment structure (Brierley and Fryirs, 2005; Rinaldi et al., 2016). According to the classification of Rinaldi et al. (2016), used in the REFORM project, channel morphology is classified primarily by the number of branches in the cross-section. A single-thread type consists of one channel, while a multi-thread type consists of multiple branches, one of which may or may not be the main channel. The second level of subdivision refers to river valley confinement. Confined rivers flow through canyons (Fig. 4A), while unconfined rivers occur in alluvial plains (Fig. 4B-F). Single-thread unconfined rivers are further



Sl. 3. Prikaz vektoriziranih prudova i korita pod vodom te konstruirane crte sredine i poprečnih presjeka na primjeru rijeke Cetine kod Blata na Cetini
Kartografska podloga: DGU (1960)

Fig. 3 Vectorized bars and wetted channel along with the constructed centreline and transects on the example of the Cetina River near Blato na Cetini
Cartographic background: SGA (1960)

dijele na ravne, vijugave (engl. *sinuous*, sl. 4B) i meandrirajuće (sl. 4C). S druge strane, složena korita (reljefno orgraničena ili ne) mogu biti isprepletena (engl. *braided*) i razgranata (engl. *anabranching*).

Oblik korita određuje se na temelju kvantitativnih indeksa i geomorfoloških obilježja korita i naplavne ravnice. Distinkcija između ravnoga, vijugavoga i meandrirajućega korita temelji se na indeksu vijugavosti, koji se računa kao omjer ukupne duljine riječnoga toka i crte sredine riječne doline (ili općenitoga smjera pružanja rijeke ili središnjice pojasa meandriranja). Ako je indeks veći od 1.05, rijeka je vijugava, a ako je veći od 1.5, ona je meandrirajućega oblika korita (Rinaldi i dr., 2015). Isprepletena i razgranata korita razlikuju se u tome što su rukavci isprepletenoga korita odijeljeni prudovima (sl. 4D), a kod razgranatoga korita odijeljeni su stabilnim riječnim otocima prekrivenima vegetacijom (sl. 4E). Riječni otoci mogu nastati erozijom naplavne ravnice, mogu biti

subdivided into straight, sinuous (Fig. 4B) and meandering (Fig. 4C). On the other hand, multi-thread channels (confined or unconfined) can be braided or anabranching.

The channel planform is determined based on quantitative indices and an assemblage of geomorphological units of the channel and floodplain. The distinction between a straight, sinuous and meandering channel is based on the sinuosity index, which is calculated as the ratio between total channel length and the centerline of the river valley (or the general direction of the river, or the centerline of the meander belt). If the index is greater than 1.05, the river is sinuous, and if it is greater than 1.5, it has a meandering channel planform (Rinaldi et al., 2015). Braided and anabranching channels differ in that the branches of the braided channel are separated by unvegetated bars (Fig. 4D), while those of an anabranching channel are separated by stable river islands covered with vegetation (Fig. 4E). Riv-

Tab. 2. Geomorfološka obilježja kao pokazatelji promjena tekućica
Tab. 2 Geomorphological characteristics as indicators of river changes

Obilježja / Characteristics	**Literatura** / Literature	**Izvori podataka** / Data sources
Duljina korita / Channel length	Hooke and Harvey (1983), Bognar (1990, 2008), Kiss et al. (2008), Kiss and Blanka (2012), Magliulo et al. (2013, 2016), Ioana-Toroimac (2016), Spada et al. (2018), Hohensinner et al. (2021)	Karte, daljinska istraživanja, terensko kartiranje / Maps, remote sensing, field survey
Širina aktivnog korita / Active channel width	Liébault and Piégay (2002), Boix-Fayos et al. (2007), Kiss et al. (2008), Swanson et al. (2011), Kiss and Blanka (2012), Magliulo et al. (2013, 2016), Provensal et al. (2014), Scorpio et al. (2015), Gurnell and Grabowski (2016), Ioana-Toroimac (2016), Kiss and Andrási (2017), Martínez-Fernández et al. (2017), Spada et al. (2018), Hajdukiewicz et al. Wyżga (2019), Scorpio and Piégay (2021)	Karte, daljinska istraživanja, terensko kartiranje / Maps, remote sensing, field survey
Nadmorska visina dna korita (poprečni presjek korita) / Channel bed elevation (channel cross section)	Surian and Rinaldi (2003), Kiss et al. (2008), Downs et al. (2013), Scorpio et al. (2015), Kiss and Andrási (2017), Fortugno et al. (2017), Kidova et al. (2021)	Topografski premjeri, terensko mjerenje (totalna stanica, GNSS uređaj) / Topographic surveys, field survey (total station, GNSS device)
Oblik korita / Channel pattern	Surian and Rinaldi (2003); Scorpio et al. (2015), Ioana-Toroimac (2016), Kiss and Andrási (2017), Hohensinner et al. (2021), Scorpio and Piégay (2021)	Karte, daljinska istraživanja / Maps, remote sensing
Indeks vijugavosti / Sinuosity indeks	Hooke and Harvey (1983), Hohensinner et al. (2004), Magliulo et al. (2013, 2016), Gurnell and Grabowski (2016), Spada et al. (2018)	Karte, daljinska istraživanja, terensko kartiranje / Maps, remote sensing, field survey
Indeks isprepletenosti / površina ili broj rukavaca / Braiding index / area or number of branches	Hohensinner et al. (2004), Martínez-Fernández et al. (2017), Hajdukiewicz and Wyżga (2019)	Karte, daljinska istraživanja / Maps, remote sensing
Broj meandara (na odsječku) / Number of meanders (on reach-level)	Bertalan et al. (2019)	Karte, daljinska istraživanja / Maps, remote sensing
Obilježja meandara (amplituda, dužina luka između infleksija, dužina između infleksija, radijus, valna duljina) / Characteristics of meanders (amplitude, bend length, chord, radius, wavelength)	Hooke and Harvey (1983), Bognar (1990, 2008), Kiss et al. (2008), Hooke and Yorke (2010), Bertalan et al. (2019)	Karte, daljinska istraživanja, terensko kartiranje / Maps, remote sensing, field survey
Tip promjene (razvoja) meandara / Type of change (development) of meanders	Hooke and Yorke (2010), Dépret et al. (2017)	Karte, daljinska istraživanja, terensko kartiranje / Maps, remote sensing, field survey
Stopa bočnog kretanja rijeke / Lateral movement rate	Hooke and Yorke (2010), Kiss and Blanka (2012), Dépret et al. (2017), Bertalan et al., (2019)	Karte, daljinska istraživanja, terensko kartiranje / Maps, remote sensing, field survey
Površina ili broj otoka / prudova / Area or number of islands / bars	Hohensinner et al. (2004), Boix-Fayos et al. (2007), Hooke and Yorke (2011), Swanson et al. (2011), Magliulo et al. (2013, 2016), Ioana-Toroimac (2016), Kiss and Andrási (2017), Hajdukiewicz and Wyżga (2019), Kidova et al. (2021), Grecu et al. (2022)	Karte, daljinska istraživanja, terensko kartiranje / Maps, remote sensing, field survey
Dinamika donosa i pronosa sedimenta / Sediment supply and transport dynamics	Keesstra et al. (2005), Keesstra et al. (2009), Provensal et al. (2014)	Terensko i laboratorijsko sedimentološko i stratigrafsko istraživanje, datiranje / Field and laboratory sedimentological and stratigraphic research, dating
Granulometrijski sastav sedimenta u koritu (prudovi, dno) / Granulometric composition of the bed sediment (bars, wetted bed)	Boix-Fayos et al. (2007), Fortugno et al. (2017)	Terensko i laboratorijsko sedimentološko istraživanje / Field and laboratory sedimentological research
Stabilnost / erozija obala / Stability / erosion of riverbanks	Henshaw et al. (2012), Klösch et al. (2015), Zhang et al. (2019)	Karte, daljinska istraživanja, terenska mjerenja / Maps, remote sensing, field measurements
Stratigrafija poplavne ravnice / Floodplain stratigraphy	Keesstra et al. (2005), Keesstra (2007), Provensal et al. (2014)	Terensko i laboratorijsko sedimentološko i stratigrafsko istraživanje, datiranje / Field and laboratory sedimentological and stratigraphic research, dating

nastavak Tab. 2. Geomorfološka obilježja kao pokazatelji promjena tekućica
continued Tab. 2 Geomorphological characteristics as indicators of river changes

Obilježja / Characteristics	Literatura / Literature	Izvori podataka / Data sources
Agradacija / erozija poplavne ravnice / Aggradation / erosion of the floodplain	Keesstra (2007), Hooke and Yorke (2010), Dépret et al. (2017), Bertalan et al., (2019)	Karte, daljinska istraživanja, sedimentološke metode, datiranje / Maps, remote sensing, sedimentological methods, dating
Priobalna vegetacija / Riparian vegetation	Martínez-Fernández et al. (2017), Hajdukiewicz and Wyżga (2019)	Karte, daljinska istraživanja, terensko kartiranje / Maps, remote sensing, field survey
Zemljišni pokrov (vegetacija) poplavne ravnice / Land cover (vegetation) in the floodplain	Liébault and Piégay (2002), Hajdukiewicz and Wyżga (2019), Scorpio and Piégay (2021)	Karte, daljinska istraživanja, terensko kartiranje, dendrokronologija / Maps, remote sensing, field survey, dendrochronology
Zaštitne građevine na obalama (obaloutvrde) / Bank protections	Scorpio et al. (2015), Dépret et al. (2017), Hajdukiewicz and Wyżga (2019)	Karte, daljinska istraživanja, terensko kartiranje, baze podataka vodoprivredne uprave / Maps, remote sensing, field survey, databases of the water management administration

posljedica taloženja unutar korita ili se mogu formirati progradacijom rukavaca unutar plavine ili delte (Nanson i Knighton, 1996). U literaturi se kao sinonim razgranatim rijekama javlja i pojam anastomozirajuće rijeke (engl. *anastomosing*), no one se u posljednje vrijeme većinom klasificiraju kao podtip razgranatih rijeka koje su obilježene malom energijom toka (Fryirs i Brierley, 2013; Rinaldi i dr., 2015). Promjene u tlocrtnom obliku za isprepletene i razgranate rijeke mogu se analizirati na temelju indeksa isprepletenosti/razgranatosti (tab. 2). Postoji više načina za njihov izračun: zbroj rukavaca odijeljenih prudovima/otocima pri niskom vodostaju (Rinaldi i dr., 2015); duljina svih rukavaca podijeljena s duljinom glavnoga korita (Knighton, 1998) ili kao udvostručena duljina svih prudova podijeljena duljinom odsječka (Fryirs i Brierley, 2013).

U Hrvatskoj su rijeke sa složenim tipom korita uglavnom rijetke, dijelom zbog reguliranja vodotoka, dijelom zbog prirodnih čimbenika. Isprepletena korita, koja općenito podrazumijevaju veću energiju toka i velik donos sedimenta, što je obilježje planinskih okoliša, vrlo su rijetka na području Hrvatske te se vjerojatno samo mjestimice javljaju na manjim vodotocima u područjima veće energije reljefa. Razgranata korita s malom energijom toka (tj. anastomozirajuća korita) u Hrvatskoj je moguće naći u poljima u kršu, npr. Cetina u Cetinskom polju i prije 1950-ih u Sinjskom polju (Pavlek i Faivre, 2020).

er islands may be formed by erosion of the floodplain, sedimentation within the channel, or by progradation of branches within the floodplain or delta (Nanson and Knighton (1996). In the literature, the term *anastomosing river* is sometimes used as a synonym for anabranching rivers, but more recently they have been classified as a subtype of anabranching rivers characterized by low-energy conditions (Fryirs and Brierley, 2013; Rinaldi et al., 2015). Changes in the planform for braided and anabranching rivers can be analysed using the braiding/anabranching index (Tab. 2). There are several options for the calculation: the sum of branches separated by bars/islands at low water level (Rinaldi et al., 2015); the length of all branches divided by the length of the main channel (Knighton, 1998); or as the doubled length of all bars divided by the length of the reach (Fryirs and Brierley, 2013).

In Croatia, rivers with multi-thread channel morphology are rather rare, partly due to river regulation and partly due to natural factors. Braided channels, which generally imply high-energy conditions and a large sediment supply (characteristic for mountainous environments), are very rare in Croatia and probably occur only in smaller streams in areas with higher relative relief. Anabranching rivers with low-energy conditions (i.e. anastomosing rivers) are found in karst poljes in Croatia (e.g. Cetina in Cetinsko and pre-1950s in Sinjsko Polje, Pavlek and Faivre, 2020). Since there are often no clear bound-

Sl. 4. Različiti tipovi korita: A) reljefno ograničeno korito Čikole nizvodno od Drniša, B) vijugavo korito Orljave kod Brodskog Drenovca, C) meandrirajuće korito Drave kod Petrijevaca, D) isprepleteno korito rijeke Tagliamento (Italija), E) razgranato (anastomozirajuće) korito rijeke Narew (Poljska)

Fig. 4. Various channel morphology types: A) confined channel of the Čikola River downstream from Drniš, B) sinuous channel of the Orljava River near Brodski Drenovac, C) meandering channel of the Drava River near Petrijevci, D) braided channel of the Tagliamento River (Italy), E) anabranching (anastomosing) channel of the Narew River (Poland)

Izvori: ArcGIS Pro (2022) (A, D, E); DGU (2019) (B, C)

Sources: ArcGIS Pro (2022) (A, D, E); SGA (2019) (B, C)

Budući da u prirodi često nema jasnih granica, postoje i prijelazni oblici korita, pogotovo kod velikih tekućica. Primjerice, složeni tip korita koji su prije regulacija imale rijeka Sava kod Zagreba i Drava kod Varaždina (sl. 5) obilježen je većim brojem rukavaca koji su djelomice odijeljeni prudovima, a

aries in nature, there are also transitional forms of channels, especially in large rivers. For example, the multi-thread channels of the Sava River near Zagreb and Drava River near Varaždin before regulation (Fig. 5) were characterised by a large number of branches, some separated by bars and others by veg-

Sl. 5. Složeno korito Drave nizvodno od Varaždina prije 1968.

Fig. 5 The multi-thread channel of the Drava River downstream of Varaždin before 1968

Izvor: DGU (1968)

Source: SGA (1968)

djelomice otocima s vegetacijom ili dijelovima naplavne ravnice. Prijelazni tip između jednostavnih i složenih korita u literaturi se naziva *wandering channel* (Brierley i Fryirs, 2005; Rinaldi i dr., 2016). Tom tipu odgovara korito Cetine iz 1951. godine prikazano na slici 2.

Glavni uzroci promjena

Kao uzroci geomorfoloških promjena tekućica u istraživanjima se navode dvije glavne skupine čimbenika: prirodne promjene i antropogeni utjecaji. Antropogeni utjecaji podrazumijevaju aktivnosti upravljanja vodotocima izgradnjom hidrotehničkih građevina za razne namjene poput zaštite od poplava, plovidbe i proizvodnje hidroenergije. Neke od najčešćih hidrotehničkih građevina su pregrade na tekućicama (brane, stepenice, preljevi i dr.), nasipi, obaloutvrde (sprečavaju eroziju obale) te aktivnosti kanaliziranja toka[2], izravnavanja toka, presijecanja meandara i uklanjanja priobalne vegetacije. Navedene mjere lokalno fizički mijenjaju izgled korita,

2 Kanaliziranje vodotoka podrazumijeva promjenu poprečnoga profila korita i inundacijskoga područja, promjenu/izravnavanje trase korita i promjenu razine dna korita u cilju povećanja protočnosti korita prirodnoga vodotoka.

etated islands or parts of the floodplain. The transitional type between single-thread and multi-thread channels is referred to in the literature as a wandering channel (Brierley and Fryirs, 2013; Rinaldi et al., 2016). The 1951 channel of the Cetina River shown in Figure 2 corresponds to this type.

The main causes of change

Two main groups of factors are mentioned in the literature as causes of geomorphological change in rivers: natural factors and human impacts. The latter includes the management of rivers through the construction of hydrotechnical structures for various purposes such as flood protection, navigation, and hydropower generation. The most common engineering works include various types of barriers (dams, weirs, sluices, etc.), embankments (artificial levees), bank protection (to prevent bank erosion), channelization[2], straightening, meander cut-offs and removal of riparian vegetation. The aforementioned measures not only alter the appearance of the chan-

2 River channelization implies a change in channel cross-section and inundation area, a change/straightening of the channel course, and a change in the bed elevation in order to increase the flow capacity of the natural channel.

ali također mogu utjecati na dinamiku erozijsko-sedimentacijskih procesa uzvodno i nizvodno zbog promjena u longitudinalnoj, lateralnoj, vertikalnoj i temporalnoj povezanosti prijenosa vode i sedimenta. Naime, brane predstavljaju prekid u longitudinalnoj povezanosti; nizvodno dolazi do reguliranja protoka vode i smanjenja prijenosa sedimenta, što često rezultira sužavanjem korita, usijecanjem i nestankom prudova, dok u uzvodnim akumulacijama dolazi do pojačane sedimentacije te posljedično i eutrofikacije (Hooke, 2006; Swanson i dr., 2011). S druge strane, obaloutvrde sprečavaju lateralno kretanje rijeke i eroziju obala kao prirodni izvor sedimenta u koritu, dok nasipi sprečavaju lateralnu povezanost korita i naplavne ravnice (Hohensinner i dr., 2004). Važan antropogeni utjecaj jest i jaružanje korita, odnosno vađenje sedimenta i produbljivanje korita da bi se dobio građevni materijal i poboljšala plovnost tekućice (Surian i Rinaldi, 2003; Provansal i dr., 2014). U indirektne antropogene utjecaje na razini porječja spadaju promjene zemljišnoga pokrova poput deforestacije, urbanizacije i dr. (Scorpio i Piégay, 2021). Naime, količina sedimenta, odnosno stopa erozije tla u porječju ovisi o zemljišnom pokrovu. Mnoge su studije dokazale da je stopa erozije tla veća na poljoprivrednom zemljištu nego primjerice na travnjacima ili u šumama (Garcia-Ruiz i dr., 2013).

Najvažniji prirodni čimbenici jesu promjene u klimatskim i geološkim obilježjima iako geološki procesi (npr. tektonika) većinom djeluju tijekom duljega razdoblja te se rijetko izravno analiziraju u istraživanjima koja pokrivaju posljednjih dvjestotinjak godina, izuzev recimo potresa koji mogu uzrokovati aktivaciju klizišta (Gong i dr., 2012). Prema tome, najznačajniji analizirani prirodni čimbenik jest klima, tj. njezin izravan utjecaj na hidrološka obilježja tekućice[3]. Klimatski čimbenici analiziraju se na temelju klimatskih i hidroloških podataka, pri čemu prednjače ovi potonji jer je protok izravni pokretač geomorfoloških procesa. Od hidroloških

3 Iako se klimatske promjene u razdobljima do 19. stoljeća mogu smatrati prirodnim čimbenikom, danas u doba globalnoga zatopljenja i one spadaju u neizravne antropogene utjecaje. Međutim, radi razgraničenja s navedenim fizičkim promjenama korita i naplavne ravnice koje je izravno uzrokovao čovjek promatraju se odvojeno. Naravno, treba napomenuti da čovjek može izravno mijenjati i hidrološka obilježja tekućica izgradnjom brana, crpljenjem vode za vodoopskrbu i sl.

nel at the local scale, but can also affect the dynamics of upstream and downstream erosion and deposition processes by altering the longitudinal, lateral, vertical and temporal connectivity of water and sediment transport. Dams represent a break in longitudinal connectivity; downstream, flow is regulated and sediment flux is reduced, which often results in channel narrowing, incision, and stabilization of bars, while upstream reservoirs experience increased sedimentation and consequent eutrophication (Hooke, 2006; Swanson et al., 2011). On the other hand, bank protections prevent the lateral shift of the channel and bank erosion, which is a natural source of sediment in the channel, while levees impede the lateral connectivity between the channel and the floodplain (Hohensinner et al., 2004). Moreover, a significant human impact is channel dredging, i.e. the extraction of sediment and channel deepening in order to obtain construction material and improve the navigability of the river (Surian and Rinaldi, 2003; Provensal et al., 2014). Indirect human impacts at the catchment scale include land cover changes such as deforestation, urbanization, etc. (Scorpio and Piégay, 2021). Indeed, sediment production, i.e. the rate of soil erosion in the catchment depends on land cover. Many studies have shown that soil erosion is higher on agricultural land than on grasslands or forests (Garcia-Ruiz et al., 2013).

The most important natural factors are changes in climatic and geological characteristics. However, geological processes (i.e. tectonics) mostly operate over a long period of time and are thus rarely analysed directly in the research of the last two hundred years (with the exception of phenomena like earthquakes, which can cause landslide activation (Gong et al., 2012)). Therefore, the most important natural factor studied is climate, i.e. its direct influence on the hydrological characteristics of rivers[3]. Climatic factors are studied from climatic and hydrological data, with the latter being predominant, since flow of water is a direct driver of geomorpho-

3 Although climate change in the periods up to the 19th century can be considered a natural factor, today, in the era of global warming, they are also part of indirect human impacts. However, to distinguish them from the aforementioned physical changes in the channel and floodplain that are directly caused by humans, they are considered separately. Of course, it should be noted that hydrological features can also be directly altered by humans, e.g. by the construction of dams, pumping of water for water supply, etc.

elemenata analizira se kretanje godišnjih maksimuma, srednjaka i minimuma, trajanje protoka i/ili vodostaja (npr. Kiss i Blanka, 2012) i učestalost poplava (npr. učestalost vrijednosti iznad određene granice, engl. *frequency of peaks over threshold*, Hooke i Yorke, 2011, ili trajanje izlijevanja vode izvan korita, Kiss i Andrási, 2017). Detaljna analiza klimatoloških i hidroloških podataka moguća je ako su dostupni relevantni instrumentalni podatci. Iako su za veće rijeke instrumentalna mjerenja dostupna za 19. stoljeće (npr. Rhône, Provansal i dr., 2014), za mnoge tekućice najstariji pouzdani podatci su iz druge polovine 20. stoljeća (Bertalan i dr., 2019; Kiss i Blanka, 2012). Kada instrumentalni podatci nisu dostupni, zaključci o hidrološkim i klimatskim uvjetima donose se na temelju sedimentoloških analiza (Keesstra i dr., 2005; Faivre i dr., 2019).

logical processes. Of the hydrological elements, the indicators studied include annual maxima, mean, minima, and duration of discharges and/or water levels (e.g. Kiss and Blanka, 2012), and the frequency of floods (e.g. frequency of peaks above threshold, Hooke and Yorke, 2011; number of overbank flood days, Kiss and Andrási, 2017). A detailed analysis of climatological and hydrological data is possible when appropriate instrumental data are available. Although instrumental measurements for the 19th century are available for major rivers (e.g. Rhône, Provansal et al., 2014), for many rivers the oldest reliable data are from the second half of the 20th century (Bertalan et al., 2019; Kiss and Blanka, 2012). When instrumental data are not available, inferences about hydrologic and climatic conditions are based on sedimentological analyses (Keesstra et al., 2005; Faivre et al., 2019).

Pregled rezultata istraživanja

Većina analiziranih istraživanja promjena riječnih korita u svijetu bavi se razdobljem od posljednjih 150 godina, što je u skladu s pojavom prvih topografskih karata detaljnije izmjere i točnosti sredinom 19. stoljeća (Downs i Piégay, 2019). Mogu se izdvojiti tri glavne faze u kojima su zabilježeni različiti trendovi: od sredine 19. stoljeća do sredine 20. stoljeća, od sredine 20. stoljeća do 1990-ih te posljednjih 30-ak godina na prijelazu u 21. stoljeće.

Overview of research results

Most of the analysed research on channel change refers to the period of the last 150 years, which is in accordance with the appearance of the first topographic maps with detailed measurements and accuracy in the middle of the 19th century (Downs and Piégay, 2019). Three main phases can be distinguished, during which various trends were observed: from the middle of the 19th century to the middle of the 20th century; from the middle of the 20th century to the 1990s; and the last 30 years around the turn of the 20th century to the 21st century.

Prvo razdoblje (1850. – 1950./60.)

Prvo razdoblje do sredine 20. stoljeća obilježeno je raznovrsnošću zabilježenih promjena koje su vjerojatno rezultat različitih antropogenih utjecaja. U Australiji su velike promjene korita nakon europske kolonizacije uzrokovane pokretanjem velike količine sedimenta zbog uklanjanja priobalne i močvarne vegetacije (Fryirs i Brierley, 2001). U Europi intenzifikacija poljoprivrede i šumarstva dovodi do deforestacije i povećanja donosa sedimenta na pojedinim rijekama što uzrokuje agradaciju korita, odnosno širenje i povećanje količine prudova u koritu (Keesstra i dr., 2005; Magliulo i

The first period (1850s–1950/60s)

The first period is characterized by a variety of recorded changes, probably due to various human impacts. In Australia, following European settlement, major channel changes were caused by the movement of large quantities of sediment resulting from the removal of riparian and wetland vegetation (Fryirs and Brierley, 2001). In Europe, intensification of agriculture and forestry led to deforestation and increased sediment supply in certain rivers, resulting in channel aggradation, i.e. expansion and enlargement of bars in the channel (Keesstra et al., 2005; Magliulo et al., 2016). Also, the progradation of river mouths dr., 2016). Također je zabilježena progradacija riječnih ušća (Kapsimalis i dr., 2005). Na području Hrvatske Benac i dr. (2017) zabilježili su progradaciju ušća Mirne (350 m) i Raše (4 km) uslijed pojačane poljoprivredne aktivnosti i erozije flišnoga zaleđa u razdoblju 1850. – 1950. Progradaciju naplavne ravnice od 500 m zabilježile su i Pavlek i Faivre (2020) na ušću Cetine, kao i pojačan razvoj prudova i širenje korita na određenim odsječcima rijeke.

Usprkos maloj količini instrumentalnih podataka u literaturi se u ovom razdoblju često spominje i utjecaj klimatskih promjena jer je to razdoblje prelaska iz Maloga ledenog doba u trenutni topli period (engl. *Current Warm Period*) (Provansal i dr., 2014; Scorpio i dr., 2015). Iako je vrhunac Malog ledenog doba u Europi bio u 16./17.st., krajem 19. stoljeća mediteranska je klima još uvijek bila obilježena nižim temperaturama i većom vlažnosti nego sredinom 20. stoljeća (Luterbacher i dr., 2012). Vlažniji uvjeti pogoduju taloženju nakon velikih poplava, progradaciji ušća, i unosu sedimenta u korito putem pojačanih padinskih procesa (Scorpio i dr., 2015).

S druge strane, na velikim rijekama koje teku gusto naseljenim područjima poput Dunava (Hohensinner i dr., 2004), Tise (Kiss i dr., 2008) ili Rhône (Provansal i dr., 2014) mjere kanaliziranja i izravnavanja korita uzrokovale su usijecanje i sužavanje korita i naplavne ravnice već tijekom 19. stoljeća. Navedene mjere provođene su ponajprije radi poboljšanja plovnosti, isušivanja naplavne ravnice i zaštite od poplava.

U Hrvatskoj su na rijeci Dravi regulacijski radovi započeli tijekom 18. stoljeća, no najvažnije aktivnosti izvedene su od sredine 19. stoljeća (Bognar, 1990). Zbog presijecanja meandara u cilju povećanja protočnosti zabilježene su bitne promjene u duljini toka: na području Križnice duljina korita smanjila se 73 % u razdoblju 1842. – 1886., dok je do 1960-ih zabilježen manji porast zbog prirodne dinamike razvoja meandara (Bognar, 2008). Na dionici između Repaša i Ferdinandovca duljina toka smanjila se za otprilike 25 % u razdoblju 1869. – 1941. (Pavlek i dr., 2022). Nadalje, prosječno smanjenje širine korita s 513 m na 361 m na cijeloj graničnoj duljini toka Drave između Hrvatske i

has also been noted (Kapsimalis et al., 2005). In the territory of Croatia, Benac et al. (2017) found that the mouths of the Mirna (350 m) and Raša (4 km) rivers increased in size due to increasing agricultural activity and erosion of the flysch hinterland in the 1850–1950 period. Pavlek and Faivre (2020) also recorded the progradation of the floodplain by 500 m in the Cetina River mouth, as well as the increasing development of bars and the widening of the river channel in certain reaches.

Despite the scarcity of instrumental data, the influence of climate change during this period is frequently mentioned in the literature because it is the period of transition from the Little Ice Age to the Current Warm Period (Provansal et al., 2014; Scorpio et al., 2015). Although the peak of the Little Ice Age in Europe was in the 16th/17th century, the Mediterranean climate in the late 19th century was characterized by lower temperatures and higher humidity than in the mid-20th century (Luterbacher et al., 2012). Such wetter conditions favour sedimentation following large floods, progradation of river mouths, and sediment input to channels via more intensive slope processes (Scorpio et al., 2015).

In contrast, on large rivers flowing through densely populated areas, such as the Danube (Hohensinner et al., 2004), Tisa (Kiss et al., 2008), or Rhône (Provansal et al., 2014), channelization and straightening measures led to incision and narrowing of channels and floodplains in the 19th century. The aforementioned measures primarily served to improve navigability, drain floodplains, and protect against flooding.

In Croatia, regulation works on the Drava River began in the 18th century, but the most significant activities were carried out starting in the middle of the 19th century (Bognar, 1990). Artificial meander cutting in order to increase flow capacity caused significant changes in channel length: in the Križnica area, river length decreased by 73% in the 1842–1886 period, while until the 1960s there was a small increase in length following natural dynamics of meander development (Bognar, 2008). In the section between Repaš and Ferdinandovac, the length of the channel decreased by about 25% in the 1869–1941 period (Pavlek et al., 2022). In addition, Kiss and Andrási (2017) recorded an average reduction in channel width from 513 m to 361 m over the entire border

Mađarske od kraja 19. stoljeća do 1960-ih zabilježili su Kiss i Andrási (2017). Značajno je smanjen i broj otoka: do 1960-ih 75 % otoka spojilo se s naplavnom ravnicom. Posljedično je Drava promijenila oblik korita: u svom prirodnom stanju početkom 19. stoljeća rijeka je do Terezina polja imala složeni oblik korita (sl. 5), dok je nizvodno on bio meandrirajući. Međutim, sredinom 20. stoljeća zbog brojnih presijecanja meandara oblik korita Drave većinom je postao jednostavan i vijugav, s kraćim isprepletenim odsječcima nizvodno od lokacija presječenih meandara, koji se razvijaju zbog povećana nagiba i erozije obala (Kiss i Andrási, 2017).

Slične promjene zabilježene su i na rijeci Savi, čija je regulacija u Zagrebu započela krajem 19. st., a završno kanaliziranje i izgradnja nasipa obavljeni su nakon katastrofalne poplave u Zagrebu 1964. godine (Slukan Altić, 2010). Sredinom 19. stoljeća širina složenoga korita Save, obilježena mnogim rukavcima, prudovima i otocima (Trenc i dr., 2019), iznosila je od 200 pa do više od 1000 metara, a duljina rijeke, izračunata prema glavnom, najširem koritu, od Podsusedskog mosta do današnjega mosta Sava – Ivanja Reka iznosila je nešto više od 34 kilometara. Danas duljina reguliranoga korita iznosi 28 kilometara, a prosječna širina oko 100 metara (Pavlek, 2019).

Drugo razdoblje (1950./60. – 1990.)

Od sredine 20. stoljeća u svijetu su zabilježene najintenzivnije promjene riječnih korita, prvenstveno sužavanje i usijecanje. U literaturi se to razdoblje naziva „veliko ubrzanje" tijekom recentnoga antropocena, razdoblja obilježenog značajnim antropogenim utjecajima koji uzrokuju ubrzavanje prirodnih procesa (Brown i dr., 2017). Iako Downs i Piégay (2019) zbog premaloga broja jasnih statističkih dokaza preispituju „nadmoćan" antropogeni utjecaj koji se često uzima kao glavni razlog svih promjena, činjenica je da evolucija riječnih korita u tom razdoblju potvrđuje postojanje „velikoga ubrzanja". Usijecanje i sužavanje rijeka povezuje se s raširenim kanaliziranjem i jaružanjem korita te velikim brojem izgrađenih brana. Poulos i Collins (2002) procijenili su da u sredozemnom slijevu donos sedi-

length of the Drava River between Croatia and Hungary from the end of the 19th century to the 1960s. The number of islands also dropped significantly: by the 1960s, 75% of the islands had merged with the floodplain. As a result, the Drava changed its channel planform: in its natural state at the beginning of the 19th century, the river had a multi-thread channel up to Terezino Polje (Fig. 5), while downstream it was meandering. However, in the mid-20th century, due to numerous meander cut-offs, the channel planform of the Drava became mostly single-thread and sinuous, with shorter braided sections downstream of the meander cut-offs that developed due to increased slope and bank erosion (Kiss and Andrási, 2017).

Similar changes were also observed on the Sava River, for which regulation works began in Zagreb at the end of the 19th century. The final channelization and levee construction took place after the Zagreb flood disaster in 1964 (Slukan Altić, 2010). In the mid-19th century, the width of the multi-thread channel of the Sava, characterized by many branches, bars and islands (Trenc et al., 2019), ranged from 200 to more than 1,000 meters. River length, calculated following the main, widest channel, from Podsused Bridge to the current Sava-Ivanja Reka Bridge was slightly more than 34 kilometres. Today, the length of the regulated channel is 28 kilometres, and the average width is about 100 meters (Pavlek, 2019).

The second period (1950/60s–1990s)

Since the middle of the 20th century, the most intense channel changes have been recorded worldwide, primarily narrowing and incision. In the literature, this period is referred to as the "Great Acceleration" during the recent Anthropocene, which itself is a period characterized by significant human impacts causing an acceleration of natural processes (Brown et al., 2017). Although Downs and Piégay (2019) questioned the "overwhelming" human influence often considered as the main cause of all modifications due to the lack of clear statistical evidence; the fact is that the evolution of channels during this period confirms the existence of a "great acceleration". The incision and narrowing of rivers are related to widespread channelization and dredging, as well as the construction of numerous dams. Poulos and Collins (2002) estimated that in the menta na prijelazu u 21. stoljeće iznosi samo 50 % od pretpostavljenih prirodnih količina zbog izgradnje brana, što dovodi do erozije delta rijeka poput Poa, Ebra ili Nila. Liébault i Piégay (2002) navode da sužavanje korita pojedinih rijeka u jugoistočnoj Francuskoj iznosi čak 55 % u drugoj polovini 20. stoljeća, uz promjenu morfološkoga tipa korita iz isprepletenoga u meandrirajuće. U Europi su takvi procesi posebno rašireni i detaljno istraženi na rijekama u Italiji (Surian i Rinaldi, 2003; Scorpio i dr., 2015), poljskim Karpatima (Zawiejska i Wyżga, 2010; Hajdukiewicz i Wyżga, 2019) i Španjolskoj (Martínez-Fernández i dr., 2017; Baena-Escudero i dr., 2019). Važan je uzrok navedenih promjena i reforestacija zbog ekstenzifikacije gospodarskih aktivnosti i zapuštanja poljoprivrednih površina, pogotovo u izvorišnim, planinskim dijelovima porječja koji su prirodno glavni izvor sedimenta u tekućicama (Scorpio i Piégay, 2021). Što se tiče prirodnih čimbenika, Kiss i Blanka (2012) zabilježile su cikličke promjene širine korita povezane s fluktuacijom količine protoka: za stabilnih uvjeta bez poplava i dužega trajanja niskih voda vegetacija kolonizira i stabilizira prudove, čime se smanjuje površina prudova i sužava korito, dok se za poplava korito širi bočnom erozijom. Također, u razdobljima smanjenog protoka zabilježile su i razvoj sekundarnih zavoja na meandrima.

Na rijeci Dravi u Hrvatskoj nakon izgradnje triju hidroelektrana u drugoj polovini 20. stoljeća dolazi do smanjenja prijenosa sedimenta (Bonacci i Oskoruš, 2010), usijecanja toka i daljnjega sužavanja korita, koje je u razdoblju 1968. – 1979. prosječno iznosilo čak 50 % (Kiss i Andrási, 2017). Također, zbog smanjenoga vodostaja i rjeđe pojave poplava prudovi zarastaju te se na taj način povećava broj otoka (Kiss i dr., 2011). Utjecaj brana značajniji je na uzvodnim odsječcima rijeke (Kiss i Andrási, 2017). Slične promjene zabilježene su i na rijeci Cetini nakon izgradnje sustava hidroelektrana: zbog znatnoga smanjenja protoka od 90 % na odsječcima toka nizvodno od brane Prančevići došlo je do sužavanja korita od 40 do 55 %, smanjenja površine prudova za oko 85 % i povećanja broja otoka za 103 % (sl. 2). Osim zarastanja prudova vegetacijom velik broj novih otoka čini i matična stijena koja je došla na površinu zbog smanjenja vodostaja (Pavlek i Faivre, 2020).

Mediterranean Basin, sediment yield at the beginning of the 21st century is only 50% of the assumed natural amount due to the construction of dams, leading to the erosion of river deltas such as the Po, Ebro, or Nile. Liébault and Piégay (2002) noted the narrowing of certain rivers in southeastern France to be as high as 55% in the second half of the 20th century, emphasising the shift in channel morphological type from braided to meandering. In Europe, such processes are particularly widespread and have been studied in detail on rivers in Italy (Surian and Rinaldi, 2003; Scorpio et al., 2015), the Polish Carpathians (Zawiejska and Wyżga, 2010; Hajdukiewicz and Wyżga, 2019), and Spain (Martínez-Fernández et al., 2017; Baena-Escudero et al., 2019). Another important driver of these processes is afforestation following extensification of economic activities and abandonment of agricultural land, especially in mountainous headwaters, which are naturally the main source of sediment in rivers (Scorpio and Piégay, 2021). As for natural factors, Kiss and Blanka (2012) found cyclical changes in channel width related to fluctuations in discharge: during stable conditions without floods and prolonged low flows, vegetation settles and stabilizes the bars, reducing the area of bars and narrowing the channel, while during floods the channel expands by lateral erosion. In addition, the appearance of secondary bends on meanders has been noted during periods of lower discharge.

On the Drava River in Croatia, a decrease in sediment transport was observed after the construction of three hydropower plants in the second half of the 20th century (Bonacci and Oskoruš, 2010), as well as incision and further narrowing of the channel, which averaged up to 50% in the 1968–1979 period (Kiss and Andrási, 2017). Due to the lower water levels and less frequent occurrence of floods, bars have stabilized and the number of islands has increased (Kiss et al., 2011). The effects of the dams are more evident in the upstream sections of the river (Kiss and Andrási, 2017). Similar changes were also observed in the Cetina River after the construction of the hydropower system: due to a significant reduction in flow (by 90%) in the river sections downstream of the Prančevići dam, a channel narrowing by 40–55%, a reduction in the area of bars by about 85%, and an increase in the number of islands by 103% were recorded (Fig. 2). A large number of new islands are not only bars stabilized by vegetation, but they also consist of bedrock exposed by low water levels (Pavlek and Faivre, 2020).

Posljednje razdoblje (1990. –)

Posljednjih tridesetak godina obilježeno je općenito smanjenim stopama morfoloških promjena na tekućicama (Downs i Piégay, 2019). Takav trend stabilizacije procesa može biti posljedica smanjene osjetljivosti tekućica na promjene zbog izvršenih hidrotehničkih zahvata poput kanaliziranja (Provansal i dr., 2014) ili zbog prihvaćanja održivijega načina upravljanja pod utjecajem okolišnih direktiva (npr. ODV; Europska komisija, 2000). U Italiji na mnogim rijekama koje nisu kanalizirane zabilježeno je širenje korita nakon poplava, čemu su također doprinijeli prestanak vađenja sedimenta iz korita i mjere obnove (Scorpio i Piégay, 2021). U poljskim Karpatima mjere obnove također pokazuju dobre rezultate prema ekološkim procjenama (Wyżga i dr., 2021), međutim zamijećeno je da širenje vegetacije na obalama i naplavnoj ravnici dodatno smanjuje dinamiku tekućica, koja je ponajviše ograničena izgradnjom obaloutvrda i kanaliziranjem (Hajdukiewicz i Wyżga, 2019; 2022). Za donji tok Dunava, zbog značajnoga širenja vegetacije na riječnim prudovima, Grecu i dr. (2022) zaključuju da je dinamika rijeke danas u usporedbi sa stanjem iz sredine 19. stoljeća smanjena zbog rijeđe pojave poplava, smanjena donosa sedimenta i hidrotehničkih mjera.

Na gornjem toku Drave u Austriji mjere obnove koje su se počele primjenjivati početkom 21. stoljeća pokazale su se izrazito uspješnima (Muhar i dr., 2018). Međutim, s obzirom na postojeće i planirane izgradnje novih hidroelektrana i zaštitnih građevina na toku Drave u Hrvatskoj može se očekivati daljnje usijecanje, sužavanje i smanjenje složenosti korita te smanjenje lateralne povezanosti s naplavnom ravnicom (Kiss i Andrási, 2017; Schwartz, 2019). Treba ipak spomenuti projekt obnove DRAVA LIFE čija je provedba planirana do kraja 2024. godine. Planirani postupci obuhvaćaju otvaranje starih te stvaranje novih rukavaca, uklanjanje i mijenjanje obaloutvrda i ostalih vodnih građevina te očuvanje retencijskih područja i prirodnih strmih riječnih obala na određenim lokacijama na cijeloj dužini toka u Hrvatskoj, osim dijela nizvodno od Osijeka do ušća u Dunav (DRAVA LIFE, n.d.).

The last period (1990s–time of writing)

Over the past thirty years, the rate of geomorphological change in rivers has decreased (Downs and Piégay, 2019). This trend toward stabilization of processes may be a consequence of the reduced sensitivity of rivers to changes caused by engineering works such as channelization (Provansal et al., 2014) or may be due to the acceptance of more sustainable management under the influence of environmental directives (e.g. WFD; European Commission, 2000). In Italy, many non-channelized rivers have experienced channel widening due to large floods, although this has also been favoured by the cessation of in-channel sediment mining and restoration activities (Scorpio and Piégay, 2021). In the Polish Carpathians, restoration measures also show good results according to ecological assessments (Wyżga et al., 2021), however, it was noticed that the spread of vegetation along the banks and in the floodplain is leading to a further reduction in river dynamics, which is mostly limited by the construction of bank protections and channelization (Hajdukiewicz and Wyżga, 2019; 2022). In the lower reaches of the Danube, due to the significant expansion of vegetation on bars, Grecu et al. (2022) concluded that contemporary river dynamics declined due to less frequent occurrence of floods, reduced sediment supply and engineering works, compared to the mid-19th century.

On the upper course of the Drava in Austria, restoration measures that have been implemented since the beginning of the 21st century proved to be very successful (Muhar et al., 2018). However, considering the existing and planned construction of hydroelectric power plants and bank protections, further incision, narrowing and reduction of the complexity of the channel and the reduction of the lateral connectivity with the floodplain can be expected on the Drava in Croatia (Kiss and Andrási, 2017; Schwartz, 2019). However, we should mention the DRAVA LIFE restoration project, whose implementation is planned by the end of 2024. The planned restoration actions encompass the opening and creation of new side-arms, the removal and modification of embankments and groynes, as well as the preservation of retention areas and natural steep river banks on selected locations along the entire length of the river in Croatia, except for the part downstream from

U Panonskoj Hrvatskoj kanaliziranje tekućica općenito je najrašireniji oblik antropogenoga utjecaja na morfologiju rijeka, osobito u slučaju tekućica srednje veličine poput Krapine, Lonje ili Česme (Čanjevac i dr., 2022). Sustavno isušivanje naplavnih ravnica u Slavoniji i izgradnja kanala za odvodnju provodi se od kraja 19. st. (Živaković Kerže, 2004). Iako je regulacija tokova i melioracija naplavnih ravnica imala pozitivne posljedice na stanovništvo, u smislu povećanja poljoprivrednih površina, smanjenja opasnosti od poplava i zaraznih bolesti (malarija), današnje hidromorfološko stanje većine tekućica u Panonskoj Hrvatskoj nije zadovoljavajuće. Naime, prema rezultatima hidromorfološkoga monitoringa u Hrvatskoj, koji se provodio od 2017. do 2020. godine (Vučković i dr., 2018; 2019; 2021), samo četvrtina od tristotinjak analiziranih vodnih tijela u Panonskoj Hrvatskoj postiže dobro stanje za sva tri elementa kakvoće (hidrologiju, morfologiju i uzdužnu povezanost) prema odobrenoj metodologiji u skladu s provedbom ODV-a (Uredba o standardu kakvoće voda, NN 96/19). Posljedice kanaliziranja tekućica posebno se ogledaju u nezadovoljavajućim ocjenama morfoloških pokazatelja, poput promjena u geometriji korita (tlocrtni oblik, poprečni presjek), strukturi priobalne vegetacije i ograničavanju bočnoga kretanja rijeke (Čanjevac i dr., 2020; Pavlek i dr., 2023). U porječju Ilove, Plantak i dr. (2016) procijenili su da morfološko stanje 38,5 % duljine vodotokâ ne zadovoljava ciljeve prema ODV-u. Od ukupno 534 km vodotokâ kanalizirano je njih oko 250 km.

Hidromorfološkim monitoringom u Dinaridskoj ekoregiji (jadranski slijev i dio crnomorskoga slijeva koji se nalazi u Gorskoj Hrvatskoj) ustanovljeno je da samo petina od oko 150 istraženih vodnih tijela zadovoljava uvjete dobroga stanja za sva tri elementa kakvoće (hidrologija, morfologija i uzdužna povezanost) (Vučković i dr., 2018; 2019; 2021). Element koji najčešće ruši ocjenu sveukupnoga hidromorfološkog stanja jest uzdužna povezanost zbog velikoga broja pregrada na tekućicama bilo radi iskorištavanja za hidroenergiju ili zaštitu od (bujičnih) poplava. Navedene pregrade mijenjaju i hidrološki režim tekućica te uzrokuju ujezerenja (Frančišković-Bilinski i dr.,

Osijek to the confluence with the Danube (DRAVA LIFE, n.d.).

In Pannonian Croatia, river channelization is generally the most widespread form of human influence on river morphology, especially in medium-sized rivers such as the Krapina, Lonja, or Česma (Čanjevac et al., 2022). Systematic drainage of floodplains in Slavonia and construction of drainage canals has been carried out since the end of the 19th century (Živaković Kerže, 2004). Although the regulation of rivers and drainage of floodplains has had positive consequences for the population by increasing agricultural land and reducing the risk of floods and infectious diseases (malaria), the current hydromorphological condition of most rivers in Pannonian Croatia is unsatisfactory. According to the results of hydromorphological monitoring in Croatia conducted from 2017 to 2020 (Vučković et al., 2018; 2019; 2021), only one-quarter of approximately 300 studied water bodies in Pannonian Croatia achieved good status for all three groups of quality criteria (hydrology, morphology and longitudinal connectivity). The applied methodology is in accordance with the implementation of the WFD (NN 96/19). The consequences of river channelization are particularly reflected in the unsatisfactory values of assessment of morphological indicators, such as changes in the channel geometry (planform, cross-section), structure of the riparian vegetation, and restrictions on the lateral shift of the river channel (Čanjevac et al., 2020; Pavlek et al., 2023). In the Ilova River catchment, Plantak et al. (2016) estimated that the morphological state of 38.5% of the river lengths did not meet the WFD objectives. Out of a total of 534 km of watercourses, about 250 km have been channelized.

Hydromorphological monitoring in the Dinaric ecoregion (Adriatic Sea basin and part of the Black Sea basin in mountainous Croatia) showed that only one-fifth of approximately 150 studied water bodies met the conditions for good status for all three quality elements (hydrology, morphology and longitudinal connectivity) (Vučković et al., 2018; 2019; 2021). The element that most often affects the assessment of overall hydromorphological status is longitudinal connectivity. This is due to the large number of barriers built either for the purpose of hydropower generation or for protection against (flash) floods. These barriers also alter the hydrological regime of rivers and cause impoundment (Frančišković-Bilinski et al., 2012; Pavlek i Faivre, 2020). Na rijeci Dobri nakon puštanja u pogon hidroelektrane Lešće 2010. godine zabilježeno je mjestimično širenje korita i pojačana erozija obala, vrlo vjerojatno zbog *hydropeakinga*[4] (Kokić, 2022).

Izazovi budućih istraživanja

Da bi se mogle objasniti dosadašnje promjene korita te predvidjeti one buduće, potrebno je uspostaviti uzročno-posljedične veze između prirodnih i antropogenih pokretača te prilagodbi morfologije. U većini analiziranih radova te se veze uglavnom temelje na stručnoj interpretaciji autora, odnosno na temelju istodobnosti i neposredne blizine pojavnosti morfoloških prilagodbi i njihovih pretpostavljenih uzroka (Downs i Piégay, 2019). Na taj način moguće je stvoriti konceptualni model morfološkoga razvoja tekućice, na kojem su obično na vremenskoj crti označene morfološke promjene i pojava pretpostavljenih uzroka tih promjena (npr. Downs i dr., 2013). Međutim, iako se morfološke promjene i njihovi pretpostavljeni uzroci kvantificiraju, konceptualni modeli rijetko se koriste kao temelj za postavljanje hipoteza o uzročno-posljedičnim vezama između pojedinih parametara koje bi se zatim statistički testirale (Liébault i dr., 2002; Downs i Piégay, 2019).

Upotreba matematičkih modela za predviđanje budućih procesa u geomorfologiji otežana je činjenicom da su geomorfološki sustavi „otvoreni" i zbog toga izrazito kompleksni (Brierley i dr., 2021). Predviđanje geomorfoloških promjena i povezivanje uzroka i posljedica kod kumulativnih utjecaja predstavlja izazov (Gregory, 2006; Fryirs, 2017; Downs i Piégay, 2019). Naime, u riječnim sustavima, kao i u drugim geomorfološkim sustavima, postoji velik broj vanjskih čimbenika koji uzrokuju promjene različitih stopa i trajanja, poput režima padalina, zemljišnoga pokrova ili izravnih antropogenih utjecaja (npr. izgradnja brana). Također, kao i u ostalim geoznanostima, posebnu važnost imaju lokalni čimbenici te prošli događaji i uvjeti poput klimatskih promjena (Brierley i dr., 2021). Zbog

4 Pojava umjetno izazvanih promjena vodostaja i protoka kao posljedica diskontinuiranoga ispuštanja vode iz akumulacije tijekom perioda veće potražnje za električnom energijom (Greimel i dr., 2018).

2012; Pavlek and Faivre, 2020). On the Dobra River, after the construction of the Lešće hydroelectric power plant in 2010, a localized widening of the bed and increased erosion of the banks has been observed, most likely due to *hydropeaking*[4] (Kokić, 2022).

Challenges in future research

To explain past channel changes and predict future ones, it is necessary to establish cause-and-effect relationships between natural and human drivers and morphological responses. In most of the papers mentioned, these relationships are mainly based on the authors' expert interpretations, i.e. the temporal synchronicity and spatial proximity of morphological adjustments and their presumed causes (Downs and Piégay, 2019). In this way, it is possible to build a conceptual model of the evolutionary trajectory of a river in which morphological changes and the occurrence of the presumed causes of these changes are (usually) marked on the time axis (e.g. Downs et al., 2013). However, although morphological alterations and their presumed causes are quantified, conceptual models are rarely employed as a basis for hypothesizing causal relationships among individual parameters that are then tested statistically (Liébault et al., 2002; Downs and Piégay, 2019).

The use of mathematical models to predict future processes in geomorphology is hampered by the fact that geomorphological systems are "open" and therefore extremely complex (Brierley et al., 2021). Predicting geomorphological change and linking cause and effect for cumulative impacts is challenging (Gregory, 2006; Fryirs, 2017; Downs and Piégay, 2019). Indeed, in river systems, as in other geomorphological systems, there are numerous external factors that cause changes of different rates and duration, such as precipitation regime, land cover, or direct human influences (e.g. dam construction). Similarly to other geosciences, local factors and past events and conditions, such as climate change, are particularly important (Brierley et al., 2021). For this reason, Downs and Piégay

4 The occurrence of artificially-induced changes in water level and flow as a result of discontinuous discharge of water from the reservoir during periods of higher demand for electricity (Greimel et al., 2018).

toga Downs i Piégay (2019) naglašavaju važnost stavljanja proučavane rijeke u kontekst cijeloga porječja, odnosno obilježja klime i geologije. Dodatni su izazov u predviđanju promjena tekućica kompleksnost i dokazani vremenski odmaci u morfološkom odgovoru na poremećaje te nelinearnost morfološkoga razvoja riječnih korita (tj. evolucijskih putanja promjene, engl. *evolutionary trajectory of change*) (Piégay, 2016).

Kao važan koncept za predviđanje budućih scenarija u upravljanju Fryirs (2017) ističe osjetljivost rijeka (engl. *river sensitivity*), odnosno mogućnost, vjerojatnost i sklonost promjeni te sposobnost sustava za obnovu nakon poremećaja. Prema tome konceptu npr. aluvijalne tekućice osjetljivije su na morfološke promjene od tekućica koje teku po matičnoj stijeni. Kompleksnost prostorne i vremenske osjetljivosti rijeka iziskuje istraživanja na razini pojedinoga porječja na temelju terenskih istraživanja, analize povijesnih izvora i modeliranja (Downs i dr., 2013; Khan i Fryirs, 2020). Fryirs (2017) nadalje naglašava važnost istraživanja graničnih uvjeta na razini geomorfološkoga oblika, odsječka i porječja (čije probijanje dovodi do morfoloških promjena) te veza i interakcija unutar cijeloga riječnog sustava. Downs i Piégay (2019) navode važnost formulacije hipoteza na temelju konceptualnoga modela (npr. Liébault i Piégay, 2002) i šire upotrebe kvantitativnih modela i statističkih metoda. S druge strane, Brierley i dr. (2021) brane važnost stručne interpretacije u geomorfološkim istraživanjima, ali naglašavajući činjenicu da se ona mora donositi na temelju dovoljnoga broja podataka, uz sve prednosti korištenja novih tehnologija i modela te važnosti testiranja i verifikacije da bi se procijenila pouzdanost predviđanja.

Zaključak

Korita mnogih rijeka u Europi danas se smatraju promijenjenima uslijed antropogenoga djelovanja. Najintenzivnije promjene zabilježene su od sredine 20. stoljeća, a uključuju sužavanje, usijecanje i promjene u obliku korita (prvenstveno prelazak iz složenoga u jednostavni oblik ili smanjenje indeksa vijugavosti kod meandrirajućih rijeka). Iako se kao njihovi uzroci ponajprije

(2019) emphasized the importance of placing the river under study in the context of its entire catchment, i.e. climatic and geologic characteristics. An additional challenge in predicting change in rivers is the complexity and proven time lags in morphological response to disturbance and the nonlinearity of evolutionary trajectories of river change (Piégay, 2016).

As an important concept for predicting future scenarios in management, Fryirs (2017) pointed to *river sensitivity*, i.e. the possibility, probability, and tendency for change, as well as the ability of the system to recover after a disturbance. For example, according to this concept, alluvial rivers are more sensitive to morphological change than rivers flowing over bedrock. The complexity of the spatial and temporal sensitivity of rivers requires research at the scale of individual catchments based on field research, the analysis of historical sources, and modelling (Downs et al., 2013; Khan and Fryirs, 2020). Fryirs (2017) also emphasized the importance of research on boundary conditions (the breaching of which leads to morphological changes) at the scale of geomorphological unit, reach, and catchment, as well as on linkages and interactions within the entire river system. Downs and Piégay (2019) emphasized the importance of formulating hypotheses based on a conceptual model (e.g. Liébault and Piégay, 2002) and the broader use of quantitative models and statistical methods. On the other hand, Brierley et al. (2021) defended the importance of expert interpretation in geomorphological research, but stressed that it must be based on a sufficient amount of data, with all the advantages of using new technologies and models and the importance of testing and verification to assess the reliability of predictions.

Conclusion

The channels of many rivers in Europe are considered to have been altered by human activity. Among the most severe changes that have occurred since the mid-20th century are channel narrowing, incision, and changes in channel pattern (especially the transition from a multi-thread to a single-thread type or a decrease in the sinuosity index in meandering rivers). Although their causes are primarily navode izravni antropogeni utjecaji, odnosno provedba hidrotehničkih mjera poput kanaliziranja ili izgradnje brana, neki neizravni antropogeni ili prirodni čimbenici poput reforestacije ili promjene režima padalina također mogu biti uzroci morfoloških promjena korita.

S razvojem svijesti o okolišu posljednjih dvadesetak godina donose se nove zakonske regulative i razvijaju novi pristupi upravljanja rijekama, koji se temelje na holističkom promatranju i poznavanju procesa u riječnom sustavu. Prema tome, istraživanja geomorfoloških promjena tekućica danas imaju vrlo raširenu primjenu u upravljanju rijekama jer pružaju informacije o prošlim i sadašnjim stanjima i procesima te različitim čimbenicima promjene. U takvim studijama posebno su važan izvor podataka kartografski izvori i daljinska istraživanja jer je na njima moguće pratiti promjene u obilježjima korita i naplavne ravnice (oblik, širina, duljina, geomorfološki oblici, priobalna vegetacija). Obradom satelitskih i zračnih snimaka te analizama digitalnoga modela reljefa u geografskom informacijskom sustavu moguće je integrirati podatke i automatizirati analize istraživanih obilježja.

U upravljanju rijekama ili planiranju njihove obnove bitno je predvidjeti moguća ograničenja ili posljedice s obzirom na različite scenarije upravljanja. Identifikacijom veza između uzroka i posljedica promjena u prošlosti moguće je predvidjeti buduće promjene. Međutim, predviđanje promjena u fluvijalnoj geomorfologiji predstavlja izazov te uvelike ovisi o stručnoj interpretaciji zbog velike kompleksnosti riječnoga sustava. Stoga je u istraživanjima uvijek potrebno utvrditi sve moguće uzroke promjena i promatrati tekućicu u kontekstu cijeloga porječja, odnosno imati na umu cijeli niz interakcija i veza koje postoje u prostorno-hijerarhijskoj strukturi riječnoga sustava.

direct human influences, i.e. the implementation of hydrotechnical measures such as channelization or the construction of dams, some indirect human or natural factors such as afforestation or alterations in precipitation regimes may also lie behind changes in channel morphology.

With increasing environmental awareness, new legislation has been enacted in the last twenty years and new approaches to river management have been developed based on holistic observation and knowledge of river system processes. As a result, studies of geomorphological change in rivers are now widely used in river management because they provide information on past and present conditions and processes, as well as on various factors of change. In such studies, cartographic sources and remote sensing are particularly important sources of data because they enable analyses of changes in various channel and floodplain characteristics (planform, width, length, fluvial landforms, riparian vegetation). By processing satellite and aerial images and analysing the digital relief model in GIS, it is possible to integrate the data and automate the analysis of the studied features.

When managing rivers or planning their restoration, it is very important to anticipate possible limitations or consequences of different management scenarios. By identifying the relationships between the drivers and channel responses in the past, it is possible to predict future changes. However, predicting changes in fluvial geomorphology is challenging and depends largely on expert interpretation due to the great complexity of river systems. For this reason, it is always necessary to identify all possible causes of change and to study the river in the context of its entire catchment, i.e. to keep the whole set of interactions and relationships that exist in the spatio-hierarchical structure of the river system in mind.

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