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TITOLO TESI:

EXPLORING SHORT-TERM GEOMORPHIC CHANGES AND BANK RETREAT EVOLUTION IN FLUVIAL SYSTEMS

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Dedicated to

my family, my girlfriend and

a friend looking from above

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Acronyms and initialisms

B.C.	Before Christ
BH	Breast Height
CDF	Cumulative Distribution Function
dGPS	differential Global Positioning System
DEM	Digital Elevation Model
DoD	Dem of Difference
EB	External Bend
EU	European Union
FIS	Fuzzy Inference System
GCD	Geomorphic Change Detection
GUI	Graphical User Interface
H	Horizontal
IB	Internal Bend
IDW	Inverse Distance Weighting
IMU	Inertial Measurements Units
LiDAR	Light Detection and Ranging
LW	Large Wood
MB	Megabyte
min LoD	minimum Level of Detection
O	Oblique
RGB	Red Green Blue (bands)
R.I.	Recurrence Interval
RMSE	Root Mean Square Error
SDE	Standard Deviation Error
SS	Straight Section
TIN	Triangular Irregular Network
TLS	Terrestrial Laser Scanner
U.S.	United States
V	Vertical
WGS84	World Geodetic System 84

Abstract

The geomorphological effectiveness of flood events may highly vary depending on several factors, including discharge, duration, frequency, ordering, environmental conditions, human interference, etc. Precise rates and patterns of change produced by flooding remain largely unknown and unpredictable and multiple sources of error undermine the achievement of accurate estimates of geomorphic variations. Focusing on channel processes, the complex control exerted by riparian vegetation at multiple scales and, in particular, on riverbank dynamics further registers a lack of understanding that may lead to possible misleading approaches to manage fluvial erosion issues. This study primarily seeks to analyse and interpret the geomorphological response of two differently-impacted gravel-bed rivers (Piave and Tagliamento rivers, Italy) to flood events slightly below bankfull discharge. Furthermore, a focus on bank erosion processes on an Australian stream characterized by extensive tree abutments and cohesive scalloped riverbanks (the King River, Victoria) will try to explain the control exerted by riparian vegetation on the evolution of bank retreat. New findings and relationships will help to create a more comprehensive conceptual model describing bank migration past forested riverbanks that will be further tested on the Piave River, offering the possibility of comparing fluvial systems with very different environmental conditions (primarily, cohesive versus non-cohesive sediment). For the detection of geomorphic variations, enhanced DoD models including a precise evaluation of flowing channels, are derived by differencing pre- and post-flood integrated DEMs (LiDAR, dGPS and colour bathymetry). The reliable estimates of change have contributed to effectively quantify planimetric and volumetric adjustments of main channels and major bank removal. On the other hand, bank migration processes were examined on the King River by surveying the characteristics of trees and bank profile spaces to uncover significant relationships explaining the retreat of vegetated riverbanks. Results on geomorphic impacts of floods have confirmed a prevalence of erosion processes in the study reaches of the Piave and Tagliamento rivers, even with a general tendency toward sediment equilibrium. Flooding has caused a nearly total reconfiguration of the main flowing channel network, contributing to erode considerable areas of stably vegetated banks. The analysis on bank migration processes has further found elements and relationships previously unconsidered in bank retreat modelling. Major findings on the King River include the proof that riparian trees mostly grow on the bank face as well as the identification of more complex patterns of hydrological erosion around riparian trees (overcutting and undercutting) suggesting tree toppling by fluvial scour than by mass failure. Further, the progression of scallop depth along riverbanks has confirmed to be fairly influenced by tree spacing, both on the King and the Piave rivers. Discussions debating the impacts of floods have highlighted the ability of events

below bankfull discharge to effectively rework the geomorphological structure of river channels at all levels. River changes appear to be also influenced by the physical characteristics of river reaches and human interventions. Moreover, the new findings on bank migration have allowed to fill some gaps of knowledge related to the complex effect of trees on riverbank erosion, leading to propose a more comprehensive conceptual model describing bank retreat evolution in forested cohesive riverbanks. Further parallelisms between King and Piave rivers have demonstrated that scallop depth features similar average magnitudes in both fluvial systems, even though the average effect of tree spacing within individual morphological units (bend- or arc-level) explains better erosion development in the Piave River. The significance of the study lies on the attempt of providing a reliable approach to meaningfully evaluate river geomorphic changes, revealing the high potential of floods also below bankfull discharge to revolutionize channel forms and patterns. The enhanced understanding of crucial channel processes as the reconfiguration of main branches and the control of riparian vegetation on bank retreat can further represent a decisive help to river experts within the complicated issue of managing fluvial systems.

Riassunto della tesi

Titolo: Analisi delle variazioni geomorfologiche di breve termine e dell'evoluzione delle dinamiche di erosione spondale nei sistemi fluviali.

Gli ambienti fluviali sono caratterizzati naturalmente dal susseguirsi di eventi di piena che svolgono un ruolo fondamentale nel mantenere il "dinamico equilibrio" di questi sistemi, integrando un gran numero di processi. Flussi idrologici, trasferimento di sedimento, interferenza di legname vivo o morto, impatto di opere antropiche ed altri fattori ancora, contribuiscono a ridisegnare la morfologia di un corso d'acqua, in un continuo cambiamento strutturale (Tockner et al., 2000). Sebbene l'effetto di piene provochi una naturale evoluzione delle forme fluviali, a partire dal secolo scorso si è registrata una consistente accelerazione del grado di impatto di questi eventi nella maggior parte dei sistemi fluviali dei "paesi occidentali" (Europa, America, Australia, ecc). Questi effetti, sempre più irregolari ed imprevedibili, oltre ad alterare le dinamiche evolutive di molti corsi d’acqua, rappresentano fattori di rischio che possono provocare ingenti danni in luoghi caratterizzati da centri abitati od opere infrastrutturali. Anche se le cause di questi cambiamenti imprevisti si pensa siano da ricollegare in gran parte all'influenza di opere antropiche, il ruolo di elementi naturali, come la vegetazione riparia, è sempre più dibattuto nell’ambito di interventi per proteggere le sponde da fenomeni erosivi e ridurre situazioni di rischio. Infatti, sebbene gli apparati radicali delle piante situate lungo le sponde aumentino la coesione del terreno, aumentando la resistenza allo scavo ed asportazione da parte dei deflussi (Hubble et al., 2010), la loro presenza in alveo e rimozione può portare a situazioni di pericolo, come per esempio blocchi a ridosso di ponti o infrastrutture. Strutture o azioni perpetrate a varia scala, di bacino, di corridoio o di alveo attivo, per scopi di protezione, regimazione, produzione di energia elettrica o prelievo di inerti, hanno compromesso per decenni direttamente o indirettamente le dinamiche evolutive di gran parte dei corsi d’acqua, creando ingenti problemi di riqualificazione ora che una nuova politica di salvaguardia naturale è in continua affermazione (Kondolf et al., 2007; Gurnell et al., 2009). Infatti, le modificazioni ai processi fluviali messe in atto negli ultimi decenni hanno così mutato le dinamiche evolutive di questi ambienti, che la volontà di ripristinare queste aree ad una condizione naturale antecedente a questi impatti è pressoché impossibile, dato che questa non si può più identificare (Wohl, 2005). In ambito italiano, questi impatti hanno provocato, in gran parte degli ambienti fluviali, fasi prolungate di restringimento ed incisione dell’alveo attivo, apportando cambiamenti anche a livello di forme planimetriche (da canali intrecciati a canale singolo). Un esempio è il fiume Piave che ha registrato un restringimento pari al 50% ed

un'incisone fino a 10 m dell'alveo attivo e le cui cause sono state ricondotte ad un'alterazione abnorme del regime di sedimento dovuto al passato prelievo intensivo di inerti e alla presenza di alcune dighe (Comiti et al., 2011). Recentemente, grazie all'accresciuta attenzione ambientale e all'esigenza di raggiungere obbiettivi designati da nuove direttive nazionali ed europee (per esempio, Water Framework Directive), molti corsi d'acqua stanno sperimentando una nuova fase sviluppo verso un ritrovato equilibrio di funzionamento.

In questo quadro, la disponibilità di strumenti accurati per valutare efficacemente gli effetti di eventi di piena ed una maggiore comprensione del ruolo della vegetazione riparia nei processi morfologici all'interno dell'alveo attivo, con particolare attenzione all'erosione spondale, svolgono un ruolo fondamentale nell'identificazione e spiegazione di dinamiche fluviali chiave per azioni di riqualificazione. Questo studio si propone di quantificare in modo preciso gli effetti geomorfologici provocati da eventi di piena al di sotto della portata bankfull che nel 2010 hanno interessato due fiumi italiani caratterizzati da un diverso impatto antropico, il Piave ed il Tagliamento. Oltre ad isolare volumi e tendenze morfologiche dominanti nei tratti di studio, verranno valutati i processi di riconfigurazione planimetrica del canale principale e le dinamiche di erosione spondale riguardanti porzioni di vegetazione stabile per comprendere meglio le conseguenze delle piene sui diversi settori del corridoio fluviale. Inoltre, il ruolo della vegetazione riparia nell'evoluzione delle dinamiche di erosione spondale, verrà approfondito in un ambiente fluviale caratterizzato da sedimento coesivo e profili spondali fortemente modificati dalla resistenza all'erosione da parte di piante adiacenti al canale attivo: il fiume King (Australia). La ricerca di relazioni che spieghino la progressione di processi di erosione laterale in sponde caratterizzate da vegetazione riparia a diversa densità avrà come obbiettivo finale la creazione di un modello onnicomprensivo che spieghi l'evoluzione dell'erosione spondale lungo anse fluviali vegetate. Un ulteriore confronto con il fiume Piave, grazie alle numerose differenze fisiche ed idrologiche (in particolare il substrato composto da materiale non coesivo), offrirà spunti di discussione interessanti per la riconsiderazione della funzione della vegetazione riparia nelle strategie di protezione e riqualificazione fluviale.

La prima parte, riguardante la stima accurata degli effetti geomorfologici provocati dagli eventi di piena del 2010, è stata sviluppata grazie alla disponibilità di modelli digitali del terreno (Digital Elevation Model – DEM) che, integrando rilievi GPS, LiDAR e provenienti da batimetria da colore, hanno permesso di riprodurre in modo puntuale la superficie complessiva (aree bagnate e non bagnate) dei tratti fluviali analizzati prima e dopo gli eventi. Attraverso un processo, modificato ad hoc, di produzione di modelli digitali di input collegati fra loro da script linguistici creati in MatLab (Fuzzy Inference System files), si è stati in grado, utilizzando l'applicazione Geomorphic Change Detection, di elaborare modelli digitali differenziali (DEM od Difference – DoD), che hanno permesso di valutare accuratamente gli impatti delle piene analizzate. I volumi ottenuti da questi modelli sono stati associati ad un calcolo preciso dell'errore che, contribuendo a fornire risultati quanto più vicini alla realtà possibile, ha permesso di estrapolare processi e tendenze evolutive dei due fiumi e di valutare la loro situazione rispetto ad una condizione di equilibrio. In seguito, la nostra attenzione si è focalizzata sul comportamento dei collettori fluviali principali che, attraverso una digitalizzazione e conseguente quantificazione dei processi erosivi e di deposizione, hanno dimostrato di aver subito una riconfigurazione morfologica pressoché completa in tutti i tratti analizzati. Infine, la stima dell'impatto di queste piene su erosioni localizzate di aree spondali caratterizzate da vegetazione stabile ed opere antropiche (fiume Piave), ha mostrato il potenziale di questi flussi idrologici nell'asportare porzioni di superficie teoricamente più resistenti grazie all'effetto stabilizzante degli apparati radicali, ipotizzando una possibile interferenza degli interventi di sistemazione idraulica. I risultati degli effetti geomorfologici a varia scala prodotti dagli eventi di piena hanno sottolineato il fatto, peraltro ribadito da altri studi (Chappell et al., 2003; Bertoldi et al., 2010), che anche eventi al di sotto della portata bankfull possono essere in grado di influenzare e riconfigurare in modo pronunciato lo sviluppo morfologico degli ambienti fluviali, oltre che aumentare talvolta il grado di rischio quando opere antropiche interferiscono con essi. I riscontri volumetrici hanno mostrato una predominanza complessiva di processi erosivi nei sottotratti analizzati, alludendo ad un deficit di sedimento ancora presente e da colmare per ottenere una condizione di equilibrio. Lo spostamento pressoché totale dell'asta fluviale principale ha infine confermato l'imprevedibilità degli effetti di piena che inoltre, asportando importanti quantitativi di aree vegetate stabili, hanno aperto nuovi interrogativi sul ruolo della vegetazione riparia nell'evoluzione dell'erosione spondale.

Questo ruolo è stato approfondito nel bacino del fiume King (Australia) che, offrendo particolari processi di interazione fra vegetazione riparia e profilo spondale, ha permesso di indagare e comprendere le dinamiche evolutive dell'erosione spondale. Il tratto studiato del suddetto fiume presenta infatti profili spondali caratterizzati dal susseguirsi di piante di diversa grandezza e densità, intervallate da concavità prevalentemente erosive, che isolano progressivamente gli appartati radicali delle piante stesse fino a farle cadere nel collettore principale. L'analisi dei parametri associati alla vegetazione riparia e a queste concavità ha permesso di trovare varie relazioni che spiegano l'avanzamento dell'erosione spondale in ambienti caratterizzati da effetti di resistenza e stabilizzazione prodotti da piante e radici. In particolare, risultati sull'importanza della densità vegetativa hanno sottolineato l'influenza di piante poco spaziate sul profilo longitudinale della sponda nel ridurre l'ampiezza delle concavità erosive. Queste incoraggianti conclusioni hanno portato alla creazione di un modello concettuale di evoluzione di profili spondali caratterizzati da sedimento coesivo e vegetazione riparia. Questi esiti sono stati poi confrontati con i tratti analizzati del fiume Piave, portando all’individuazione di alcune dinamiche simili e altre moderatamente diverse. Alcune caratteristiche di sviluppo dei profili spondali erosivi hanno dimostrato di essere comuni nei due sistemi fluviali, come ad esempio il ruolo della densità della vegetazione riparia attiva sulla sponda, che promuoverebbe una limitazione dell’avanzamento dell'erosione laterale. Al contrario altri aspetti, fisici e di scala di processo, hanno riportato profonde differenze, probabilmente date dalle diverse caratteristiche climatiche, di portata, di funzionamento e, non da meno, di substrato (coesivo contro non coesivo) dei due ambienti fluviali.

Concludendo, il presente studio ha indagato con successo le ripercussioni geomorfologiche causate da eventi di piena moderati, ottenendo stime verosimili di processi erosivi e di deposizione che hanno altresì permesso di valutare la condizione attuale degli ambienti fluviali analizzati. Piene anche al di sotto della portata bankfull hanno avuto effetti su tutte le componenti geomorfologiche a livello di tratto, includendo la riconfigurazione dell’asse fluviale principale e l’erosione laterale di aree vegetate stabili. L’approfondimento del ruolo della vegetazione riparia nel ridurre i processi di migrazione erosiva e il successivo confronto fra ambienti fluviali diversi, ha incrementato la nostra conoscenza su queste dinamiche che sono alla base di azioni di protezione e riqualificazione fluviale. I significativi risultati raggiunti da questa ricerca possono infine rappresentare un importante arricchimento per gli esperti del settore che, a fronte delle tendenze emerse, potranno usufruire di un ulteriore base su cui progettare nuove e più efficaci strategie di gestione degli ambienti fluviali.

1. INTRODUCTION

1.1. Research rationale

1.1.1. Understanding fluvial processes and risks

Rivers represent a cardinal element of the natural environment, attracting people's attention for a wide variety of aspects including water supply, navigation, power generation, recreation and aesthetics. As continuously renewable resources, they generate physical, political, social and economic influences, ruling crucial concerns of world's nations that need to assure their sustainable management to keep benefiting in the future. Despite representing a unique opportunity, rivers may also generate threats, undermining human population and properties with a wide range of processes, including floods, draught, pollution and erosion (Knighton, 2014). Through their action, streams deliver water and sediment from the land surface to the oceans, shaping the landscape with erosion, transport and deposition phenomena (Sear et al., 2003). Even storing only less than 0.005 per cent of continental water, stream power is able to complete the global hydrological cycle, representing one of the most formidable forces on Earth, capable to carry 19,000 million tonnes of sediment each year. Fluvial environments, through their continuous reshaping, provide also rich habitat diversity, contributing to host and preserve wildlife across their ecological corridors (Knighton, 2014).

Fluvial systems are governed by climate, geology, basin morphology and land use, whose integrated effects together induce their hydrological regime and type and quantity of sediment delivered. Climate supplies energy for basic and crucial river processes, directly affecting basin hydrology and erosion dynamics. Geology represents a main control on stream motion capability as well as potential removal of sediment, particularly in mountain basins, where flow is generally constrained by bedrock structures that limit also material supply. Basin morphology stands at the basis of surface runoff, guiding water flow down to slopes until the oceans and thus influencing a wide range of forces and processes, including rates of sediment erosion and transport. Finally, land use and, more in general, human pressure have registered an increasing impact on fluvial environments during history and continue to regulate and divert river behaviour from natural dynamics. The management of riparian vegetation is included in this important field as its interaction may highly change the geomorphic evolution of river systems. The stability of hydrological and physical form and processes of a river system depends on the energy generated in it that needs to be in balance with the carried water volume and the type and volume of sediment delivered. When altered by human or natural mechanisms, a river channel seeks to readjust to its previous balance, changing its dimension, profile, pattern or course on the landscape (Knighton, 2014).

The study of rivers embodies several sciences which analyse the entire spectrum of components and processes related to fluvial environments, from water quality to stream ecology, from sediment transport to flood risk, etc. Fluvial geomorphology, among river disciplines, seeks to understand streams, both in their natural settings and responses to human-induced changes. One of the main objectives deals with the detection and interpretation of the morphological variations that a river may undergo when affected by alterations in watershed conditions. Their further analysis and prediction lead to estimate the impact of changes on the environment and human infrastructures.

An important aspect of fluvial geomorphology, beside the comprehension of river processes, is the evaluation of risks related to stream activity. The most impacting natural phenomenon faced by rivers is, without a doubt, flooding which can lead to remarkable and unexpected changes in fluvial dynamics, undermining human lives, properties and structures. When "water comes outside its normal confines" (FLOODsite, 2005), enhanced stream power can wash out through bank erosion large portion of land surface, causing agricultural and recreational soil losses. Nevertheless, flooding represents a natural event that forms an integral part of the hydrological cycle and has contributed to the development and continue to sustain human civilization (i.e. River Nile, Egypt). Therefore, flood risk expresses entirely a human concern, consisting of the combination between flood hazard (i.e. inundation) and vulnerability to damages generated by flooding on what is exposed to inundation (i.e. people, properties, infrastructures) (Samuels et al., 2006). In the past decades, buildings and human infrastructures were located too close to riverbanks or areas of active river processes requiring strategies to mitigate the risk, that very often have implied the construction of protection measures with detrimental effects on the equilibrium of fluvial systems. A recent international practice based on sustainable human activities and social responsibility is finally changing the approach of managing rivers, moving towards the concept of preserving river evolutionary space (i.e. erodible river corridor) (Piégay et al., 2005).

1.1.2. Gaps in current research

The impacts of floods on river morphology and processes have increasingly been analysed in the recent times as an effective indicator of the power of the water flow in producing important spatial and volumetric changes in river channels. Further, flood effects can be used to evaluate the suitability of human protection measures and provide plausible forecasts to avoid risk and economic losses (Mitchell, 2003). From limited results derived by planform changes and few cross-sections at local reach-scale (Lane, 1998; Brewer and Passmore, 2002), new technological advances have allowed experts to rapidly acquire topographic data on larger extents at very fine resolutions, offering the possibility of achieving precise and meaningful estimates of river adjustments (Heritage and Hetherington, 2007; Milan et al., 2007; Marcus and Fonstad, 2008). Among these, the use of LiDAR (Light Detection and Ranging) has helped to render more accessible the detection of vast fluvial areas, reporting laser pulses information able to reconstruct terrain surfaces with relatively low errors (± 15/20 cm) (Charlton et al., 2003; Cavalli et al., 2008). Nevertheless, most of remote sensing techniques are unable to provide reliable topographic data of submerged areas, featuring significant limitations in surveying and, consequently, precisely reproducing flowing channels (Reusser and Bierman, 2007; Notebaert et al., 2009). A rapid and cost-effective solution, out of rather expensive and field-problematic bathymetric sensors, is represented by colour bathymetry which uses aerial images to calibrate depth-reflectance relationships and reconstruct wet channel elevations (Moretto et al., 2012). Even requiring contemporary control points derived from field surveys for each case study, this empirical method can be very helpful to integrate reliable representations of flowing channels in surface modelling. Unfortunately, recent researches, to avoid costly bathymetric LiDAR surveys, have too often attempted to digitally reproduce river reaches using one or integrated remote-sensing technologies that feature high imprecision in wet channels or the need of time-demanding field campaigns (Lallias-Tacon et al., 2014). The capability of producing integrated DEMs (Digital Elevation Surfaces), taking advantage from quick and inexpensive opportunities that accurately replicate wet channel areas (as colour bathymetry) - generally the zones with the highest rates of geomorphic changes - is essential to develop more effective and affordable topographic studies.

Patterns and volumes of geomorphic changes caused by flooding can be now precisely estimated through DoD (DEM of Difference) models that compare pre- and post-event digital surfaces obtained by integrated and repeated topographic surveys. A decisive aspect to consider during the entire procedure of detection of erosion and deposition processes is uncertainty, whose reliable evaluation can help to distinguish real change from noise (Wheaton et al., 2010). Several studies using DoD applications have pointed out the importance of a careful evaluation of error propagation influence in fluvial geomorphology (Brasington et al., 2000; Lane et al., 2003; James et al., 2012). Accounting for uncertainties featured in the different stages of data processing and modelling, represents a crucial aspect to isolate and interpret topographic changes which very often exhibit similar magnitudes to operator, device and elaboration errors (Brasington et al., 2003). In this context, a helpful approach to produce precise DoD maps, plausible geomorphic estimates and an accurate uncertainty analysis was developed by Wheaton et al. (2010), through a wizard-driven Matlab software application called GCD (Geomorphic Change Detection). Thanks to an evaluation, at a cell-by-cell basis, of a spatially-variable uncertainty which can recover information normally below detection thresholds, and the consideration of a probabilistic coherence of erosion and deposition units, real change can be more effectively isolated. Even though this method represents nowadays the most reliable tool to obtain close-to-real rates of geomorphic changes, the mere use of literature input factors without a case-study calibration, or the lack of a precise evaluation of flowing channel areas, can originate several limitations. The ability of selecting appropriate input variables and defining targeted rules stands at the basis of this method which can otherwise lead to untrue results and consequent misinterpretation.

Accurate volumetric estimates of geomorphic changes, even representing static images of sediment balance featured by a river reach after a certain period of time or specific flood events, can disclose substantial information on river system dynamics. Closing a total sediment budget is an objective so far attempted by very few studies (i.e. Raven et al., 2010; Erwin et al., 2012) that have anyway reached uncertainty levels often higher than real change, leading to possible misinterpretation of fluvial processes. Sediment dynamics caused by floods or flood pulses are important indicators of the sediment equilibrium featured by a river reach in a certain time span, that is in turn a condition influenced by a wide range of factors, including natural topographic constrains, riparian vegetation interference and human interventions. Dominance of erosion processes, for instance, may indicate a sediment deficit in the study reach, either natural or due to human pressure that can represent a possible future risk for adjacent human properties or infrastructure. The role of major flood events in changing considerably geomorphological assets of channels has been widely recognized (Fitzpatrick and Knox, 2000; Nardi and Rinaldi, 2014). Other researches focusing on flood pulses below or equal to bankfull discharge have revealed the significant impact also of smaller hydrological events in causing significant geomorphic variations (Chappell et al., 2003; Formann et al., 2007). Nevertheless, the interpretation of the effects of floods, especially below bankfull discharge, still represents a huge challenge in the academic world. Their unpredictability and the possible lack of knowledge of the exact initial condition of river channels keep providing high levels of uncertainty and misleading results. An important effect of flood impact is expressed by the planimetric adjustment of main flowing channels, a process which still remains poorly studied (Bertoldi et al., 2010). Quantitative evidences confirming sudden channel shifting and direct relationships with hydrological processes are still missing, delineating this phenomenon as highly unpredictable and dangerous in impacted fluvial environments with artificially-reduced active channels.

A major role in geomorphic processes is played by river bank erosion, the process by which sediment is remobilized from storage in the floodplain (Prosser et al., 2000). Bank removal represents a natural process and one of the most significant contributors of sediment input in river channels, delivering large volumes of material, especially during flood events. Its unpredictability and potential severity are a factor of risk in densely populated areas, where humans have tried to prevent and limit rates of bank degradation through extensive protection measures (i.e. in Europe). Often, such interventions have produced negative and unforeseen effects, especially when thought outside of a large-scale and comprehensive management strategy, contributing to shift the problem to another portion of the river system (Wolfert, 2001; Vandenberghe et al., 2012; Delai et al., 2014). A major control in bank erosion and retreat dynamics is represented by riparian vegetation which provides significant mechanical and hydrological influences (Simon and Collison, 2002). Its stabilizing effect is probably the most accepted process: through the root plates, bank trees are able to increase soil cohesion thus reducing shear stress and limiting bank erosion (Abernethy and Rutherfurd, 2001; Griffin et al., 2005; Hubble et al., 2010; Gurnell, 2014). Even if numerous effects of riparian vegetation have successfully been isolated and documented, its dynamic interaction with retreating bank profiles is poorly investigated. The evolution of forested riverbanks still features several knowledge gaps. Revealing how bank retreat develops by coherent and repetitive stages that lead to tree toppling into channels, represents a decisive finding to enhance our understanding on the impact of riparian vegetation in river morphological evolution and address effective restoration strategies, including the much debated issue of channel revegetation.

1.1.3. Significance of the study

The study aims at overtaking some limitations featured by recent academic research on topics related to the estimation and interpretation of geomorphic changes caused by floods below bankfull and bank retreat evolution in forested riverbanks.

The first stage, carried out on the Piave and Tagliamento rivers (Italy), will include the production of reliable digital surface representations of river reaches (pre- and post-flooding) derived by refined and integrated surveys: LiDAR data will be used for the dry areas whereas wet channel elevations will be obtained by colour bathymetry. This approach will offer the opportunity of reaching high reproduction precision of the entire active channels, representing a cost-effective and low time-consuming modelling trade-off, especially when topographic detection of flowing channels through onerous bathymetric technologies is not possible or affordable. The further surface differencing to form DoD models will be processed in a GCD (Geomorphic Change Detection software) environment, using a multi-input raster methodology which evaluates also the precision of channel topography derived by colour bathymetry. This procedure joined to the use of FIS (Fuzzy Inference System) rules calibrated on our case studies, will perform a spatially-variable calculation of elevation uncertainty. The resulting DoD surfaces will provide reliable volumetric estimates of geomorphic changes obtained from a spatially-variable and calibrated threshold of detection which is able to report real variations and recover true and previously-discarded information. Such analysis of sediment balance will demonstrate highly significant because the resulting change volumes and dynamics will be revealed through the most up-to-date and precise methodology of change detection, further adjusted on our case study characteristics. In turn, such reliable results will be crucial to understand the real potential of below-bankfull floods on active channel processes, identifying morphological trends and sediment dynamics without incurring in misinterpretation.

Impacts of flooding will be further isolated, analysing major bank erosions and planimetric adjustments of the main flowing channels. Volumetric estimates of lateral shifts removing vegetated banks will give us an indication of the capability of fairly low floods to affect more stable and resistant areas of riverbanks. Moreover, the comparison between pre- and post-flood dynamics of main flowing branches will strengthen our knowledge on this poorly explored phenomenon of river system evolution. In fact, the assessment of the ability of low-magnitude flood events to cause important reconfigurations of the channel network will help us to better understand this highly unpredictable process.

The evolution of bank retreat in forested riverbanks will be further examined on the King River, an Australian stream characterized by cohesive soils, extensive scalloped riverbanks and tree abutments. The detection of bank tree characteristics as well as properties of bank profile spaces will lead to the identification of relevant relationships linking riparian vegetation and bank retreat. New evidences concerning the position of trees on banks, the complex impact of hydraulic processes as well as the influence of tree spacing in reducing scallop depth will help to fill gaps presented by recent modelling (Pizzuto et al., 2010). A novel and more comprehensive conceptual model will finally try to describe coherent and repetitive stages of development of bank retreat evolution in forested cohesive riverbanks.

A final comparison with bank retreat processes in the Piave River (Italy) will enrich the study with meaningful results between two very different fluvial environments, offering interesting opportunities for discussion.

1.2. Key concepts

1.2.1. Geomorphic changes

Geomorphic changes are commonly described as the changes that take place in the evolution of landforms. In fluvial geomorphology, they embody areal and volumetric variations featured by active channels, mostly due to the impact of flood events. Dynamic river corridors are continuously reshaped by erosion and deposition processes that, even representing natural phenomena, often create risks when occurring in populated areas. Many variables characterizing river systems can actively interact and influence patterns and magnitudes of geomorphic changes, including standing and dead wood, topography and sediment grain size. The estimation and interpretation of morphological variations has increasingly been studied in the last years as it represents a reliable indicator of flood potential and river equilibrium, both important aspects to consider for targeting effective protection and restoration projects. Thanks to the enormous advances in survey technologies and elaboration softwares, geomorphic changes can now be precisely estimated also over large extents and processed with an accurate evaluation of uncertainty, providing meaningful information of river evolution.

1.2.2. Bank retreat evolution

This concept refers to lateral migration processes occurring in fluvial systems as a natural progression of river course action. Enhanced by floods, bank retreat finds in outer bends, where fluvial scour features higher potential shear stresses, the most suitable areas for its development. Stream power, soil characteristics and riparian vegetation represent the major controls on patterns and rates of bank migration. Recent studies have underlined the presence of coherent and repeated stages in the evolution of bank retreat in forested riverbanks: these stages derive from the interaction among hydraulics, removal of bare soil between bank trees and final tree toppling (Pizzuto et al., 2010). Root plates of riparian plants can strongly affect bank retreat development, enhancing soil cohesion and reducing vulnerability to fluvial scour. The analysis and estimation of bank retreat processes represent a crucial aspect in the evaluation of flooding potential and dynamism of river systems. Rates and development patterns of lateral migration are of great importance for the management of forested riverine areas and for helping to target effective strategies against soil loss and flood risk.

2. BACKGROUND

2.1. Fluvial forms and processes

2.1.1. Introduction

Fluvial systems, through the action of running water, are significant land-shaping agents. Erosion, transport and deposition of sediment take place in different topographical units of the basin and sculpt the land surface, creating a wide variety of landforms. Climate, geology, topography, vegetation, soil type and human pressure can highly affect magnitudes and patterns of such processes, leading to variations in active channel characteristics. An important distinction in fluvial geomorphology regards stream nature and affects the degree of river changes: streams can be alluvial or colluvial. Alluvial streams, typical of large floodplain valleys, flow in a channel formed in and by sediment transported by the stream itself under its current flow pattern; therefore they are able to adjust their shape to match changing hydrological conditions by moving on the material forming their boundaries. Sediment flux is transport-limited here. Colluvial streams generally feature in steep mountain basins, artificial canals and canyons and are bounded by bedrock or concrete, thus being very limited or unable to produce morphological variations. In this case, sediment flux is supply-limited. Fluvial systems are driven, at basin-scale, also by spatial connectivity that affects the evolution of channels from the headwaters to the outlet. In their uppermost portion, river systems are fully-coupled, featuring active sediment supply to the channel from hillslopes and active channel erosion impacting hillslope dynamics. Following downstream, stream channels are partially decoupled in their mid-portions with floodplain areas that buffer temporarily the connection between hillslope and channel. Finally, in their lower course, river systems become un-coupled with discontinuity between hillslope and channel elements. Furthermore, connectivity can be divided in lateral (i.e. hillslope-channel connection), longitudinal (i.e. upstream-downstream flows) and vertical (i.e. river-aquifer interactions) (Arthington et al., 2006).

2.1.2. River dynamic equilibrium

A fluvial system represents an open dissipative process-response system which self-adjusts to external and internal changes to achieve a dynamic equilibrium between discharge, sediment supply, channel geometry and slope. Schumm (1977) has introduced the geomorphic concept as a useful tool to understand river changes: the response of fluvial systems may be strongly influenced by geomorphic thresholds, either external (reaction to external influences) or internal (adjustment to a condition of intrinsic incipient instability). External disturbances as dam construction, occurrence of landslides or removal of riparian vegetation are common elements undermining fluvial stability. For instance, a reservoir causes sediment trapping, inducing water released downstream to scour the riverbed and consequently leading to channel degradation until a new dynamic equilibrium is established. Over a long-term time span, the dynamic equilibrium of a river channel refers to the condition where the river capacity to transport sediment is in balance with the upstream sediment supply. Changes in sediment supply and hydrological conditions will influence the behaviour of the river that will continue to adjust its bed and banks. A qualitative relationship describing channel equilibrium considering sediment load and size, river slope and water discharge, was developed by Lane (1955):

$$Q_S d \ \alpha \ Q_W S \tag{1}$$

Where Q_s is sediment load (of sizes represented in the riverbed), d is sediment particle diameter of the riverbed, Q_w is water discharge and s is river channel slope (Fig. 1). According to this formula, when sediment load decreases, sediment particle diameter of the riverbed will tend to increase, whereas channel slope to decrease. Similarly, if water discharge reduces, river slope will tend to increase and sediment particle diameter to decrease.

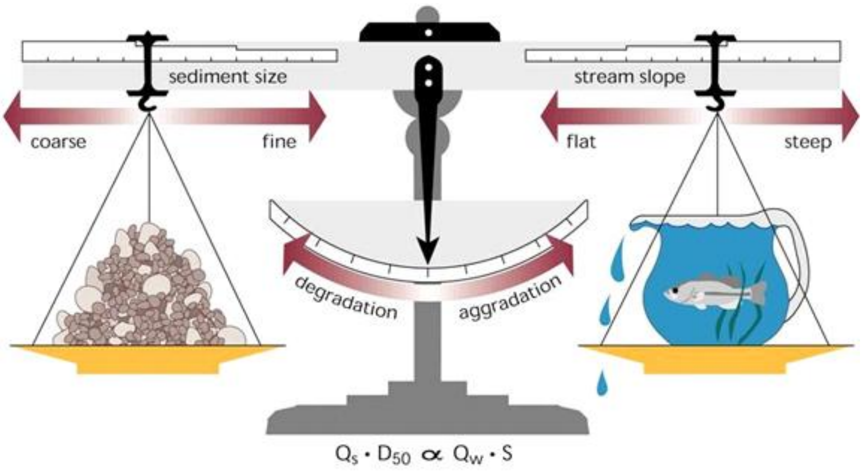


Figure 1: Lane's balance**.**

2.1.3. River hydraulics

Water flows in rivers through spatially- (non-uniform) and temporally- (unsteady) variable velocity, but for many applications of morphological research, a steady uniformed flow is assumed. This case is generally acceptable for relative narrow and short reaches (uniformity in space) during short times (temporal steadiness). Flow depth varies in function of discharge, being theoretically described with geometrical power functions. Water velocity is strongly influenced by cross-section geometry and, generally, finds its maximum values just below the water surface (0.05 m ÷ 0.25 m). In narrow cross-sections, higher velocity gradients are close to the side banks, while in wide cross-sections, higher gradients feature near the bottom. Velocity profiles can change considerably, especially depending on relative roughness of the bed and zones of maximum turbulence can trigger large erosion processes. A uniform flow that features an equilibrium between gravity force acting on the fluid and all dissipative forces (total friction), exerts a shear stress on the bottom. Generally, the deeper is the flow, the steeper is the channel, the highest is the shear. Flow power can dissipate its energy by skin friction, form or drag resistance and wave resistance. The sources of resistance derive from bottom roughness (i.e. sediment size), bed forms (i.e. step-pools), obstacles (i.e. vegetation) or bedload sediment transport. Flow regimes can be further described by flow Reynolds number, laminar or turbulent (natural streams are always turbulent), roughness Reynolds number, smooth, transitional and rough, and flow Freude number, subcritical, critical and supercritical.

2.1.4. Flooding and magnitude-frequency concept

Flooding represents a natural and essential process in river systems, a major contributor of channel adjustments, sediment and organic matter transport (Fig. 2). It can be divided in flow and flood pulses, the former being expansion-contraction events fairly below bankfull stage, whereas the latter indicating events with magnitude near and above bankfull discharge (Tockner et al., 2000).

The complex nature of flooding effects renders difficult also to univocally define formative conditions of flood events (Ashmore, 2001; Bertoldi et al., 2009a). The relationship between magnitude and frequency of floods is a very debatable issue in fluvial geomorphology, especially when experts seek to explain the evolution of fluvial forms and processes. Small and frequent events have been often compared to infrequent large events depending on their ability to effectively provide geomorphological variations of river channels. What is meant for "geomorphically significant" may highly vary, including the identification of threshold amounts of transported sediment, erosion of the channel bed, main channel reconfiguration, bank erosion, etc (Marren, 2005). In humid-temperate environments, flood events with low magnitude and high frequency are considered dominant, if sediment transport is the reference process to measure geomorphological efficiency. Recent researches, as Chappell et al. (2003) and Hassan et al. (2006), have underlined the importance of this type of flood progress in modifying channel forms through sediment redistribution. Moreover, the impact of flooding may highly vary depending on local reach characteristics, including topographical, geological and vegetational settings. Another aspect adding complexity to flood efficiency is flood duration. In this regard, Costa and O'Connor (1995) have distinguished in their study three types of floods: long duration floods with insufficient stream power to overcome erosion thresholds, floods reaching very high peaks of stream power but very short duration and long duration floods with high stream power peaks. The first two cases can lead to minimal geomorphological changes, while the latter will be the most effective in producing significant channel and floodplain variations. A last consideration that it is worth mentioning on the magnitude-frequency concept is the importance of recurrence interval and temporal order of floods, as proposed by Kochel (1988). A short recurrence interval between high-magnitude flood events will induce individual floods to have small impacts on river channel; by contrast long recurrence intervals will promote greater geomorphological impacts by individual floods. Temporal order is also very important as in systems not used to experience large floods, the first flood will have significant geomorphic effects with the subsequent events producing little changes independently on their sizes, until the channel has recovered. Flood ordering through time may largely affect geomorphic impact potential also in the case successive floods mobilise variable amounts of sediment in different channel sectors, changing sediment patterns to be reworked by subsequent events.

Figure 2: Flooded river.

2.1.5. Bank erosion and sediment transport

Bank erosion and retreat typically develops through the synergy of two mechanisms: fluvial erosion and bank failure (Prosser et al., 2000). The former includes the detachment of individual or aggregated soil particles due to hydraulic forces, while the latter refers to the physical collapse of banks when geotechnically unstable (Wynn et al., 2004). Streambank erosion represents the major sediment input in streams and a river management problem of global significance at the same time (Henshaw et al., 2012). Bank sediment sources are highly variable depending on many controls influencing fluvial environments and, in some case, they can reach the 80% of the total eroded sediment (Simon et al., 1996). The controls acting on riverbank erosion include cohesion or non-cohesion of bank material, antecedent bank moisture, bank texture, vegetation cover as well as anthropogenic activities (Simon et al., 1999). Human impacts play a major role in modifying natural loads of bank eroded sediment, even though also land-use changes or riparian revegetation can have a strong impact too (Rutherfurd, 2007). Being a substantial portion of the total sediment mobilized by rivers, bank erosion represents a fundamental component for estimating sediment budget. Several studies have tried to understand the controls and mechanics of this process (Rinaldi and Darby, 2008), however spatial coherence and volumetric contributions of streambank erosion remain still largely undocumented (O’Neal and Pizzuto, 2011). Improvements in the understanding of bank erosion processes may allow to effectively handling problems related to accelerated rates of bank retreat.

Although bank erosion is considered a natural channel response process, accelerated rates of lateral adjustments can lead to disturbances and hazardous situations (Fig. 3). Despite having positive effects as keeping the conveyance capacity of alluvial channels and enhancing biological diversity in riparian zones (Lane et al., 2006), lateral migration can also generate negative impacts. Especially after flood events, bank soil removal induced by fluvial activity can modify river evolutionary trajectories, threating agricultural land or human infrastructures. The increase of downstream sedimentation is a typical consequence of enhanced amounts of riverbank erosion and may lead, in turn, to issues for aquatic habitats, water quality and flood risk (Owens et al., 2005; Printer and Heine, 2005).

Figure 3: Large removal of soil by riverbank erosion.

Sediment in rivers is generally denoted by a diameter (D) that often considers the medium axis (b axis) of a particle. A sediment size classification was firstly developed by Wentworth (1922) that, in a diagram scaling grain size in terms of a base-two logarithmic scale (phi scale), has separated the range of sediments in clay, silt, sand, gravel, cobbles and boulders (from fine to large). Sediments and, more generally, materials can be transported by a stream through different mechanisms: solution, under flotation, in suspension or by traction at the bed (Fig. 4). In river morphology, bedload transport has the greatest influence among transport mechanisms, even though suspended load is important for the formation of floodplains.

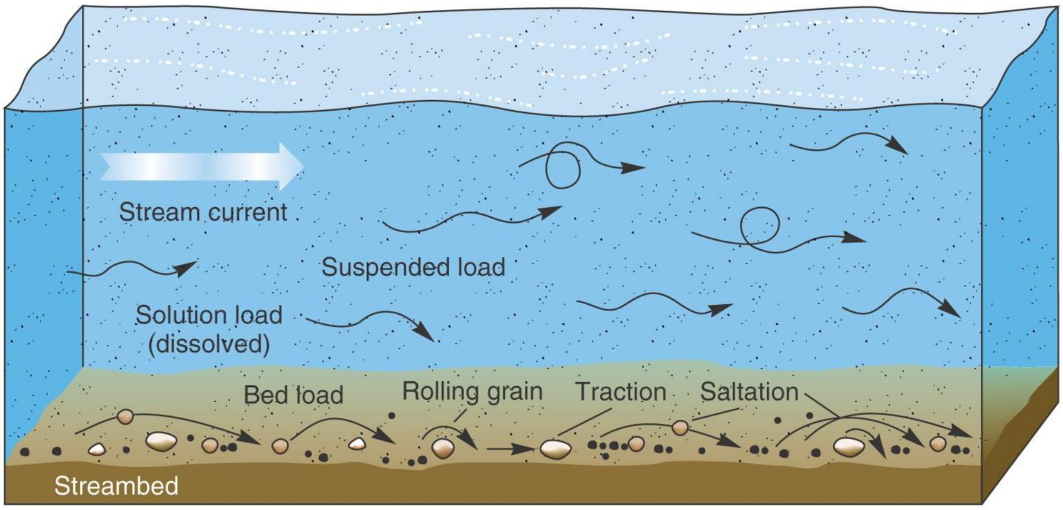


Figure 4: Types of sediment transport.

The threshold by which sediment can be mobilized under a given water discharge condition was found by Shields (1936), through a physical approach. The detachment of a particle is seen as a balance between resisting forces versus hydrodynamic forces. Shields expressed this threshold in a dimensionless way using the parameter θ_c (critical dimensionless shear stress) which was found to be a function of the grain Reynolds number (parameter defining flow regime: laminar or turbulent):

$$\theta_c = \frac{\tau_c}{(\gamma_s - \gamma)\, d} \tag{2}$$

Where τ_c is the critical shear stress (N m^{-2}), γ_s is the specific weight of sediment (N m^{-3}), γ is the specific weight of water (N m^{-3}) and d is the particle diameter (m). The critical value of the Shields parameter corresponds to the beginning of motion which is mostly affected by the prevalent flow regime (laminar or turbulent) around the particle and by the particle size itself. Despite the significance of this finding, several factors influencing sediment mobility, as longitudinal channel slope, lateral channel slope, relative submergence, sediment non-uniformity and sediment imbrication, were not accounted in this theory that several research have tried to improve throughout last decades (i.e. Bathurst et al., 1987).

2.1.6. Channel planforms and bedforms

The active channel of a river is described as the channel area filled by water at bankfull stage. Bankfull discharge is the water discharge reaching the top of the riverbanks and it is also called formative flow, due to its capability of determining the main morphological parameters (Recurrence Interval - R.I. of 1.5 years on average).

Literature has initially divided river planforms into three categories, as depicted in Fig. 5: straight, braided and meandering (Leopold and Wolman, 1957). In more recent times (Billi, 1994), planform types have reached five classes depending on the interaction and equilibrium of a wide range of variables, including grain-size, slope, sinuosity, width/depth ratio and sediment transport dynamics. The five categories now used are: straight, braided, wandering, meandering and anastomosed.

Straight reaches are typically confined streams located in narrow mountain valleys. They are characterized by high slopes, low width/depth ratio and low sinuosity. The river bed is generally formed by bedrock, cobbles and boulders with consecutive steps, riffles and pools as run units. Bars can be absent or possibly laterally alternated and channels are prone to incision during floods.

Braided patterns are normally located in wide valleys or piedmont plains and present both gravel and sandy river beds. Their peculiarity is to feature multiple channels even at low- to moderate flows. Other characteristics include a very large width/depth ratio, highly variable slopes and a low sinuosity. Moreover, this very dynamics reaches feature riffle/pool bedforms, longitudinal bars and are prone to deposition during large floods.

Wandering reaches represent a transition from a braided to a meandering structure and mainly feature gravel-beds with few sandy patches. Slopes normally vary from 0.1% to 0.5% and sinuosity is moderate to high. Crescent-shaped lateral alternate bars are dominating and it is worth noticing the presence of backwater and chute channels with riffles and pools. Wandering reaches are often the result of human-induced alteration of braided channels due to reduction of sediment transport.

Meandering reaches present sandy beds with cohesive riverbanks. Slopes are very low, sinuosity very high at all stages and the channel is not confined. Their dynamism is rather low due to resistant banks and the formation of oxbow lakes when meanders are cut-off for high sinuosity is possible.

Finally, anastomosed reaches feature in wide flat valleys or coastal areas (deltas) and are characterized by multiple channels even at bankfull flow. Slopes are extremely low and the active channel presents sandy beds and cohesive riverbanks. Such systems are very stable with channels, that can be meandering or straight, that enclose floodplain basins.

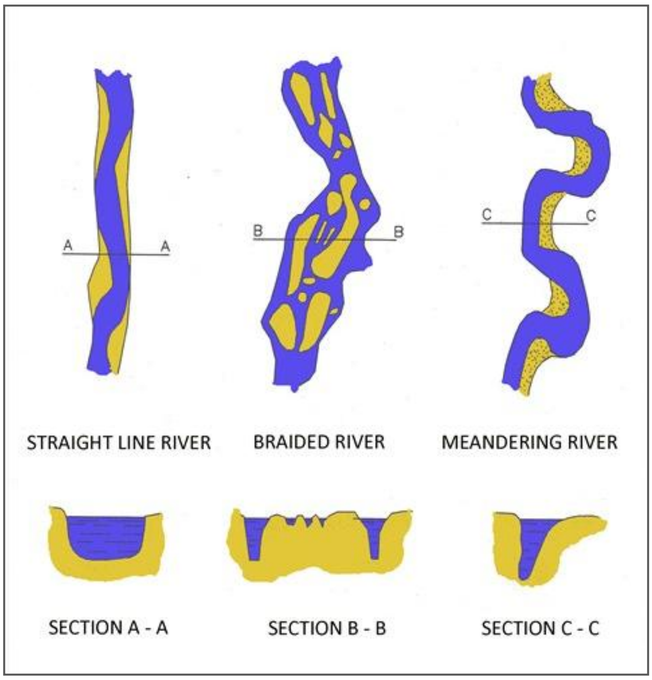


Figure 5: Original channel planform types**.**

Bedforms represent the range of structures that we can find at the bottom of river channels and develop as a response to bedload transport. Different classifications were developed to describe bedforms in the diverse evolutionary sections of river channels. Montgomery and Buffington (1997) have provided a classification of bedforms for mountain streams (Fig. 6), following a trend of decreasing slope, in order: cascade, step-pool (Fig. 7), plane-bed, pool-riffle and dune-ripple.

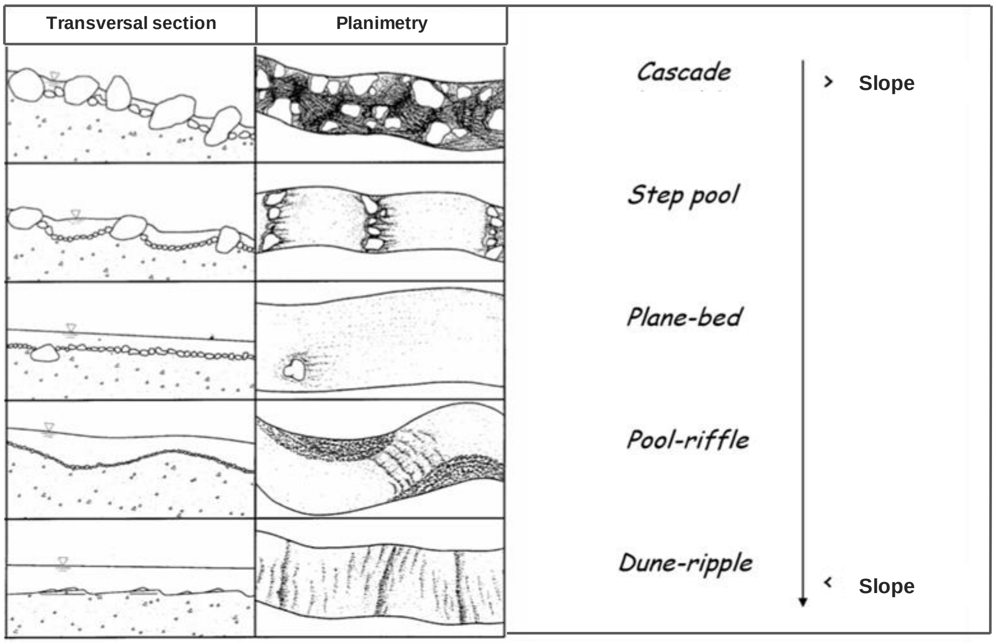


Figure 6: Bedform types in mountain streams.

Figure 7: Example of step-pool structure in a mountain stream.

2.1.7. Channel migration

River channel migration consists in the lateral motion of an alluvial channel across its floodplain through erosion and deposition processes affecting its banks and bars. Despite being a natural process, its incidence represents an important engineering issue, as transportation infrastructures result undercut and damaged frequently.

In braided streams or river portions, channel shift is mainly induced by sediment transport that causes the remobilization of barforms or floodplain portions through the channel. The scour of outer banks or in-channel bars is typically produced by streamlines curvature and causes frequent and strong variations of active channel width. In this sense, channel migration occurs much faster than in meandering streams leading to significant geomorphic changes even at relative low water stages (Bertoldi et al., 2010).

Meandering behaviour represents a distinctive characteristic of low-gradient rivers and contributes to develop meanders along the stream course, wave-shaped bends having one or multiple maxima of curvature. Meandering channels are composed by the outward side of the river bend (concave portion), the inward side of the river bend (convex portion) and the relative straight area among successive bends which is characterized by inflection points where curvature direction changes. Meander planform is the result of complex interactions among channel morphology, flow structure and sediment transport, and develops through the lateral and downstream migration of river channels. Thus, migrating meanders need erodible and retreating channel banks to develop and their characteristics (i.e. grain size) and associated components (i.e. riparian vegetation) may greatly affect spatial and temporal evolution patterns.

Bed morphology of meandering river curves generally consists of an elongated pool along the outer bank and a point bar along the inner bank. Sinuosity and curvature often increase as meanders widen and migrate through bank erosion processes until the extreme case of meanders intersection where their cut off may create free-standing water bodies called oxbow lakes (Frothingham and Rhoads, 2003; Seminara, 2006).

The hydraulics operating in meandering bends is highly three-dimensional and it is characterized by an imbalance over water depth caused by curvature between the centrifugal force directed outward and perpendicular to the channel centerline and the opposed pressure-gradient force directed inward and originated by water surface superelevation (Dietrich, 1987). The resulting motion, called helical, develops as a continuous spiral heading downstream throughout the water mass, with flow direction lines pointing the outer bank near the surface and the inner bank near the bed. This spatial pattern of flow velocity leads, in turn, to spatial variations in boundary shear stress and sediment transport, generating scour processes along the outer concave bank and deposition processes along the inner convex bank, as depicted in Fig. 8 (Nelson and Smith, 1989).

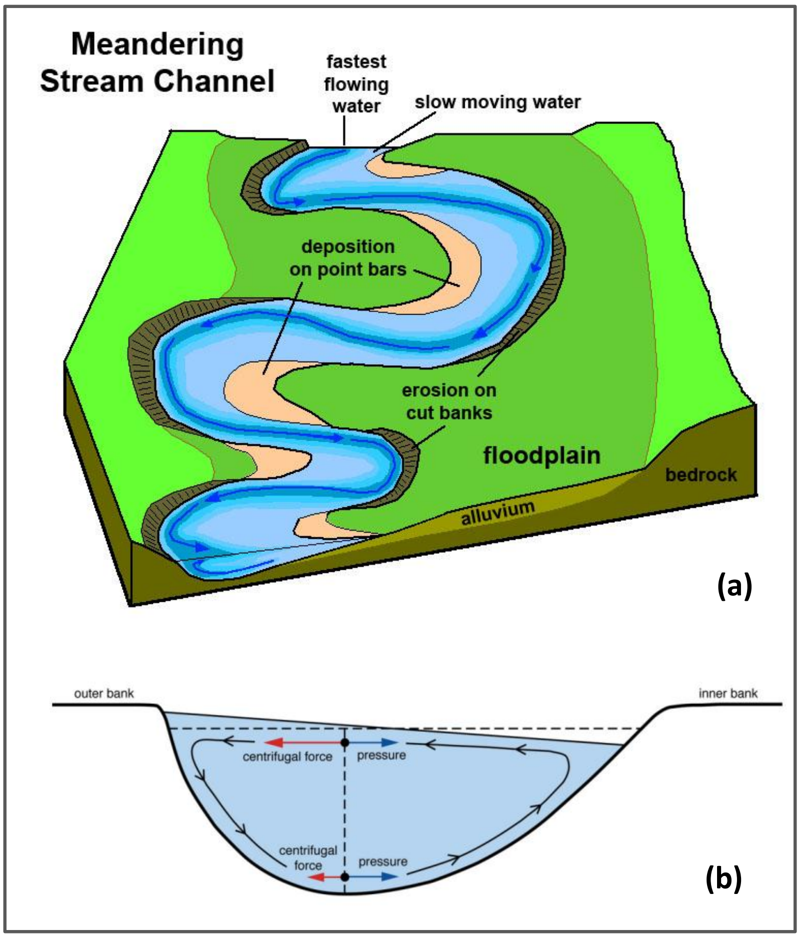


Figure 8: Characteristics of meandering stream channels (a) and helical motion in meanders (b).

The degree of meander curvature is the driving physical factor promoting flow convergence in the outer pool which accelerates stream power towards the concave bend, producing the potential for enhanced turbulence, boundary shear-stress and consequent sediment removal in the near-bank region. Field research supports the existence of a relationship between rates of bank erosion and magnitudes of near-bank velocities (Pizzuto and Meckelnburg, 1989; Constantine et al., 2009).

2.1.8. Spatial and temporal scales

Considering appropriate spatial and temporal scales is a fundamental aspect in the effective analysis and understanding of fluvial systems. Spatial scales include river basin, channel reach and channel unit (Fig. 9). The basin of a river is the portion of the landscape draining to a given channel cross-section and represents the essential physical unit for hydrological, morphological and ecological research. A river reach embodies a channel length featuring approximately uniform characteristics: slope, width, sediment size, morphology, etc. Its length needs to be enough to capture meaningful hydraulic processes (usually at least ten times the bankfull width) and it represents the appropriate spatial scale to evaluate river changes for flood hazard, ecological assessment and stream restoration perspectives. Within a reach, a channel is composed by units that can be divided according to the prevalent mechanism of their formation. Erosional units are the channel itself and the pools, portions of the bed featuring deeper and slower flows. A mixed unit is the meander or rather a self-formed bend which flows on gentle slopes with fine sediments, generally in lower river plains. Depositional units are floodplains (surfaces outside of the active channel flooded at least every 1-2 years), bars (sedimentary features within the active channel emerging at low flows), islands (surfaces within the active channel featuring a pluriannual vegetation), riffles (short length of the channel featuring shallower and faster water depth because of a local higher slope) and steps (vertical drops in the longitudinal profile). Planform structure results from the interaction of channels, floodplains, bars, islands and meanders, whereas the river longitudinal profile is determined by sequences of riffles, steps and pools.

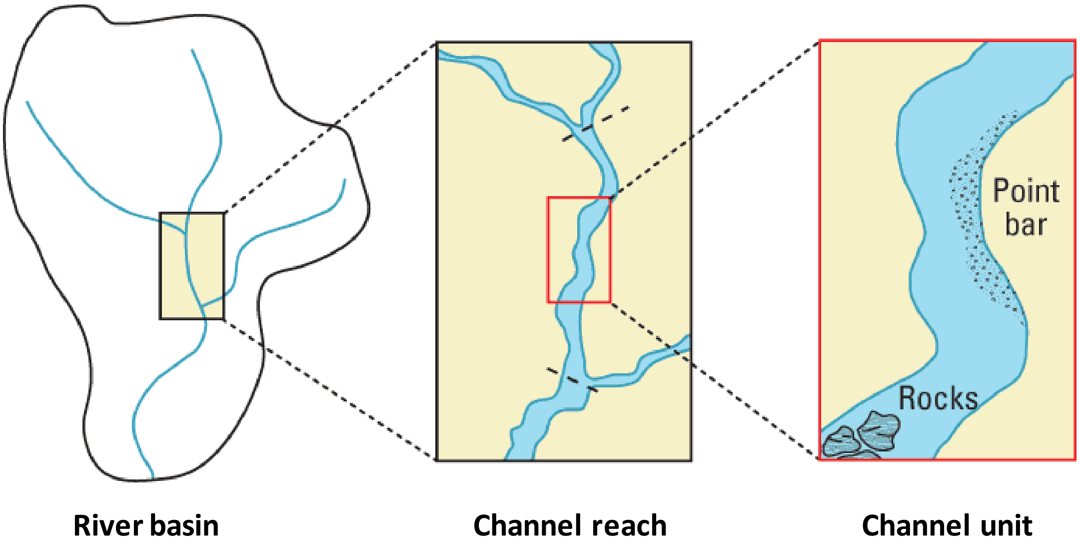


Figure 9: Spatial scales in river systems.

Temporal scales are also decisive for understanding river dynamics and the magnitude of geomorphic changes. The unit of measure here is the Recurrence Interval (R.I.), a statistical estimate of the likelihood of an event to occur. High flows with a monthly R.I. (0-1 year) are generally restricted to in-channel areas and scour and sculpt, from month to month, fluvial features, slowly but constantly changing the environment over millennia. A time-span of years (1-10 years) can produce highest annual flows that, from year to year, can be contained in the channel borders or inundate the near floodplain. Yearly time-range is also the dimension for natural rivers of bankfull floods, the formative discharges which affect the entire width of the active channel, producing balanced erosion and deposition processes that maintain channel size and form although favouring a redistribution of sediment. Recurrence intervals of decades (10-100 years) correspond to large floods which can result in large adjustments of river size and morphology. In this case, the channel will feature a predominance of erosion processes that will adjust the channel extent to accommodate the increased flow. During the variable inter-flood periods, vegetation can establish especially colonizing flood deposits and reducing channel width. Finally, a time-scale accounting for centuries (100-1000 years) includes also extreme floods which can significantly alter river character, even those sections been stable for several lifetimes. These rare events can also cause disturbances to habitats, planform realignment and transport of enormous volumes of sediment, leading to dramatic changes in the most part of the river basin (Fryirs and Brierley, 2012).

2.2. Impact of riparian vegetation on fluvial processes

2.2.1. Introduction

Riparian vegetation represents a key element in fluvial environments, controlling and being controlled at the same time by river processes. Periodic flooding can significantly regulate the development of many vegetation patterns along fluvial channels, promoting a dynamic equilibrium with no loss of species compositional integrity (Kirkman and Sharitz, 1994; Osterkamp et al., 1995). When riparian vegetation undergoes erosion and topples into river channels, LW (Large Wood) may affect several aspects of fluvial systems including braiding, meandering, avulsion processes as well as sediment dynamics and morphological changes (Piégay, 2003; Montgomery and Piégay, 2003). Moreover, LW can help the formation of stable channel units, controlling hydraulics and riparian-forest development that, through sediment aggradation, can have availability of new sites for colonization (Abbe and Montgomery, 1996). Bank trees and shrubs also provide essential ecological values to river systems, as filtering out pollutants from water run-off and creating important habitat attributes including shade, shelter and food for wildlife and fishes. The amount and type of vegetation on the banks further affect rates and patterns of bank erosion processes. Nevertheless, the dynamic interaction between bank trees and soil removal as well as the evolution of bank retreat considering different vegetation structures (i.e. density, size, etc.) still feature several knowledge gaps that would be important to overtake in order to help reaching the best practice for river restoration purposes.

2.2.2. Control on bank dynamics

Riparian vegetation represents a major control in fluvial geomorphology, influencing bank dynamics through both important mechanical and hydrological effects (Simon and Collison, 2002). Bank trees and shrubs are generally thought as elements producing positive effects on bank equilibrium; however they may also generate destabilizing processes. Analysing and estimating these effects becomes crucial to better understand the role of riparian vegetation in the dynamic evolution of migrating riverbanks and consequently target effective restoration measures.

2.2.2.1. Stabilizing effects

The influence of trees and their root plates in generating soil cohesion thus contrasting erosion by reducing shear stress (Abernethy and Rutherfurd, 2001; Griffin et al., 2005; Hubble et al., 2010; Gurnell, 2014), and extracting soil moisture for transpiration (Van de Wiel and Darby, 2007), has been widely recognized, leading to the conclusion that forested banks migrate slower than unvegetated banks (Allmendinger et al., 2005). Plants and shrubs, through their elastic roots, reinforce the soil decreasing tension-crack formation and reducing the likelihood of mass failure, as presented in Fig. 10 (Abernethy and Rutherfurd, 2000; Bischetti et al., 2003; Bischetti et al., 2009; Hubble et al., 2010). When channels migrate into riparian trees, slower local erosions due to roots resistance may create a scalloped bank line, where protruding tree abutments and root crowns represent evidences of the erosion-resistant effect of woody vegetation (Rutherfurd and Grove, 2004). Also grassy vegetation may provide an equal or even stronger influence than woody vegetation for achieving certain stream management goals, as preventing bank erosion and trapping suspended sediment (Lyons et al., 2000). Furthermore, the depth of the root plate may strongly influence erosion dynamics since bank toes, featuring less compactness exerted by roots, normally undergo greater scour processes. Even though few spaced trees do not seem to alter the long-term migration evolution of bends, changes in plant density and size may lead to high rates of spatial and temporal variability in bank retreat (Rutherfurd and Grove, 2004).

Figure 10: Stabilizing effect of riparian vegetation on the King River (Australia). Root plates, enhancing soil cohesion, contribute to reduce bank retreat.

2.2.2.2. Destabilizing effects

Increased surcharge, higher pore-water pressure due to canopy and stemflow interception and higher infiltration capacity due to macropores creation by biological activity are commonly seen as the main detrimental consequences undermining streambank stability (Simon and Collison, 2002; Wynn and Mostaghimi, 2006). Moreover, riparian vegetation may strongly interact with the flow when submerged during flooding, modifying its hydrodynamic structure and causing local scour (Schnauder and Moggridge, 2009; Samarakoon et al., 2013). In fact, vegetated banks lead to variations in near-bank velocity and turbulence intensity, as highlighted by studies that use flume experiments with different vegetation treatments (Hopkinson and Wynn, 2009) and overbank flow dynamics (McBride et al., 2007) or form drag modelling of small-scale topographic features (Kean and Smith, 2006). Changes in near-bank hydraulics can be produced also by root plates that, creating local eddies between consecutive trees along the bank line, may favour the amplification of erosion and buttressing dynamics (Pizzuto et al., 2010). Bank trees eventually toppling into river channels can bring along large amounts of bank sediment trapped in their root plates (Fig. 11).

Figure 11: Bank trees toppled in the river channel, bringing along considerable portions of bank sediment trapped in their root plates.

2.2.3. Bank retreat evolution in vegetated riverbanks

A particular sequence of bank retreat processes has been observed when channels migrate toward forested riverbanks. Few studies have attempted to interpret this phenomenon that often creates, especially on the outer side of bends, a series of concave erosional features alternated with tree root-plate abutments. Rutherfurd and Grove (2004) firstly tried to describe tree abutments as distinct fluvial features in some Australian rivers. They found out that root plates resisting to fluvial shear stress had a semi-circular shape centred on the trunk and abutment radius was generally the half of the canopy radius. Moreover, all the considered abutments were deeply undercut with overhanging root plates exposed from 0.5 to 1 m and a distinct deepening of the bank at the tip of the abutment. The overall conclusion of this study was that, even though such features had different and complex effects on bank retreat by interacting with hydraulic and erosion mechanisms, the isolated character of the analysed trees would not have altered the long-term migration rate of bends.

More recently, Pizzuto et al. (2010) have documented spatial and temporal patterns of bank retreat. After recognizing abutments as key elements in decreasing local rates of bank migration and creating a scalloped bank morphology, this study has proposed a cyclic conceptual model describing the retreat of forested cohesive riverbanks through time. The evolution of bank retreat is described as a process formed by coherent and repeated stages where hydraulics of the river, removal of soil between trees growing near the bank and ultimate tree toppling into the channel, interact together. At the beginning, riparian trees grow at some distance from the bank, on the floodplain, and after a certain time, they come in contact with the migrating bank. Large trees may make a stand to fluvial scour, creating scalloped bank longitudinal profiles and "recirculating eddies" between the abutments. Near-bank hydraulics results modified, further influencing bank retreat dynamics. The behaviour of bank trees is then described as a slow sliding process that brings their root plate to a lower position where they become partly inundated under base flows and increasingly undercut. Tree trunks start to lean toward the channel with roots growing back into the bank until their position becomes untenable and they topple into the flow, straightening the bank line for a further evolution (Fig. 12).

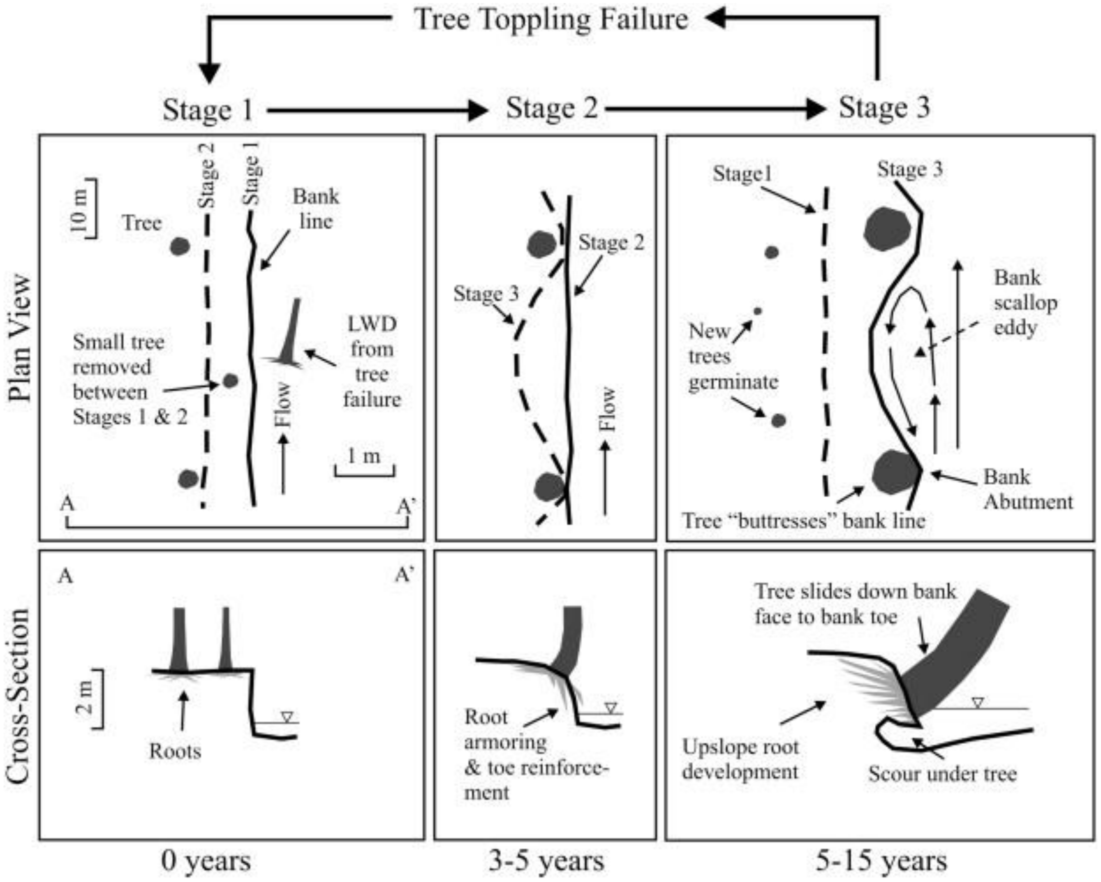


Figure 12: Three stage conceptual model illustrating the interactions between migrating cutbanks, soil removal, and riparian trees (reproduced from Figure 15 in Pizzuto et al. (2010)).

2.3. Human impact on rivers

2.3.1. Introduction

Human impacts on river systems started several thousand years ago and include alteration to water and sediment yields and dynamics both at drainage basin- and channel-scales. The anthropogenic activity which goes the farthest back in time is land use that, essentially since people became able to control the land, has continuously affected, through its change, fluvial environments. Such indirect practice comes along with many other impacting phases of human development as grazing, cropping, deforestation, urbanization, industrialization, mining and infrastructural building. Among direct activities affecting river systems, the most significant is probably flow regulation and, in particular, dam construction that has been producing stream segmentation in almost 80% of the Northern Hemisphere's rivers (Dynesius and Nilsson, 1994). Within the United States, their impact is even greater, accounting for 80,000 dams that are affecting approximately 98% of nation's streams (Graf, 2001). Dams, beside providing enormous social and economic benefits such as navigation and hydroelectric power generation, contribute to reduce flood hazard protecting agricultural lands and urban areas but at a very high environmental cost. River engineers have always aimed at producing stable, unchanging and predictable fluvial systems, contributing to produce several losses of river natural functions. In the last years, the changed social values and a new emphasis on environmental uniqueness of rivers, claim the reduction of human pressure on streams and the need of restoring their dynamic equilibrium, starting from their physical integrity (Graf, 2001).

2.3.2. Risks induced by rivers

Rivers embody innumerable beneficial aspects, but they can also provide challenging and risky situations, enhanced by the more and more frequent extreme events induced by climate change. Despite their natural phenomenology, large floods represent the greatest risk for river-affected areas and can lead to extensive property and infrastructure damages that need expensive and time-consuming actions to be recovered (Fig. 13 and 14). Flooding can also promote channel reconfiguration and avulsion processes which can develop through bank erosion. Accelerated rates of bank removal, influenced also by human interventions, can further produce diffuse hazardous conditions. In degraded systems, bank erosion causes soil and land losses, affecting agricultural and recreational lands. To prevent and control riverbank erosion, extensive protection measures have been taken in the last century in many European fluvial environments. These interventions may produce many negative and unforeseen effects, specifically when bank stabilization works are outside of a comprehensive management policy. In some cases, poorly planned stabilization works has resulted in shifting the hazards downstream of the mitigation area (Wolfert, 2001; Vandenberghe et al., 2012).

Finally, rivers can trigger environmental concerns when pollution undermines fluvial habitats. Pollution can derive from both point-source polluters, as sewage systems and factories, and by non-point-source polluters, as for example the combined effect of farm runoff or urban storm drains.

Figure 13: Impact of bank erosion on human properties.

Figure 14: Impact of bank erosion on infrastructures.

2.3.3. European and Italian river alteration

Most of rivers have suffered, at some point and at some degree, human impacts, insomuch as the delineation of a reference condition of a river in the absence of human influence is almost impossible. Recent human interventions have affected hydrological and sedimentological regimes of rivers, both for material/energy supply or protection. Activities that can create disturbance to the river corridor include the construction of dams (Fig. 15), levees, diversions, infrastructures, bank protection, removal of woody debris, logging, gravel mining, grazing, urbanization and recreation (Wohl, 2005). Particularly, channelization was a common procedure utilized in the last decades to control flooding and drain wetlands. Such practice, affecting nearly all hydrogeomorphic river forms and processes, has led to extensive degradation and erosion of channel bed and banks, inducing fluvial channels to attain a new equilibrated condition (Simon and Hupp, 1992).

Although narrowing and incision periods could represent natural dynamics of streams, in the last century the most part of European and Italian rivers have experimented larger rates of adjustments in respect to those being expected. The causes are probably referable to the human impacts perpetrate both at the basin- and channel- scales (Kondolf et al., 2007; Gurnell et al., 2009; Surian et al., 2009; Comiti et al., 2011). Dams, sediment mining, channelization, land-use changes, torrent- control works have led to variations in water and sediment fluxes as well as boundary conditions (riparian vegetation and bank stability), generating in turn widely studied channel-response processes (Surian and Cisotto, 2007).

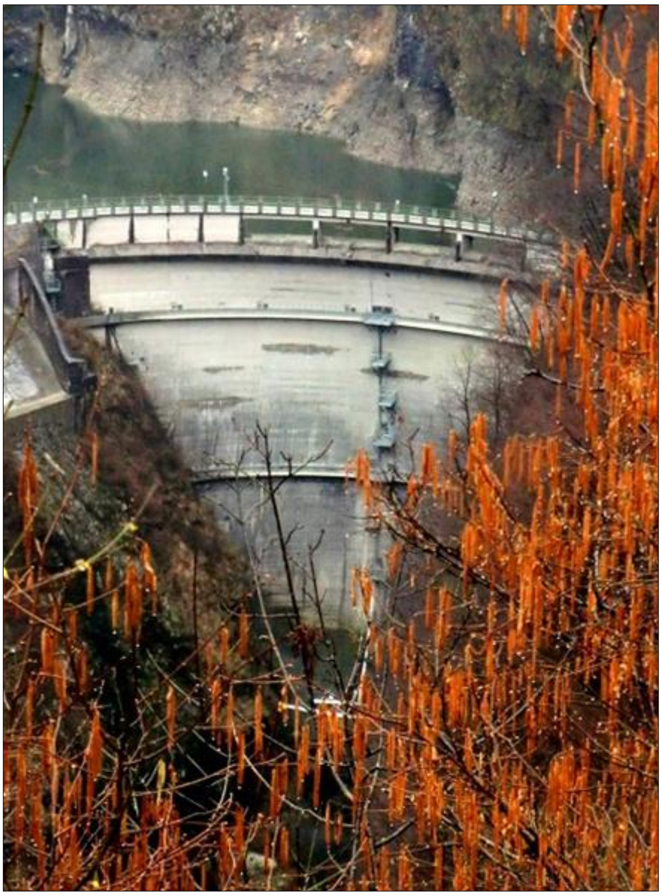


Figure 15: Example of a dam (Corlo dam, Brenta River).

Focusing on Italian rivers, significant channel adjustments have been registered in the last decades, consisting in a major phase of narrowing and incision, followed by a recent trend towards equilibrium. The Piave River, for example, has suffered bed incisions up to 10 m and a narrowing phase accounting for about 50%. Gravel mining, beside the presence of dams for hydroelectric power generation, has been recognized as the key driving factor of the past changes leading to a dramatic alteration in sediment regime (Comiti et al., 2011). The strong narrowing tendency has also caused, in some reaches, the shifting from braided to wandering/single-thread morphology of the channel. In this sense, the encroachment of riparian vegetation has been favoured and consistent woodlands are now developing within the river corridor. This situation can be considered positive for many aspects including the improvement of biodiversity conditions by the creation of many different habitats with great ecological values. Nevertheless, such situation may also lead to issues related to possibly more frequent flooding or displacement of potentially dangerous wood elements in the channel (Comiti et al., 2011). In fact, velocity reduction caused by plant community can encourage deposition of suspended sediment with consequent material accumulation and proto-islands formation (Coulthard, 2005).

2.3.4. Legislation and restoration design

River geomorphological studies have grown in importance in the recent years, being included in two EU Directives on Water (2000) and Flood Risk (2007). These novel legislation acts, beside considering activities to mitigate risks induced by rivers, seek to promote a sustainable use of streams and their restoration to a hypothetical natural state. River restoration includes a large variety of physical, ecological, spatial and management measures and practices aimed at sustaining river functions and promote biodiversity, recreation, flood management and landscape development. In the last few decades, a growing awareness of the impacts of river-engineering approaches has developed. Management goals were previously focused on increasing navigation and flood conveyance to provide protection to adjacent development and infrastructures. Extensive environmental impacts began to be considered as society was moving towards a new conception of fluvial systems as natural environments. Therefore, current restoration objectives include, as integral parts, the maintenance of natural river processes and the conservation of ecological habitats. An important concept to support geomorphological functions of rivers preserving the role of bank erosion is to promote an erodible corridor providing streams with room to dynamically evolve (Piégay et al., 2005).

Considering that reporting rivers to a pristine situation with no human impacts is unreal for many reasons, including the non-existence of a reference condition and the improbability of relocating human structures, the historical knowledge of human impacts suffered by different river reaches forms in any case a crucial component of restoration design (Wohl, 2005). River restoration commonly attempts to meet society expectations, especially regarding appearance or function (Comiti, 2012). Fluvial function is mainly achieved with the restoration of processes providing self-sustaining aquatic or riparian habitat, whereas projects focused on appearance tend to act at localized reach-scale. Concentrating on appearance can lead to misleading results that satisfy only apparently the general public's conception of river health as having clear waters and non-eroding banks. Such appealing characteristics can strongly compromise stream function if flow and sediment are no longer moving downstream, creating a segmented fluvial environment. In this sense, a successful restoration project needs to develop a compromised approach, promoting attractiveness of rivers together with the maintenance of hydrologic and geomorphic processes to reach ecosystem integrity. Understanding what types of disturbances have played and are continuing to play an active role in forming the actual channel condition represents an integral part of an effective river restoration project (Wohl, 2005).

2.4. Digital surface modelling of fluvial systems

2.4.1. Introduction

The evaluation of the morphological dynamics of rivers is increasingly focusing, in recent years, on quantitative estimates of change to identify geomorphic trends through time and, consequently, forecast targeted restoration actions. Erosion and deposition processes can be detected using a large array of technologies that have proved to be consistent and accurate devices to capture changes of the earth's surface through time. Topographic data can be handled by ArcGIS platform that permits a large array of elaborations including interpolation of Digital Elevation Models (DEM). Comparing temporally different DEMs may lead to obtain DEMs of Difference (DoD), where patterns of erosion and deposition can be visually recognized and an estimation of sediment balance (scour and fill volumes) can be operated. By reproducing earth's surface, increasingly important is becoming the evaluation of uncertainty influence, considering that, in several cases, errors may exceed real rates of morphological changes (Lane et al., 2003; Wheaton et al., 2010; Milan et al., 2011; James et al., 2012).

2.4.2. Surface modelling and change detection

The representation of topographic surfaces using Digital Elevation Models (DEMs) has experienced a well-documented increase in geomorphology in the last years. This progress has been possible thanks to the recent advances of survey technologies that allow now the rapid acquisition of data at spatial resolution and extents previously unimaginable (Heritage and Hetherington, 2007; Milan et al., 2007; Marcus and Fonstad, 2008). Spatially-distributed and morphologically-based attributes can be captured by a wide arrange of techniques as total stations (Fuller et al., 2003, 2005), GPS - Global Positioning System - (Brasington et al., 2003; Wheaton et al., 2010), airborne LiDAR - Light Detection and Ranging - (Devereux and Amable, 2009), TLS - Terrestrial Laser Scanning - (Heritage and Milan, 2009; Hodge et al., 2009). The use of modelling softwares as ArcGis and Matlab for filtering and process LiDAR points can further lead to the interpolation of DEMs (Fig. 16). Digital Elevation Models are representations of the ground surface topography (elevation), generally produced in a raster format or in a triangular irregular network (TIN). In the raster representation, the topographical area is split in a grid containing same-sized small cells which embody (each) one alphanumeric value corresponding to one attribute linked to the portion of the area performed. In the TIN model, the topographic area is divided into a connected series of variable-sized triangles, set unevenly in the space. DEMs usually feature a composition of georeferenced matrices which are related to terrain elevation values and allow to obtain a series of attributes (gradient, exposure, curvature and topographical indexes). In raster format, they are generated from the interpolation of points coming from surveys (GPS, LiDAR, etc).

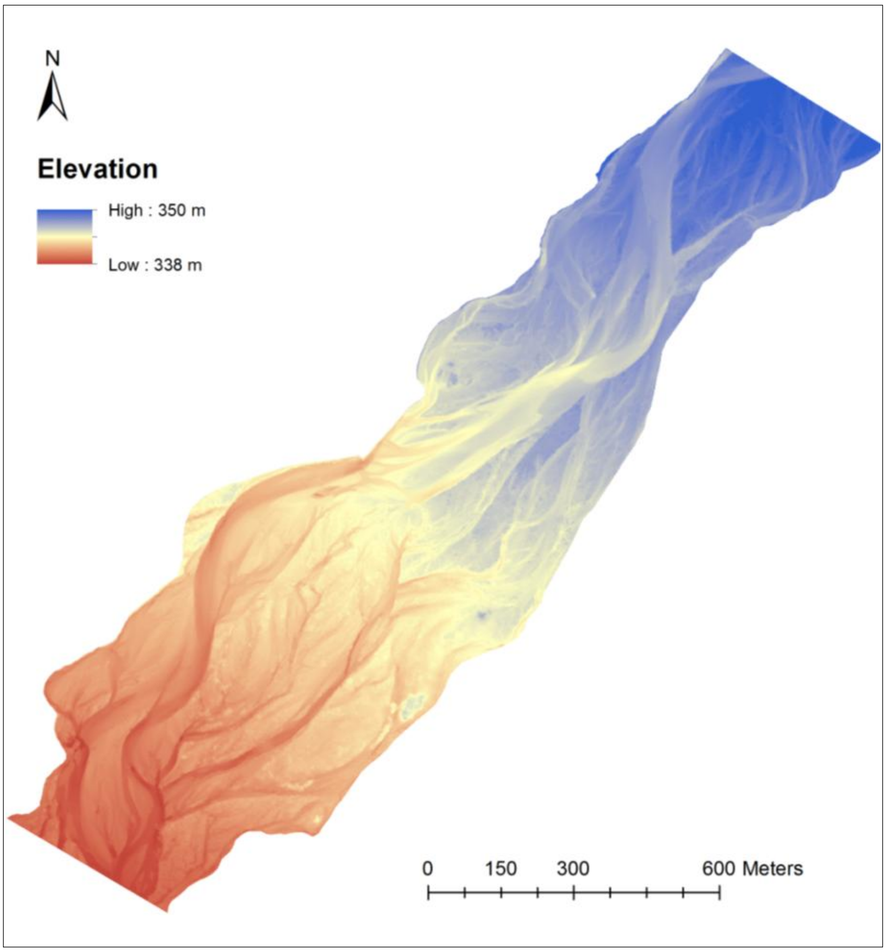


Figure 16: Digital Elevation Model (DEM) of Belluno reach (Piave River).

The use of the right interpolation method can also affect the accuracy of final DEMs, choosing among:

- *Theissen Polygons*: appropriate to define the “influenced zone” of a point or line using the “nearest neighbor” approach. A set of polygons encoded with the nominal value for each point (to form a proximal map) represents the region of influence.
- *Spline*: approximation of a function by means of series of polynomials over adjacent intervals with continuous derivatives at the end-point of the intervals. An iterative process is used to estimate the best outcome that can be found, for example, by smoothing the interpolation in order to control the variance of the residuals over the dataset.
- *Inverse Distance Weighting* (IDW): the estimates are based on values of nearby locations weighted only by distance from the interpolation location. The only utilized

assumption regards the nearby points that should be more closely related to the value than distant points. Cell values are calculated by using a linearly weighted combination (inverse distance function) of sample points. The significance of known points upon the interpolated values can be controlled by the user.

- *Trend Surface*: a floating-point grid is created by using a polynomial regression to fit a least-square surface to the input points. The polynomial order utilized to fit the surface can be checked by the user and varies from 1 to 3 allowing to choose the best fitting performance of the interpolated area.
- *Natural Neighbour Interpolation*: based on Voronoi tessellation of a discrete set of spatial points, this interpolation method offers the advantage of providing a smoother approximation of the underlying “true” function. The computation of the weights and the selection of the interpolating neighbours allow a more “close to reality” representation of the surface.
- *Kriging*: the interpolated values derive from variograms of spatial relationships and not from physically sampled points. Kriging is based on a regionalized variable theory which provides an optimal interpolation estimate for a given coordinate location, as well as a variance estimate for the interpolation value. The spatial behaviour is investigated before generating the output result through the assumption of statistic homogeneity of variation of the entire surface. Datasets with abrupt morphological changes are not appropriate for the Kriging method.

The development of new tools in GIS environment capable to handle large datasets and rapid and accurate interpolation of DEMs has permitted the repeated use of surveys with the aim of estimating both spatial patterns of erosion and deposition and change volumes (scour and fill). This result can be achieved by differencing successive concurrent DEMs to create DEM of difference (DoD) according to this formula:

$$\Delta \mathrm{Eij} = \mathrm{Z2ij} - \mathrm{Z1ij} \tag{3}$$

where ΔEij is the I,j grid value of change in the elevation model, Z1ij is the I,j value of the early DEM, and Z2ij is the I,j value of the later DEM. In the resulting DoD, elevation reductions are represented by negative values, while positive values express elevation increases. Despite the static mode, DEM differencing is an important tool for analysing geomorphological dynamics, as identifying location of geomorphic stability or change, past trends, rates of change, as well as sediment budgeting. Nevertheless, further improvements on precision and reliability of scour and fill estimates derived from DoD are needed, especially through a robust assessment of multi-level uncertainty (Wheaton et al., 2010; Milan et al., 2011).

2.4.3. Quantifying uncertainty in surface representations

The estimation of uncertainty in DEM elaboration and, subsequently, in DoD analysis has gained an increased attention in geomorphological studies in the last years. This grown-up importance is justified by the need of distinguishing real geomorphic changes from noise in surface representations, given that in fluvial research these two outcomes commonly feature similar magnitudes. For this reason, an effective and comprehensive technique to quantify the uncertainty related to change estimates from digital models is increasingly required (Brasington et al., 2003; Lane et al., 2003; Wheaton et al., 2010).

Errors in DEM production can derive from multiple factors including survey point quality, sampling strategy, surface composition, topographic complexity and interpolation methods (Wechsler, 2003; Hancock, 2006; Wechsler and Kroll, 2006). The accuracy of data during the acquisition phase is of great importance and can be influenced by both systematic (e.g. accuracy of the survey equipment) and random (e.g. triangulation when surveying with a dGPS) errors. Also survey point density and spatial distribution according to different morphological units play a fundamental role as demonstrated by Heritage et al. (2009) that underlines how the error is uneven distributed in this phase, featuring lower values across uniform surfaces and higher values on the occasion of breaks of slope such as banks and bar edges. Furthermore, in DEM production very important is the choice of the interpolation algorithm that should take into account surface composition and topographic complexity (Lloyd and Atkinson, 2001; Siska and Hung, 2001; Chaplot et al., 2006). Modelling irregularly-distributed surface data (in order to highlight morphological features) has emphasized TIN (Milan et al., 2007; Rumsby et al., 2008) and Kriging (Fuller et al., 2003) interpolators as the best to represent landscape terrain data returning lower elevation errors in comparison to other interpolation schemes (Holmes et al., 2000).

After considering the sources of error prior to DEM differencing analysis, it is noteworthy to focus the attention on the existing approaches to quantify the influence of surface representation uncertainty on sediment budget derived from DoDs. The actual estimation of uncertainty follows three stages: the assessment of the surface representation error in the individual DEMs being compared, the propagation of such uncertainty into the DoD and, finally, the quantification of the significance of the propagated uncertainty. The DEM intrinsic error is denoted by δz and it is related to the actual elevation (Zactual) according to this equation:

$$\mathrm{Zactual} = \mathrm{ZDEM} \pm \delta \mathrm{z} \tag{4}$$

Where Zactual is the true value of elevation and ZDEM the spatially-paired DEM elevation. In this sense, δz accounts for many components, including all uncertainty sources previously presented, from measurement error to sampling bias, interpolation methods, etc. Evidences have demonstrated that δz tends to exhibit patterns in its spatial variability that are coherent and predictable (Wheaton et al., 2004).

The propagation of the individual errors from the DEMs into the DoD has been expressed by Brasington et al. (2003) as:

$$\delta u_{\mathrm{DoD}} = \sqrt{(\delta z_{\mathrm{new}})^2 + (\delta z_{\mathrm{old}})^2} \tag{5}$$

Where δuDoD is the propagated error in the DoD and δZnew and δZold are the individual errors in DEMnew and DEMold, respectively. This technique assumes the randomness and independence at cell-scale of the error that can be estimated as a single value of combined error for the entire DoD. Otherwise, slightly different approaches consider spatial variability independently for both DEMs and δuDoD can be calculated on a region-by-region (Lane et al., 2003; Westeway et al., 2003) or cell-by-cell basis (Wheaton, 2008).

The last step embodies the assessment of the significance of the DoD final uncertainty on predicted elevation changes. There are two primary methods of calculation based on thresholding the DoD by applying a minimum Level of Detection (minLoD), below which elevation variations are discarded or weighted. In the first approach, the outcome of the propagated uncertainty (e.g. δuDoD) is used to express the thresholded elevation change (or minLoD). Areal and volumetric estimates of morphological variations proved to be very sensitive to the minLoD; thus, the more uncertain the DEMs (higher the minLoD), the more information is lost from the budget. The second approach, presented by Brasington et al. (2003) and Lane et al. (2003) and relying on Taylor (1997), demonstrates that thresholding can be based on probability using an arbitrary-defined confidence interval. If δz estimate is seen as a reasonable approximation of the error standard deviation (SDE), we can modify equation (5) as follows:

$$U_{\mathrm{CRIT}} = t\left(\sqrt{\mathrm{SDE}_{\mathrm{new}}^2 + \mathrm{SDE}_{\mathrm{old}}^2}\right) \tag{6}$$

Where Ucrit is the critical threshold error, based on a critical student’s t-value at a chosen confidence interval, where

$$t = \frac{|\mathrm{Zdem}_{\mathrm{new}} - \mathrm{Zdem}_{\mathrm{old}}|}{\delta u_{\mathrm{Dod}}} \tag{7}$$

In Equation (7), $|\mathrm{Zdem}_{\mathrm{new}\_}\mathrm{Zdem}_{\mathrm{old}}|$ represents the absolute value of the DoD. The probability of a DoD predicted variation in elevation occurring purely due to chance measurement error can then be calculated by relating the t-statistic to its cumulative distribution function (CDF). In this sense, we can obtain an error-reduced DoD by discarding all changes with probability values less than the chosen threshold.

As we can observe, the detection of uncertainty significance in δuDoD shows a certain inability in estimating reliable elevation changes below the minLoD threshold and the development of a spatially variable δz assessment still represents a major challenge.

2.4.4. Estimating geomorphic changes through a spatially-variable detection threshold

Wheaton et al. (2010) has proposed two methodological innovations regarding spatially variable assessment of uncertainty and spatial coherence of change with the aim of better quantifying geomorphic changes. The basic concept relies on the evidence that in areas of the DoD where δz is lower than the currently presumed, a less restrictive minLoD may be applied locally and more information recovered (e.g. shallow deposition on bar top) and, in the same way, in zones where δz results higher than currently presumed (e.g. steep banks), a more restrictive minLoD may be applied to adjust the accuracy of volumetric changes accounting for this higher uncertainty. The first innovation is based on the probabilistic modelling of uncertainty using Fuzzy Logic Statistics (Matlab software), which represents a trade-off between significance and precision (Jang and Gulley, 2007) (Fig. 17). Fuzzy Inference Systems (FIS) can help geomorphologists to understand the significance of the total uncertainty on the geomorphic interpretation by creating convenient frameworks that take known information as inputs and produce an appropriate output.

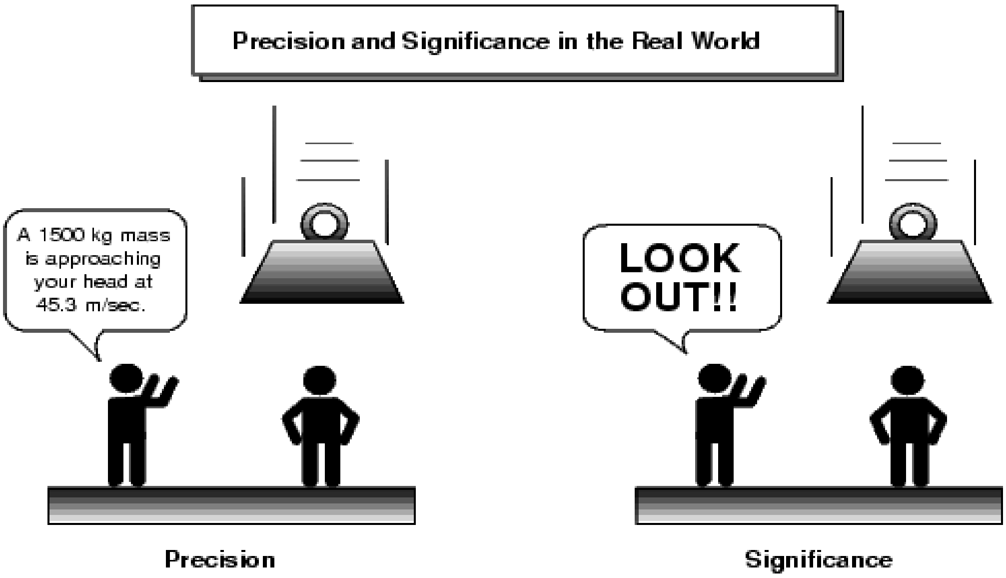


Figure 17: Example of trade-off between precision and significance in the real world.

The input information of this study were represented by point density and slope surfaces which were joined to the basic DEM. Their influence on the output surface was mediated by the definition of relation-rules in the FIS and a spatially variable estimation of δz was acquired by applying the FIS process on a cell-by-cell basis to the entire raster DEM.

The second innovation of this article was the identification of spatially-coherent units of erosion and deposition. Contiguous areas of net erosion and net deposition are generally elongated in a streamwise orientation, offering the opportunity of identifying or classifying these coherent changes. In this sense, DoD predicted variations in elevation within those units can feature a higher probability of being true, whereas changes in areas without structured patterns of cut and fill can be assigned to a lower probability. Coherent units were identified using a simple algorithm consisting in a 5 x 5 moving window across the DoD surface. Spatial contiguity was defined by counting if one cell was erosional or depositional and looking also to the surrounding cells in order to attribute a higher spatial erosional or deposition contiguity index to that cell. If the DoD predicts for a cell to be erosional, the spatial contiguity index for erosion will be used. The index is then related to a probability that each cell belongs either to a class of erosion or deposition, by a linear transform function. An example to better understand the concept is given: if a cell is assessed to be erosional but its magnitude falls beneath the calculated minLoD for that cell, it would normally be discarded. Otherwise, if that low-magnitude erosion cell is surrounded by all or primarily erosional cells, that cell has a high probability to be actually erosional and the previously “undetectable” change to be real. In the reverse case, if a cell is depositional and all the cells around it are erosional, the probability for that cell to be depositional is much less. The final probability of coherent erosional and depositional areas has been then conjoined using the Bayes Theorem and a confidential interval of 95%. The resulting DoDs that use this uncertainty analysis generally account for more conservative volumetric changes in respect to those utilizing the standard spatially-uniform (minimum Level of Detection) technique. This method is able to guarantee more plausible and physically-meaningful results, being very accessible as it can be downloaded in a wizard-driven Matlab software application and extended to any topographic survey.

Another approach aiming at developing a spatially-distributed LoD (Level of Detection) that can be applied to DoDs to produce more reliable change estimates is proposed by Milan et al. (2011). Starting from DEMs derived from a "total station" survey campaign, the method establishes local surface topographic variability by defining the local elevation standard deviation (σz) in a 1-m radius moving window over the entire raw point cloud. A zero value was assigned to areas with less than eight points present into the window. The standard deviation of DEMs has shown the highest values located at breaks of slope such as bar and bank edges. Then, a local topographic roughness was extracted from the σz grid for each x, y survey coordinates and elevation errors measured from the difference between modelled and surveyed elevations. The comparison between elevation error plots and local surface variability has indicated that smaller elevation errors (± 0.1 m) are featured in flatter areas where the local topographic variation is < 0.2 m. By contrast, much larger elevation errors were found in areas with greater local topographic variability (> 0.2 m), such as bar edges. Furthermore, standard deviation was calculated for different classes of roughness and plotted together to obtain, through linear regression equations, spatial error grids for each survey. Applying the formula of RMSE (Root Mean Square Error) to the spatial error grid files used in DEM subtraction with a t value of 95% of confidence interval, a spatially-distributed LoD grid was created for each DoD. Finally, the LoD grid file was subtracted from the raw DoD grids, obtaining DoDs with spatial error estimation.

The results of volumetric changes detected by the spatially-distributed LoD method in comparison with raw DEMs and uniform LoD (based on the averaged RMSE) approaches have demonstrated some dramatic differences. The uniform methods have shown to capture less and biased change (areas with more local topographic variability) in respect to the spatially-distributed detection that seems to be more effective to recover information of otherwise "undetected" areas.

3. RESEARCH OBJECTIVES

3.1. Overarching

The first overall objective of the study is to investigate the geomorphological response of differently impacted gravel-bed rivers (Piave and Tagliamento, NE Italy) to flood events slightly below formative conditions. The main hypotheses of this section are: i) floods below bankfull stage are able to produce significant geomorphic changes, in terms of extent and amount of sediment remobilised, further affecting all channel processes, including channel network reconfiguration and bank erosion, ii) erosion processes will dominate the sediment balance of the study reaches as human pressure in the last decades has produced a sediment deficit that has not been recovered yet by the fluvial systems.

Further, the research will focus on bank retreat processes, aiming to describe how bank erosion develops through forested riverbanks. Improvements to previous conceptual models (Pizzuto et al., 2010) will be attempted by exploring characteristics and relationships of riparian trees and bank profiles on the King River (Victoria, Australia). The role of riparian trees on bank retreat processes will be further analyzed on the Piave River (Italy), offering interesting insights for comparison. In detail, the main hypotheses of this section are: i) the pattern of interaction between bank trees and stream scour is much more complex than described by recent research (Pizzuto et al., 2010). Riverbanks do not migrate past riparian trees only through undercutting erosion and mass failure processes, ii) Scallop depth on the bank profile depends on tree size and spacing as root plates promote cohesion along riverbanks. Thus, if tree diameter is kept constant, we expect deeper scallops the further apart the trees are spaced. Similarly, for the same tree spacing, we expect smaller scallops the larger the tree diameter.

3.2. Specific

3.2.1. Piave and Tagliamento rivers (Italy)

The geomorphic impacts of subsequent floods slightly below bankfull discharge (2010) will be accurately analysed through the use of digital surface representations based on the integration of multiple topographic data: LiDAR, dGPS and colour bathymetry. The role of such floods in efficiently change the morphological configuration of these fluvial systems will be explored through an accurate quantification of volumetric and planimetric processes. Further, the interpretation of crucial channel processes as channel network reconfiguration and bank erosion of forested riverbanks will enhance our understanding on the importance of low-magnitude floods to producing multi-scale channel reconfiguration.

The detailed objectives can be listed as follows:

- Obtain accurate estimates of geomorphic changes caused by 2010 floods through the development of enhanced DoD models accounting for a precise detection of flowing channel areas;

- Interpret geomorphic variations as well as sediment balance induced by floods below bankfull stage;

- Evaluate and interpret planimetric adjustments of main flowing channels;

- Analyse major bank erosion processes, possibly influenced by human interventions (Piave River);

- Explore possible relationships explaining scallop depth in relation to tree characteristics (i.e. size, longitudinal spacing, distance from bank edge) to understand how bank retreat develops through forested non-cohesive riverbanks (Piave River).

3.2.2. King River (Australia)

The King River (Victoria, Australia) represents an ideal environment to analyse the spatial evolution of bank retreat past large trees as it is characterized by extensive root-plate abutments and scalloped bank profiles. This section of the study will aim at identifying the main scour mechanisms affecting bank trees and leading to their failure into river channels. Further, the role of riparian trees in reducing bank retreat will be explored through the analysis of erosional gaps along the bank profile. The identification of possible relationships between tree and scallop characteristics will help us to explain the complex interaction driving bank retreat of forested cohesive riverbanks. New findings will demand for the integration of significant uncovered variables and relationships in future bank migration modelling. Finally, the research will lead to delineate coherent stages of bank retreat progression past forested cohesive riverbanks.

The specific objectives of this section will be addressed as follows:

- Identify main scour mechanisms around trees and bank profiles leading to tree toppling;

- Explore possible relationships linking scallop depth progression to tree characteristics (i.e. size and spacing);

- Create a novel and more comprehensive conceptual model describing the evolution of bank retreat in outer meandering bends characterized by forested and cohesive riverbanks.

4. STUDY SITES

4.1. Piave River (Italy)

4.1.1. Climatic and geomorphological characteristics

The main stem of the Piave River flows for a total length of 220 km in the north-eastern Italy, featuring a total drainage basin of approximately 3,900 km^2 (Fig. 18). Its headwaters are located at 2,030 m a.s.l. near to Mount Peralba and its course flows towards south-east, ending in the Adriatic Sea, near to Venice. The main tributaries are three, two of them, Boite and Mae rivers, located on the northern side of the basin, whereas the Cordevole River collects water from the western region. The climate of the basin is humid temperate-continental, rather common in the eastern Italian Alps, and precipitation features a very high spatial variability due to the complex topography of the region. Mean annual precipitation accounts for 1,350 mm, with the highest values concentrated in the central-eastern areas (Vajont zone). The rainiest periods of the year are autumn followed by spring, with November and June generally registering the highest rainfall rates (Comiti et al., 2011).

The basin results mainly composed of sedimentary rocks, specifically limestone and dolomite, but in some areas volcanic and metamorphic rocks can be found. Three main sections of the river course can be recognized: an upper segment, featuring a narrow single-thread channel due to the presence of bedrock, a middle course which includes the study reach and presents a very wide gravel riverbed and a multithread channel pattern and, finally, the lower portion characterized by a sand-bed with a meandering channel (artificially straightened in some points) (Picco et al., 2014).

4.1.2. Human impacts

Intense and multiple human impacts have been registered in this basin that suffered a severe alteration in its morphological evolution and sediment budget. Starting from the Roman colonization (2nd century B.C.), the Piave river area has featured a progressive increasing population, except for the Middle Ages when a depopulation trend took place with a consequent forest expansion (Lazzarini, 2002). After the minimum vegetation cover registered between the 18th and 19th centuries, a natural and artificial reforestation has developed, in particular after the 1950s, due to abandonment of traditional farming and cropping activities near mountain slopes (Del Favero and Lasen, 1993). Strong and impacting human interventions related to regulation of stream flow for irrigation and hydroelectric power generation were carried out from 1930s with the construction of several dams which have trapped sediment for more than 50% of the drainage area. Starting from the 1960s, the diverted water volume has increased leading to the ongoing regime which alters both flow duration characteristics and volume of annual runoff in the river. Another important and strong human action regarded gravel mining activities which were carried out in the main channel and its tributaries for about 30 years, from 1960 to 1990. Recent studies based on topography and considering a long reach of the Piave River, indicate a possible total extracted volume of about 6 million cubic meters (Comiti et al., 2011). Finally, channel morphology and sediment yield have been affected, starting from 1970, by effective erosion and torrent control works, especially in the upper portion.

4.1.3. Study reach

The study reach of the Piave River is located between Ponte delle Alpi and Busche (Belluno Province) and features a length of approximately 30 km. The drainage area at Busche is 3,174 km^2 and the dominant morphological patterns of the channel are braided and wandering, even though narrower reaches present an alternate bars structure. The average slope is approximately 0.45% and the median surface grain size is comprised between 20 mm and 50 mm (Surian, 2002). The width of the fluvial corridor ranges between 100 m and 2,000 m depending on the presence of geological constrains, such as terraces or hillslopes.

Within the study reach, two sub-reaches have been identified, basing the selection on the homogeneity of river corridor width, presence of artificial elements (i.e. groynes, bank protections) and historical and morphological patterns (Fig. 18). The sub-reaches are located upstream of the largest tributary of the Piave, the Cordevole River, the first, Belluno, features a length of 2.2. km whereas the second, Praloran, of 3.2 km.

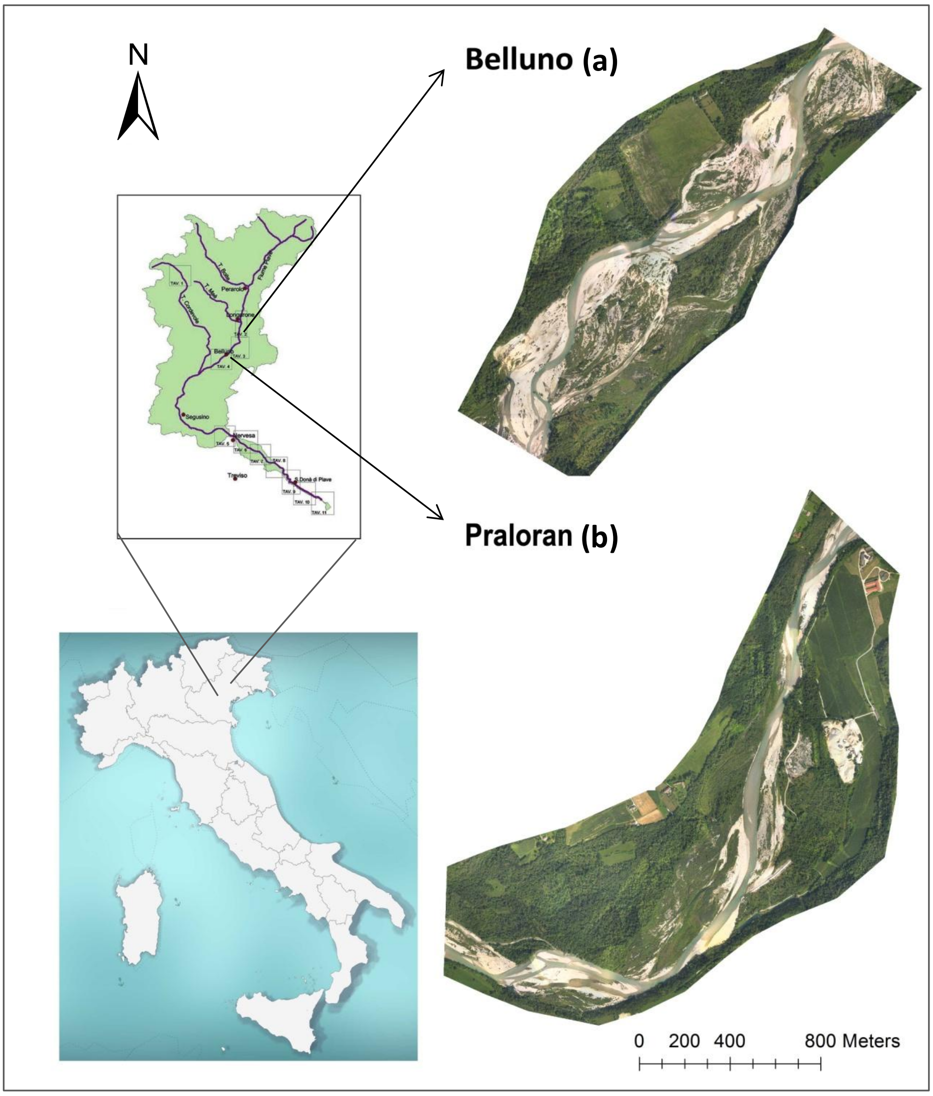


Figure 18: Location of the study reaches of the Piave River: Belluno (a) and Praloran (b).

The analysed flood events have occurred at the end of 2010 as a consequence of heavy and continued rains, especially over the pre-alpine areas (Fig. 19). From the gauging station of Belluno, we could identify two main and different peak discharges of 498.44 m^3s^{-1} and 407.03 m^3s^{-1}, respectively (Fig. 20). The flooding crests were moderate as they felt below the bankfull discharge, estimated around 700 m^3s^{-1} (R.I.~ 2 years) by Comiti et al. (2011).

Figure 19: Piave River during 2010 floods by Belluno reach.

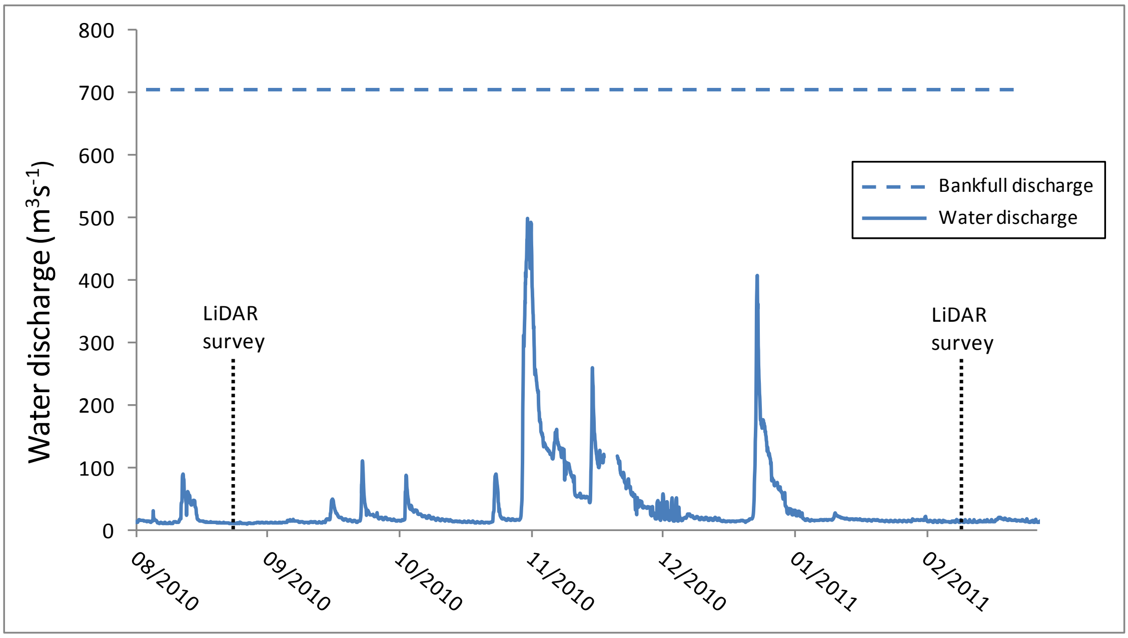


Figure 20: Hourly water discharge registered at the Belluno gauging station during the study period. Dates of topographic surveys and the level of bankfull discharge are also reported.

4.2. Tagliamento River (Italy)

4.2.1. Climatic and geomorphological characteristics

The Tagliamento River is one of the last European rivers that keeps maintaining a high degree of naturalness. Its strong longitudinal, lateral and vertical connectivity, high habitat heterogeneity, high biodiversity and characteristic sequence of geomorphic patterns, indicate the significance of this stream as a crucial bio-geographical corridor connecting the Alps with the Adriatic Sea. The presence of extensive vegetated islands and gravel bars are key indicators of its natural condition, while engineering works for flood control or navigation have eliminated such features in most European water courses (Tockner et al., 2008).

The Tagliamento River is a gravel-bed river located in north-eastern Italy, mostly within Friuli Venezia Giulia region (Fig. 21). It originates at 1,195 m a.s.l. and flows for 178 km to the northern Adriatic Sea, thereby forming a link corridor between the Alpine and the Mediterranean zones. Its drainage basin covers 2,871 km^2. The river has a straight course in the upper portion, while most of its course is braided shifting to meandering in the lower portion, where dykes have constrained the lower 30 km that are now little more than an artificial channel, about 175 m wide. However, the upper and central portions are more or less intact, thus the basic river processes, such as flooding and the erosion and accumulation of sediment, take place under near natural conditions. In fact, in this section, the main stem of the river flows through a very large morphological active zone that accounts for about 150 km^2 with a floodplain width up to 1.5 km. A strong climatic gradient exists along the length of the river which has a significant influence on precipitation, temperature, humidity and, consequently, vegetation patterns. The active floodplain that is included in a continuous riparian woodland, is dominated by braided patterns and highly variable vegetated island cover (Bertoldi et al., 2010).

The climatic regime of the Tagliamento River falls in a transition belt between Alpine and Mediterranean areas. Its hydraulic regime is characterized by irregular discharges and high sedimentation load, due to climatic and geological conditions affecting especially the uppermost portion, where some areas are among the wettest over Italy with annual precipitation reaching over 3,000 mm (Ziliani and Surian, 2012). Intense thunderstorms and snow melt in the mountainous portion of the catchment often generate high flood flows that can feature also a flashy behaviour. Flooding dynamics also below bankfull discharge (i.e. flood pulses) are very important to maintain high levels of habitat heterogeneity and ecosystem processes (Bertoldi et al., 2010). Geology of the basin is dominated by limestone, occasionally intermixed with layers of gypsum which causes high sulphate concentrations in the river (Arscott et al., 2000).

4.2.2. Human impact

Despite being recognized by its naturalness, the Tagliamento River features slightly-altered conditions, due to human pressure. Major human impacts include: water abstraction, organic pollution and gravel mining activities. In particular, water collection for electric power production has altered consistently low flows since 1940s. The few protection or regulation interventions are located at a significant distance from the active corridor, which is morphologically intact for most of its length. Although such slight impacts have been influencing the Tagliamento River for the last decades, this stream is still considered a natural laboratory for exploring geomorphological and ecological processes and interactions of large fluvial systems (Ziliani and Surian, 2012; Surian et al., 2014).

4.2.3. Study reach

Two are the study reaches in Tagliamento River, called from upstream to downstream: Cornino and Flagogna (Fig. 21). Cornino, that shows a predominant braided morphology with channels separated by vegetated islands and gravel bars, features a length of about 3 km, a width between 700 m and 1 km and a slope around 0.35%. Flagogna registers instead a predominance of wandering patterns characterized by central bars and dead channels. The length of this downstream reach accounts for 3.5 km, the active channel width is between 300 m and 800 m and the slope is about 0.30%.

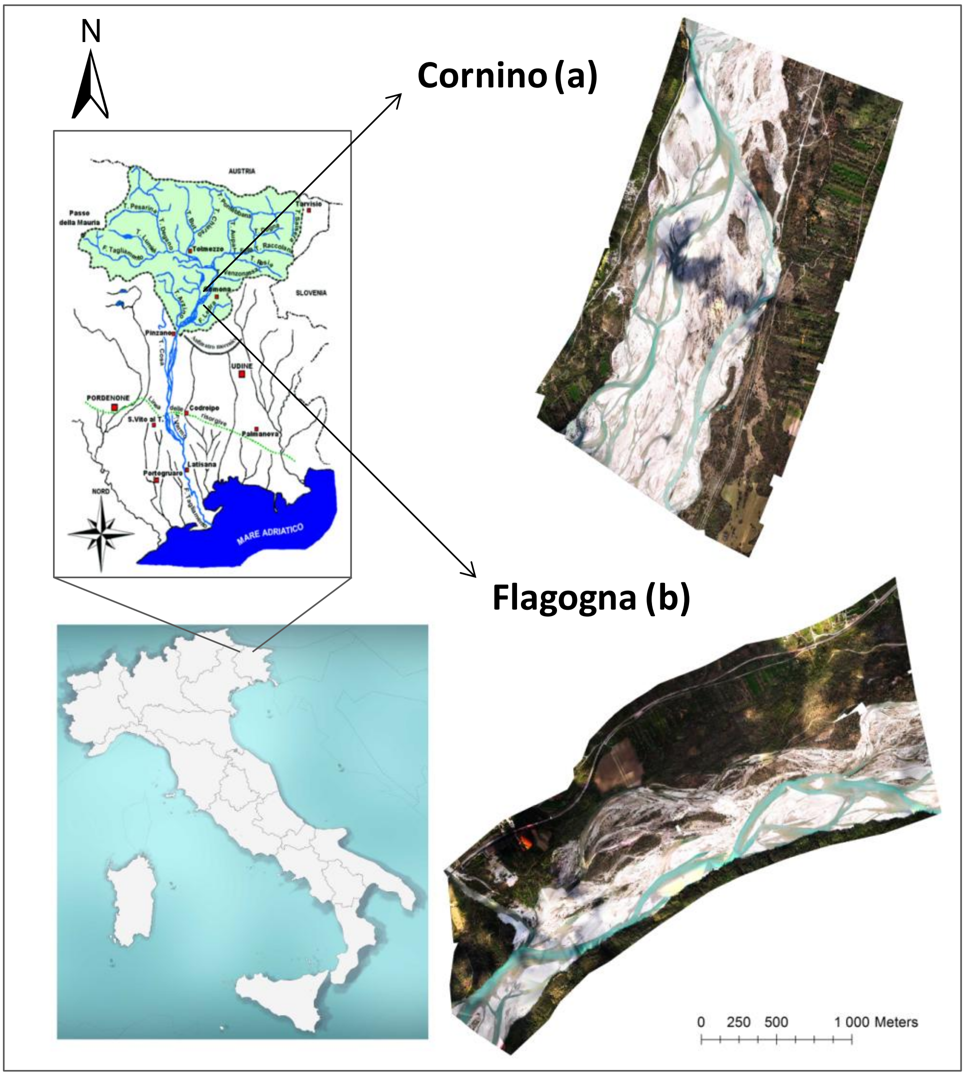


Figure 21: Location of the study reaches of the Tagliamento River: Cornino (a) and Flagogna (b).

The analysed flood events have occurred, similarly to the Piave River, at the end of 2010 as a consequence of heavy and continued rains, especially over the pre-alpine areas. From the hydrometric station of Venzone, we could identify two main and different peak water stages of 2.90 m and 2.57 m, respectively (Fig. 22). The flooding crests were considered to be moderate as they almost reached the bankfull water level, estimated around 3 m (corresponding to a discharge of ~ 1700 m^3s^{-1} and a R.I. of ~ 3 years) by Bertoldi et al. (2010).

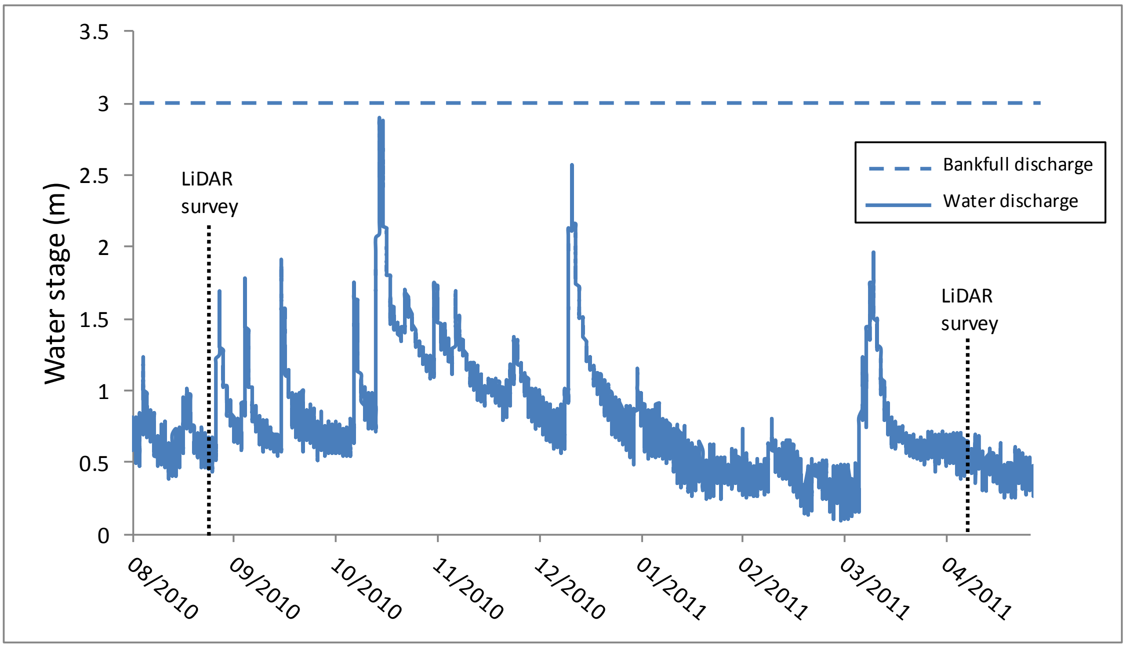


Figure 22: Water level data taken with a half-an-hour time-series at the Venzone hydrometric station. Dates of topographic surveys and the bankfull stage are also reported.

4.3. King River (Australia)

4.3.1. Geomorphological characteristics and human pressure

The King River is a 126 km-long stream located in north-eastern Victoria, Australia, and it is a tributary of the Ovens River. The headwaters rise on the northern slopes of the Great Dividing Range, at an elevation of 1,460 m, below Mount Buggery. We consider the floodplain segment of the river here (draining an area of about 1,400 km^2). The King River is characterized by anastomosing dynamics, especially in the second half of its course when valley and channel slopes markedly decrease (Schumm et al., 1996).

The study area is a low-gradient anastomosing stream, generally 15-20 m wide and 2-3 m deep. In this portion of the river, channel capacity is relatively low and the floodplain is frequently inundated, featuring avulsion and lateral migration processes. Bank profiles characterized by buttressing are frequent due to strong flow resistance exerted by trees, as reported in Fig. 23 (Schumm et al., 1996).

Human impacts on the King River include gold mining activities in the past and current water abstraction for agricultural use. The former has affected the river especially during the first half of the twentieth century, when the river bed suffered dredging activities. Gold mining is believed to have contributed also to filling processes of sand and gravel featured by many pools in the last 50 years (Schumm et al., 1996).

Figure 23: Scalloped bank profiles characterized by root-plate abutments along the King River.

4.3.2. Study reach

The study reaches are ten (Fig. 24) and were identified taking into account the representativeness of different avulsion stages and morphological sections (straight sections, inner and outer bends). Reach length was determined by multiplying ten times the average bankfull width of each analysed portion of the river and varies from 120 m to 260 m. The bank profiles are characterized by different tree densities and sizes and feature extensive root-plate abutments and scalloping. Most of the riparian trees are river red gums (*Eucalyptus camaldulensis*) with occasional exotic willows (*Salix fragilis*).

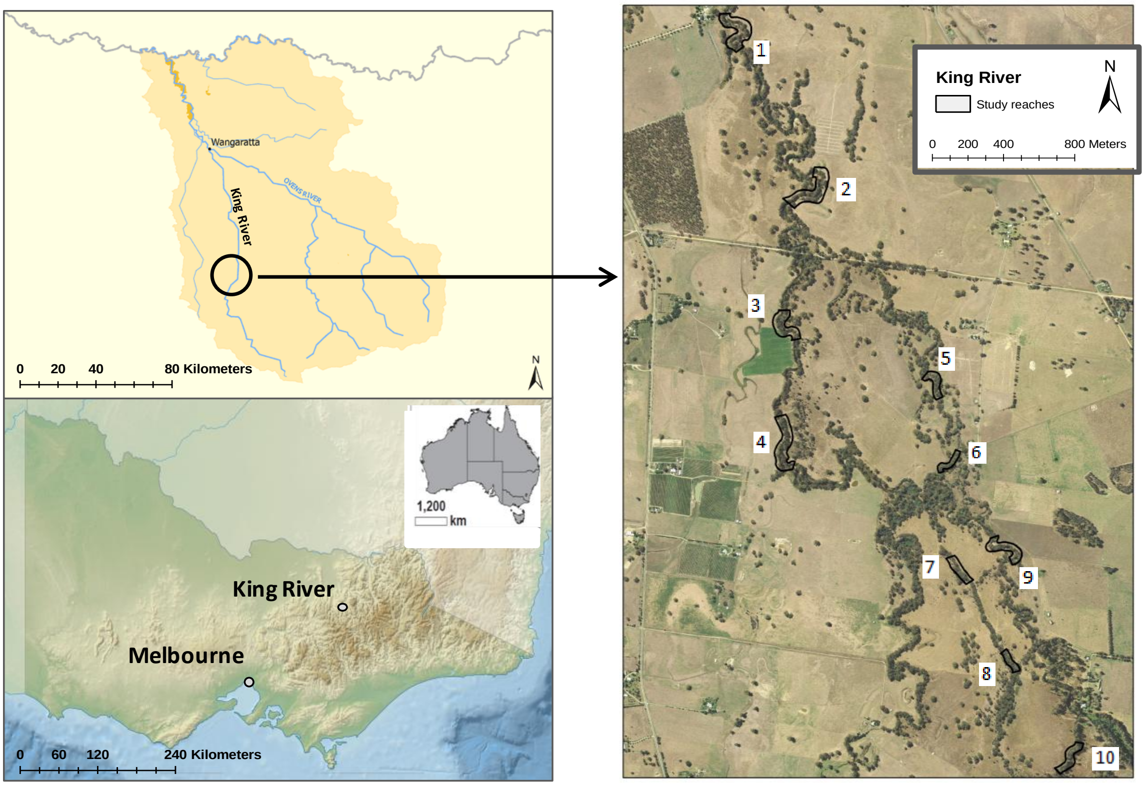


Figure 24: Location of the study reaches of the King River (note that flow is from bottom to top of the map).

5. RESEARCH MATERIALS

5.1. Technologies and devices

5.1.1. Aerial images

Aerial photography consists of taking images of the ground surface from an elevated position with a camera usually not supported by ground-base structures. In fluvial geomorphological research, the use of aerial imagery is of great importance to analyse and estimate a large variety of aspects of river channels, including physical characteristics, geomorphic changes, etc. In this field, platforms of aerial photography are usually mounted on aircrafts or helicopters flying at low altitudes (~ 800 m) or, in the very recent times, on drones.

5.1.2. Global Positioning System (GPS)

The GPS is a positioning system based on satellites which guarantees a continuous and global cover and it is managed by the U.S. Defence Department (Fig. 25). This technology consists of a constellation of 24 satellites that provides real-time or pre-recorded, anywhere and anytime, positioning, timing and navigation services of any user. The GPS position is given on an ellipsoid having a three-dimensional geodetic datum which is called World Geodetic System (WGS84) and it is defined through mathematical relations. GPS measurements are characterized by many different sources of errors which may be quantified by observing the effects on the satellite-receiver distance and need to be eliminated or minimized in order to reach the maximum potential of this technology. There are two main types of GPS, non-differential GPS provided with a base station, and differential GPS that enables to minimize several errors due mainly to signal delay.

Figure 25: GPS device.

5.1.3. Light Detection and Ranging (LiDAR)

LiDAR is a remote sensing technique which enables to determine the distance of an object or a surface by measuring the return time of a laser pulse, as simplified in Fig. 26 (the “range” can be calculated using light velocity). A modern LiDAR is composed of: a rapid pulsing laser scanner (with continuous wave lasers which obtain, through phase measurements, range values), precise kinematic GPS positioning, orientation parameters from Inertial Measurement Units (IMU), a timing device (clock) capable of recording travel times to within 0.2 of a nanosecond, a suite of robust portable computers, and substantial data storage (100 GB per mission). A vertical accuracy of 0.15 m Root Mean Square Error (RMSE) and a horizontal accuracy about two times the footprint has been verified. Data collection can be performed in all “clear” conditions (day or night), since this technology features an active illumination system.

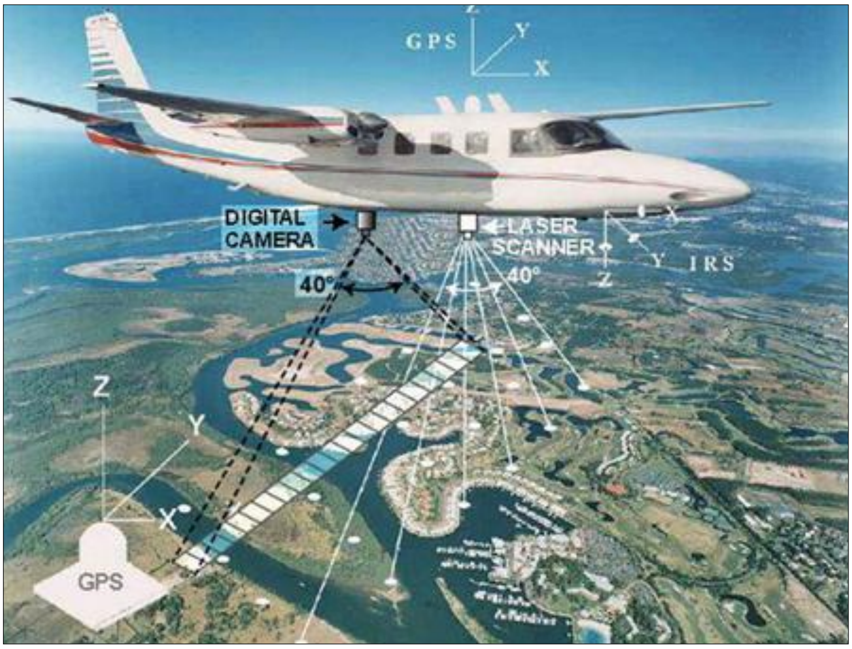


Figure 26: Airborne LiDAR survey technology.

The acquisition of data should start from a well-defined flight plan in order to meet the project aims. The density of points is in function of the precision level required for your final DEM and, in the accuracy of survey, a crucial role is played by flight height which can modify scan angle and, thus, density. On the analysed ground surface, a base station with a multi-channel GPS for correction of LiDAR points coordinates needs to be displaced in a known location and initialized according to the GPS receiver onboard the aircraft. The acquisition of data can be performed very quickly as the system emits 15,000 pulses per second and can record 5 returns per pulse, accounting for a capture potential of 75,000 values per second. Most part of LiDAR technologies utilize near-infrared laser that entails the complete absorption of pulses falling on standing water; nevertheless "green laser" capable to receive return pulses also from water bodies are now developing even if they feature high costs and uncertainty levels. Finally, collected points need to be georeferenced in order to be observed in ArcGIS environment and validated with in-situ surveyed data.

The first phase of LiDAR data processing consists of the automatic filtering of points from the rough cloud. Their separation in different classes allows to isolate the ground layer which needs further manual filtering to control errors due to the automatic procedure. Given that the average dimension of a LiDAR dataset encompasses 80-100 MB per Km^2 (with 2-3 ground point per m^2), adequate data processing softwares and hardwares are necessary.

5.2. Platforms and softwares

5.2.1. ArcGIS

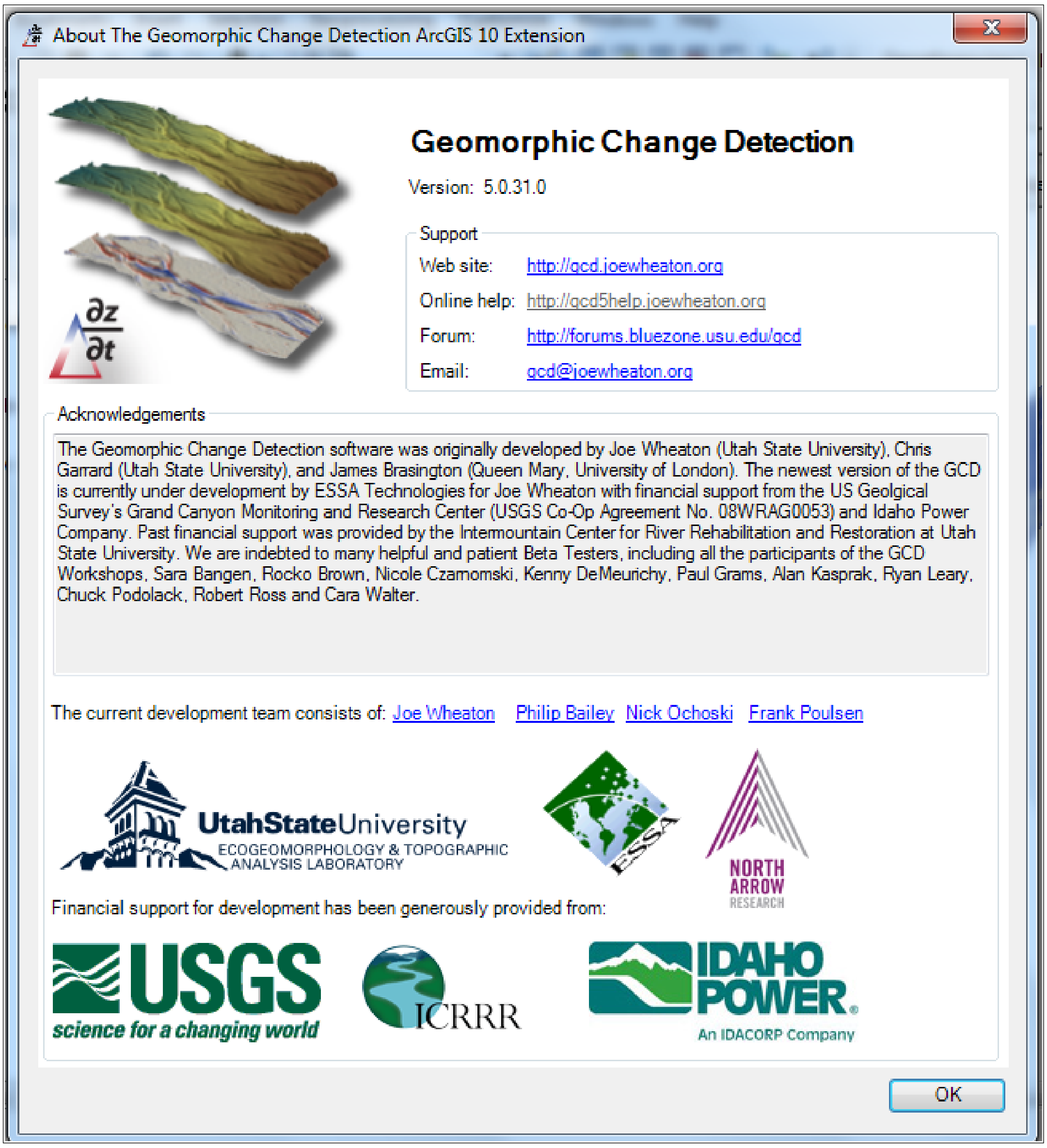
ArcGIS is a comprehensive platform that allows people to collect, organize, manage, analyse, communicate, and distribute geographic information. As the world's leading platform for building and using geographic information systems (GIS), ArcGIS is used by people all over the world to put geographic knowledge to work in government, business, science, education, and media.

5.2.1.1. Geomorphic Change Detection (GCD)

The GCD software was developed for morphological sediment budgeting purposes in rivers (Fig. 27). The volumetric change in storage is calculated from the difference in surface elevations from digital elevation models (DEMs) derived from repeated topographic surveys. As each DEM is an uncertain surface representation (which may vary spatially and temporally), the ability to detect changes between surveys is highly dependent on surface representation uncertainties inherent to the individual DEMs. The fundamental problem is separating out changes due to geomorphic variations from noise in survey data. GCD provides a suite of tools for quantifying those uncertainties independently in each DEM and propagating them through the DEM of difference. The program also provides ways for segregating the best spatial estimates of change using different types of masks. The overall suite of tools is more generically applicable to many different detection problems of spatial change (Wheaton et al., 2010).

The quantification of spatially-variable uncertainty and the identification of spatially-coherent erosion and deposition units is achieved by using Fuzzy Logic (Matlab). Once the associated surfaces representing important variables for the reliable calculation of changes (slope, point density, etc) are created, a Fuzzy Inference System (Jang and Gulley, 2007) can be modelled. The membership functions need to be denoted by adequate adjectives as "high", "medium" and "low" and the range of values described by adjectives. The creation of FIS rules relates linguistic inputs (using their different adjectives) to a single adjective for the output that needs to be formed by membership functions corresponding to realistic empirical values. In conclusion, spatially-coherent scour and fill units are detected through a 5x5 moving window and transformed into a probability to be real by Bayes Theorem. Running the GCD application, by inserting basic DEMs, associated relevant surfaces (slope DEMs, point density DEMs, etc), created FIS file and choosing the method of spatial change and uncertainty detection (uniform

$_{min}$LoD, spatially-variable $_{min}$LoD using or not Bayesian updating), can lead to the creation of a DoD map with reliable estimates of change and associated uncertainty (Wheaton et al., 2010).



About The Geomorphic Change Detection ArcGIS 10 Extension

Geomorphic Change Detection

Version: 5.0.31.0

Support

Web site: http://gcd.joewheaton.org

Online help: http://gcd5help.joewheaton.org

Forum: http://forums.bluezone.usu.edu/gcd

Email: gcd@joewheaton.org

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The current development team consists of: Joe Wheaton Philip Bailey Nick Ochoski Frank Poulsen

Financial support for development has been generously provided from:

Figure 27: The GCD software application.

5.2.2. MatLab

MATLAB (matrix laboratory) is a numerical computing environment and fourth-generation programming language. It allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and Fortran.

5.2.2.1. Fuzzy Logic Toolbox

The Fuzzy Logic Toolbox provides facility for the development of fuzzy logic systems using command line functionality and five graphical user interface (GUI) tools: Fuzzy Inference System (FIS) Editor, Membership Function Editor, Rule Editor, Rule Viewer and Surface Viewer (Fig. 28).

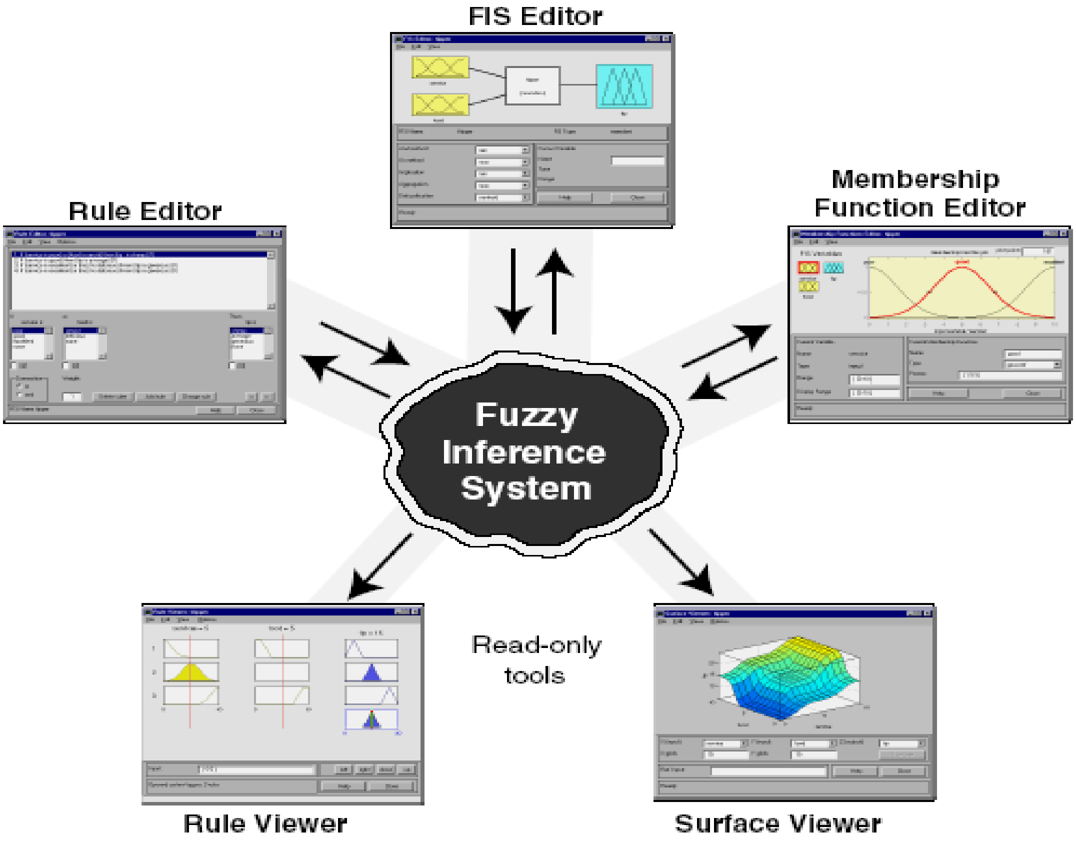


Figure 28: Graphical user (GUI) interface tools of Fuzzy Logic Toolbox.

Fuzzy Inference Systems (FIS) are among the most important applications of fuzzy logic. Fuzzy logic is a precise problem-solving methodology based on mathematical rules and able to simultaneously handle numerical data and linguistic knowledge to achieve the most accurate conclusion possible (Fig. 29). It defines how likely an imprecise phenomenon is a member of a set (or class) by assigning real values between 0 and 1 (fuzzification process), representing the degree to which an element belongs to a given set. Inputs are applied to a set of if/then control rules and the results of various rules are summed together to generate a set of “fuzzy outputs”. Fuzzy outputs are finally combined into discrete values (defuzzification process). Fuzzy logic is designed to solve problems in the same way that humans do: by considering all available information and making the best possible decision given the inputs.

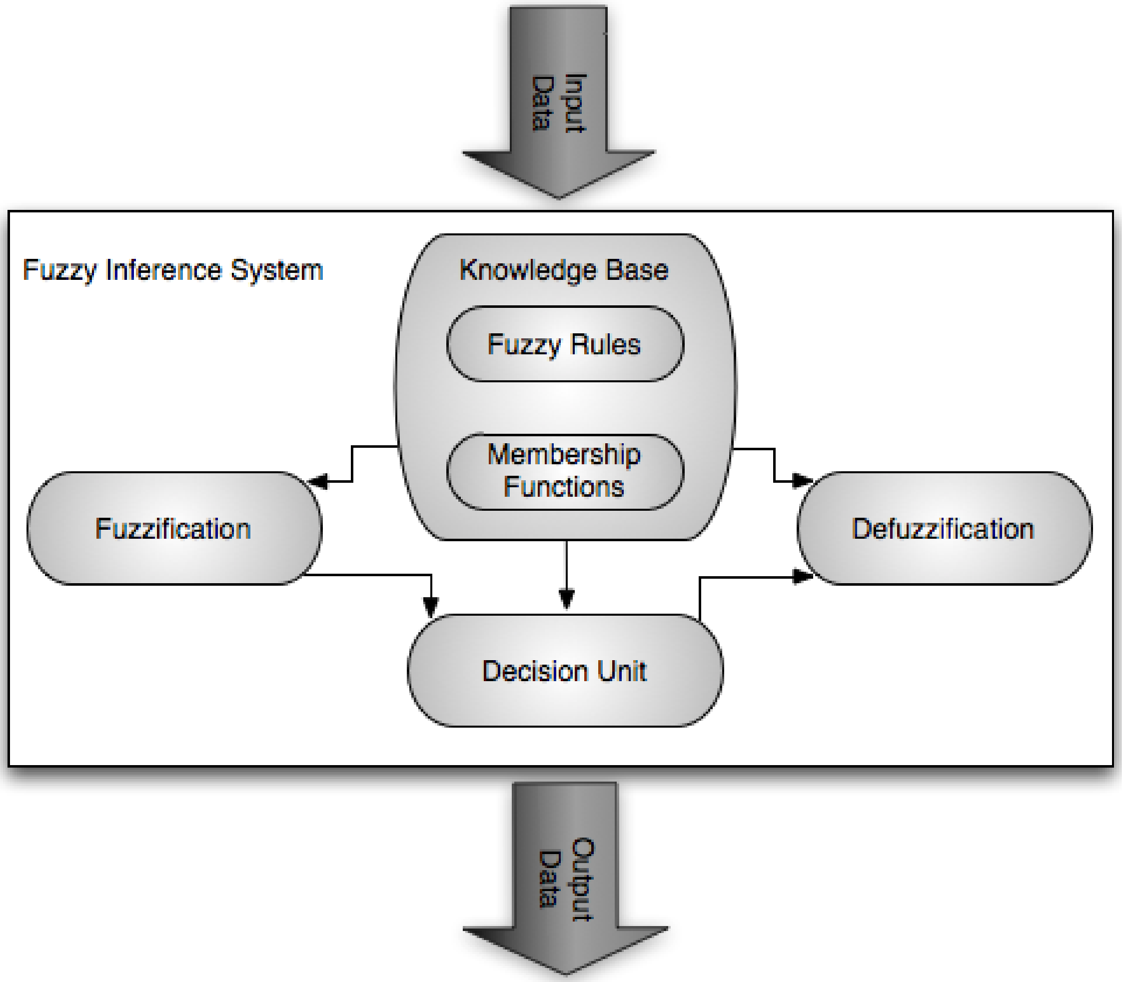


Figure 29: Fuzzy Inference System.

5.2.3. Statistica

Statistica is an analytical-statistical software providing a comprehensive array of data analysis, data management, data visualization, and data mining procedures. The platform offers a large selection of approaches including predictive modelling, clustering, classification and explanatory techniques.

5.3. Field instruments

Field instruments include several tools generally used in survey campaigns to acquire information about dimensions of elements and processes. In fluvial geomorphology, widely-used devices are: measuring stadia and tape, compass and tree caliper (Fig. 30).

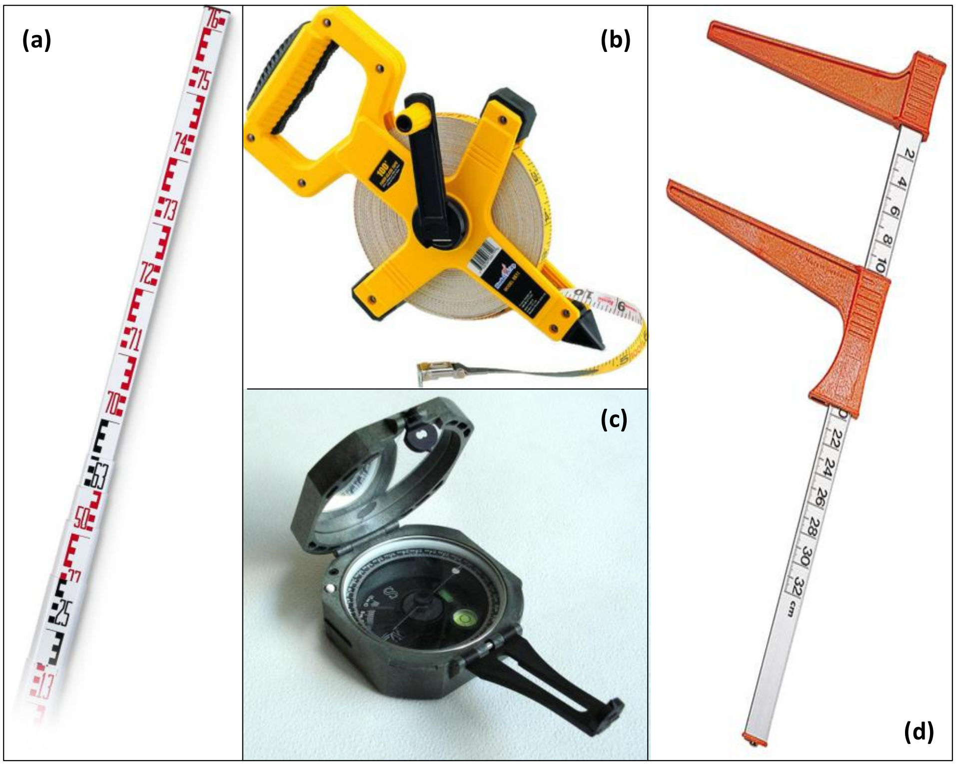


Figure 30: Field tools, stadia (a), measuring tape (b), compass (c) and tree caliper (d).

6. METHODOLOGICAL FRAMEWORK

6.1. SECTION I - Piave and Tagliamento rivers (Italy)

6.1.1. Research data and field investigations

The survey analyses consist of three different data sources acquired before and after the below-bankfull floods occurred at the end of 2010: LiDAR, dGPS and aerial photos. LiDAR and aerial photo captures were performed on August 23, 2010 and February 9, 2011 for the Piave River and August 26, 2010 and April 6, 2011 for the Tagliamento River, both by Blom GCR SpA using an OPTECH ALTM Gemini Sensor (flight height ~ 850 m). Data acquisition was carried out with the best weather and low water level conditions and LiDAR points were filtered from vegetation using Terrascan software (Terrasolid). Point density was commissioned in function of the required DEM resolution (0.5 m cell-size) accounting for at least two ground points per m^2 and the average vertical error was estimated through further dGPS comparison. LiDAR acquisition was associated with a series of RGB aerial images featuring 0.15 m of pixel resolution. Finally, dGPS points were taken contemporary, covering different morphological units and water stages. Totally, 337 dGPS points in 2010 and 2,301 in 2011 for the Piave River and 1,107 dGPS points in 2010 and 9,366 in 2011 for the Tagliamento River, were surveyed (dGPS average vertical error ± 0.025 m).

Through the method proposed by Moretto et al. (2012) that derives water depth by calibrating a regression model between Z-detrended dGPS coordinate and image colour bands (Red, Green and Blue), bathymetric points for the wet areas and LiDAR filtered points for the dry areas were integrated to build accurate hybrid DTMs for 2010 and 2011. First results obtained through the use of this methodology are reported in Moretto et al. (2012, 2013, 2014) and Delai et al. (2014).

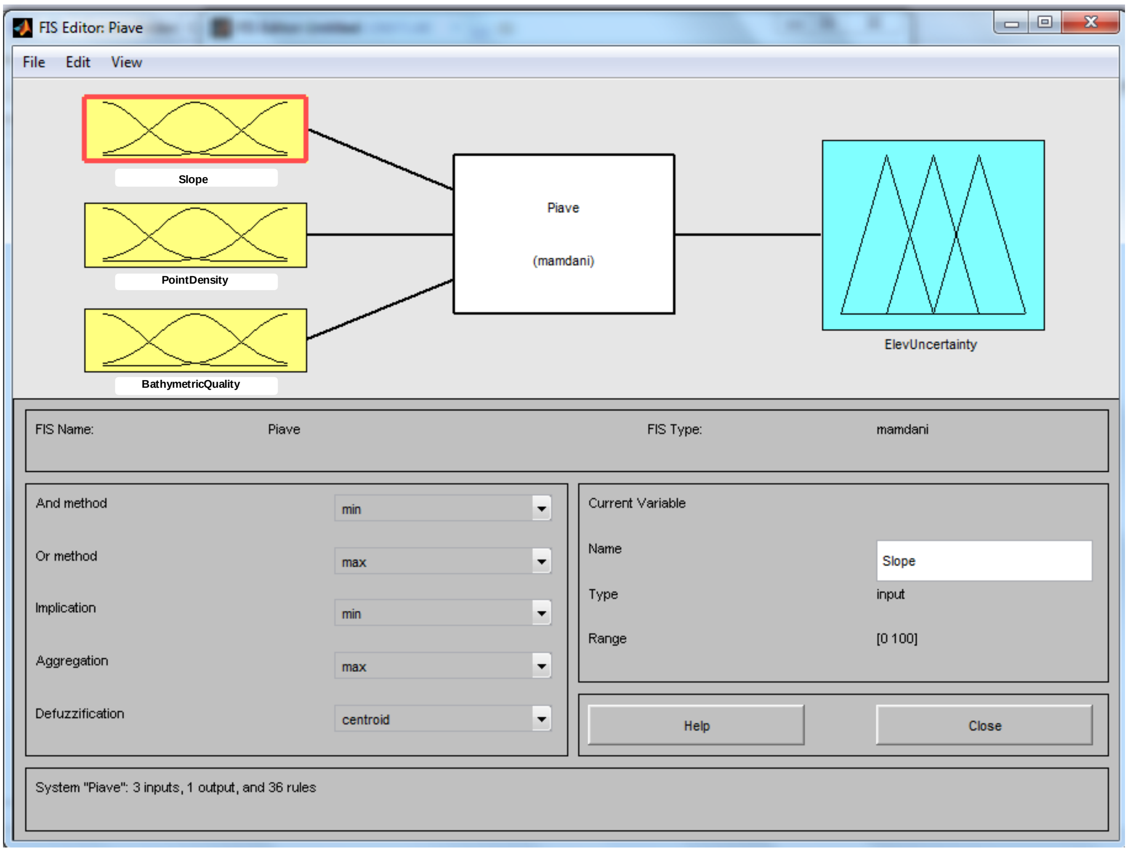
6.1.2. Creation of enhanced DEMs of Difference (DoDs)

6.1.2.1. Introduction

For an accurate and reliable detection of geomorphic changes, three attributes were believed to be significant indicators to use in the process of DoD creation. Slope, point density and bathymetric quality were selected and utilized as inputs to help reaching trustworthy estimates of change. "Ad hoc" Fuzzy Inference System (FIS) files, organizing and relating linguistically input properties were developed. Then, also associated input DEMs on which FIS scripts were designed to act were produced. At this stage, all the components were ready to be run in the GCD environment. Through this software application, related uncertainty rasters performing a spatially-variable threshold of change detection were generated. Finally, the recovery of potential true change through the Bayesian method for spatially-coherent units of erosion and deposition has contributed to achieve precise DoD surfaces.

6.1.2.2. Fuzzy Inference System (FIS)

In Matlab environment (Fuzzy Logic application), “ad hoc” FIS files featuring a Mandani approach and a three-input structure were created. As inputs, slope, point density and bathymetric quality were chosen for being the most appropriate to provide relevant information for change detection and elevation uncertainty was the designed as the output (Fig. 31).



FIS Name: Piave

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

Current Variable

Name: Slope

Type: input

Range: [0 100]

System "Piave": 3 inputs, 1 output, and 36 rules

Figure 31: Fuzzy Inference System featuring "Slope", "PointDensity" and "BathymetricQuality" as inputs and "ElevUncertainty" as output.

Slope and point density classes were divided in low, medium and high and the choice of their ranges was performed taking into consideration literature values (Wheaton et al., 2010), the analysed fluvial environments (gravel-bed rivers) and related field experience (Table 1).

Table 1: Categories and ranges used to describe slope and point density inputs in the FIS file.

	Slope (%)				Point density (Pts m^{-2})			
Low	0	0	5	10	0	0	1	1.2
Medium	5	10	15	20	1	1.2	2	2.2
High	15	20	100	100	2	2.2	15	15

The third input variable, bathymetric quality, represents the innovation of this geomorphic approach as we believed that the achievement of reliable final geomorphic estimates was highly dependent on the precision of flowing channel representations, derived by colour bathymetry (Moretto et al., 2012). The accuracy of in-channel topographic surfaces in the DEMs was evaluated considering four classes: low, medium, high and "OutChannel", the latter including all the dry areas that were thought to be excluded from analysis in this input. Due to the variability of precision in bathymetry output results (Moretto et al., 2012), categorical limits of bathymetric quality input have featured slight differences among rivers and years, as reported in Table 2.

Table 2: Categories and ranges used to describe bathymetric quality input in the FIS file.

	Piave				Tagliamento 2010				Tagliamento 2011			
Low	-3	-3	-1.4	-1.3	-3	-3	-0.8	-0.7	-3	-3	-1.5	-1.4
High	-1.4	-1.3	-0.3	-0.2	-0.8	-0.7	-0.25	-0.15	-1.5	-1.4	-0.3	-0.2
Medium	-0.3	-0.2	0.25	0.3	-0.25	-0.15	0.25	0.3	-0.3	-0.2	0.25	0.3
OutChannel	0.25	0.3	1	1	0.25	0.3	1	1	0.25	0.3	1	1

The output variable, elevation uncertainty, was finally organized in four categories: low, average, high and extreme (Table 3).

Class ranges in the output variable were established as follows:

- *low*, in areas featuring the best input conditions (i.e. low slope, high point density and high accuracy of bathymetric output). Further, cells with overlapping survey points and thus increased point density, may present elevation uncertainty below the instrumental and interpolation errors, as demonstrated by the comparison of our terrain models with dGPS control points that has reported errors also < 0.10 m. Recent research has confirmed that the further the same area is surveyed by a topographic device, the more the error decreases until a given minimum and constant value (Hodge et al., 2009);
- *average*, the upper limit of this class was appointed by considering the average error of the primary survey sources, in our case LiDAR and colour bathymetry (~ ± 0.20 m);

- *high*, the upper limit of this class was appointed by reporting the cell-size of the DEMs, in our case 0.5 m. This cell-size was selected to be the most suitable, according to the morphology of our study reaches, to efficiently investigate erosion and deposition processes;
- *extreme*, the upper limit of the class was appointed after a dGPS validation on the areas featuring the less accurate elevation estimates, in this case derived from bathymetric survey (~ 1 m), as reported by Moretto et al. (2012).

Table 3: Categories and ranges used to describe elevation uncertainty output in the FIS file.

	Elevation uncertainty (m)			
Low	0	0	0.1	0.12
Average	0.1	0.12	0.2	0.22
High	0.2	0.22	0.4	0.5
Extreme	0.4	0.5	1	1

After appointing classes and ranges to input and output variables, three FIS files differing in the ranges of bathymetric quality input were produced and called: Piave, Tagliamento 2010 and Tagliamento 2011. In Fig. 32 we can appreciate an example of Fuzzy Inference System (Piave River).

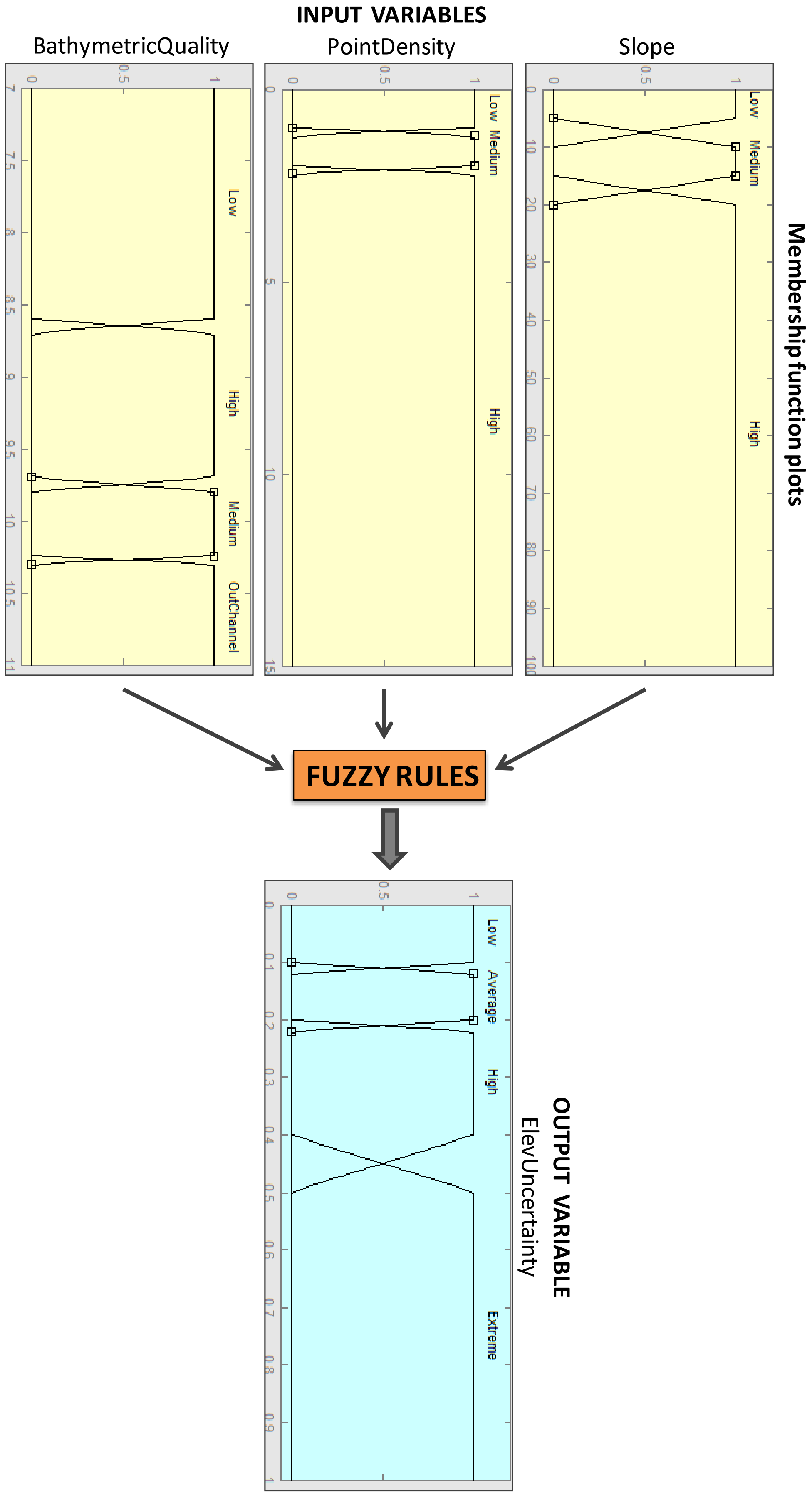


Figure 32: Input and output variables and classes of the Fuzzy Inference System (FIS) for the Piave River.

All categorical limits of bathymetric quality input were increased by 10 in order to avoid problems of negative and “crossing-zero” values in the Fuzzy Logic application. Finally, 36 FIS rules were edited, taking into account the accuracy and relevancy of the selected input variables in this specific case study. We used the following linguistic connectors, "if", "and" and "then": if slope is "low" and point density is "medium" and bathymetric quality is "high", then elevation uncertainty is "low" (Table 4). Rules from 28 to 36 present only two combined inputs (slope and point density) due to the need of evaluating dry areas without the interference of the bathymetric quality input.

The operating principles of the FIS rules that combine, through a fuzzification process, the input variables to obtain a crispy output value of elevation uncertainty, are shown in Fig 33. Here, we can appreciate the distinctive advantage of this approach that considers the implementation of fuzzy borders among membership function plots, thus avoiding fixed and exact limits between input classes. The ability of controlling class shifts, providing a continuous flow of attributes, creates a better correspondence with processes occurring in natural environments, helping final decision makers. In the example of Fig. 33, we can observe as a slope of 7.71 %, a point density of 2.13 Pts m^{-2} and a bathymetric quality of 9.74 m, produce a final elevation uncertainty of 0.0945 m (ϱz). This uncertain range will be applied and discarded from real change in the following DoD models.

For details on FIS logic and procedure we refer to Wheaton et al. (2010).

Table 4: Fuzzy Inference System (FIS) rules connecting input and output variables.

	INPUT			**OUTPUT**
Rule	**Slope** (%)	**PointDensity** (Pts m^{-2})	**Bathymetric Quality** (m)	**ElevUncertainty** Ϙz (m)
1	low	low	low	high
2	low	low	medium	high
3	low	low	high	average
4	low	medium	low	high
5	low	medium	medium	average
6	low	medium	high	low
7	low	high	low	average
8	low	high	medium	average
9	low	high	high	low
10	medium	low	low	high
11	medium	low	medium	high
12	medium	low	high	high
13	medium	medium	low	high
14	medium	medium	medium	average
15	medium	medium	high	average
16	medium	high	low	average
17	medium	high	medium	average
18	medium	high	high	low
19	high	low	low	extreme
20	high	low	medium	extreme
21	high	low	high	high
22	high	medium	low	high
23	high	medium	medium	high
24	high	medium	high	average
25	high	high	low	high
26	high	high	medium	high
27	high	high	high	average
28	low	low	-	average
29	low	medium	-	low
30	low	high	-	low
31	medium	low	-	high
32	medium	medium	-	average
33	medium	high	-	low
34	high	low	-	extreme
35	high	medium	-	high
36	high	high	-	high

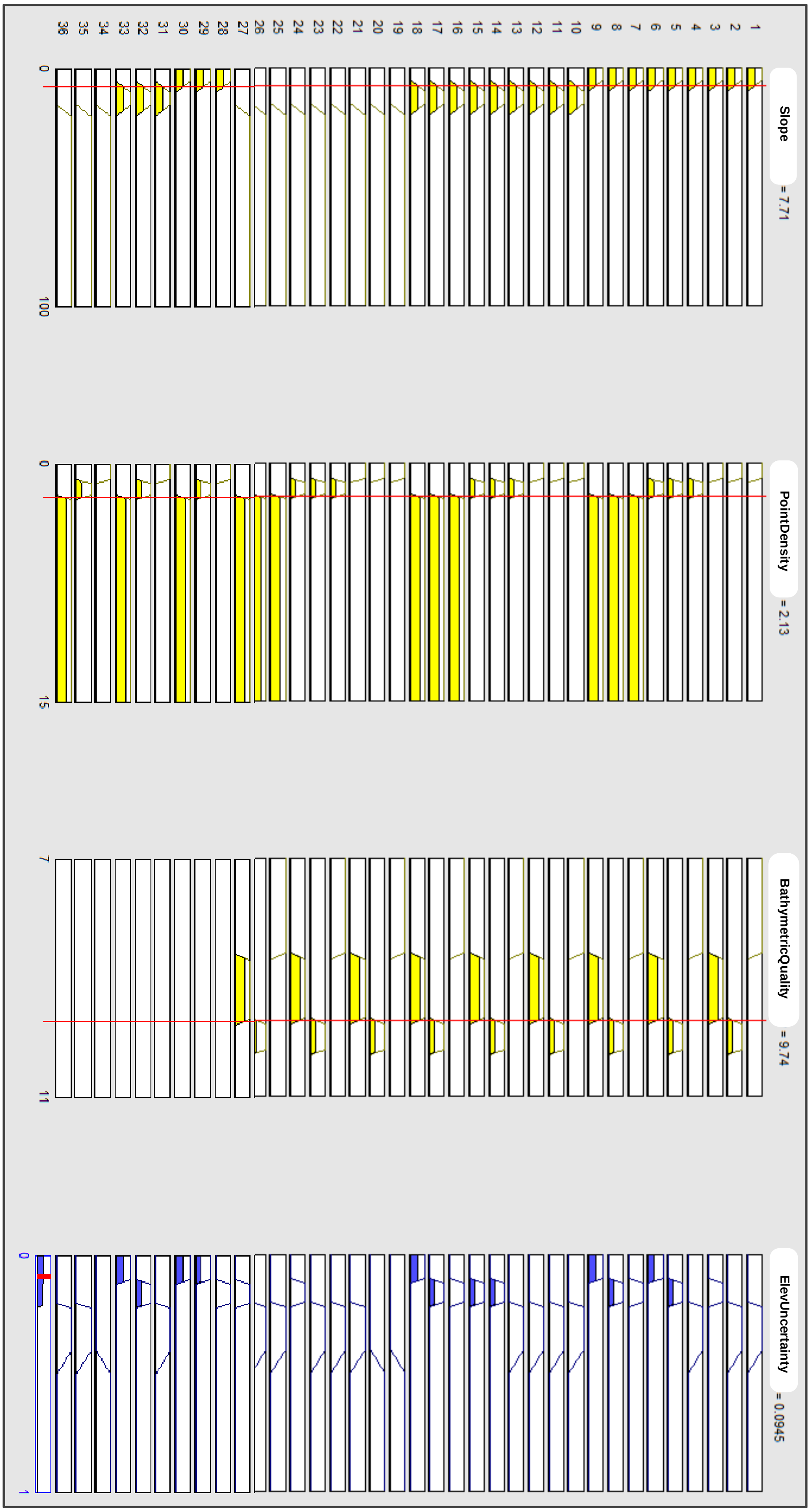


Figure 33: Combination and control of FIS rules and associated output value of elevation uncertainty.

6.1.2.3. Associated input DEMs

In ArcGIS 10.0 (ESRI) environment, three DEMs associated to the input variables (slope, point density and bathymetric quality) on which FIS rules were ideated to operate, were created for each sub-reach (Belluno and Praloran for the Piave River; Cornino and Flagogna for the Tagliamento River) and year (2010 and 2011). Basic hybrid DEMs were used as source. Slope (Fig. 34) and point density (Fig. 35) DEMs were interpolated using the correspondent ArcGIS tools. The DEM describing bathymetric quality was reproduced through a surface interpolating in the wet areas the depths (increased by 10) derived by colour bathymetry (Moretto et al., 2012), and in the dry areas a unique value of 11 m to include all outer channel regions (Fig. 36).

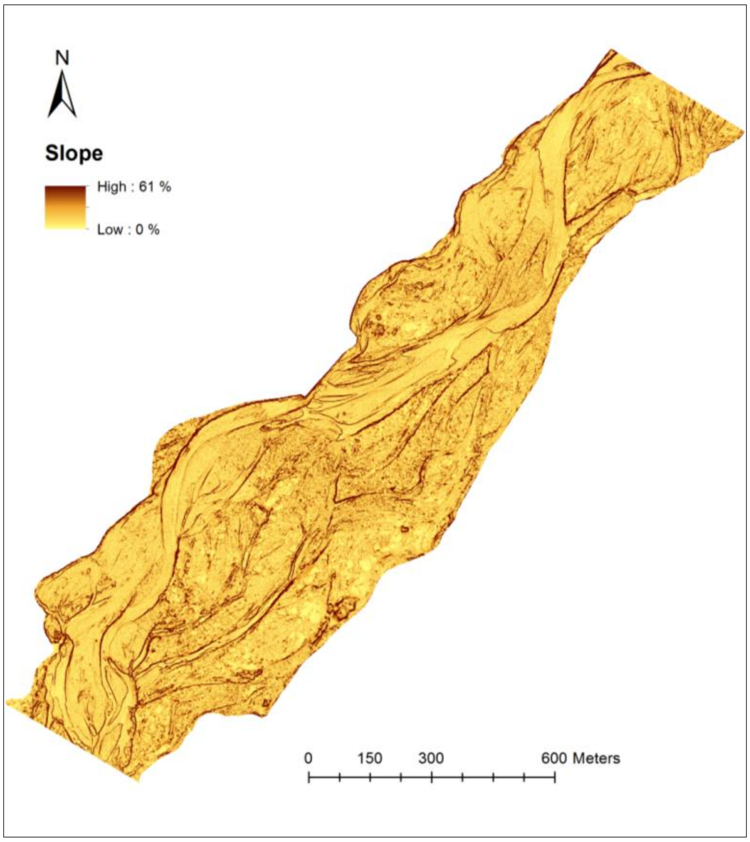


Figure 34: Slope input DEM of Belluno reach (Piave River).

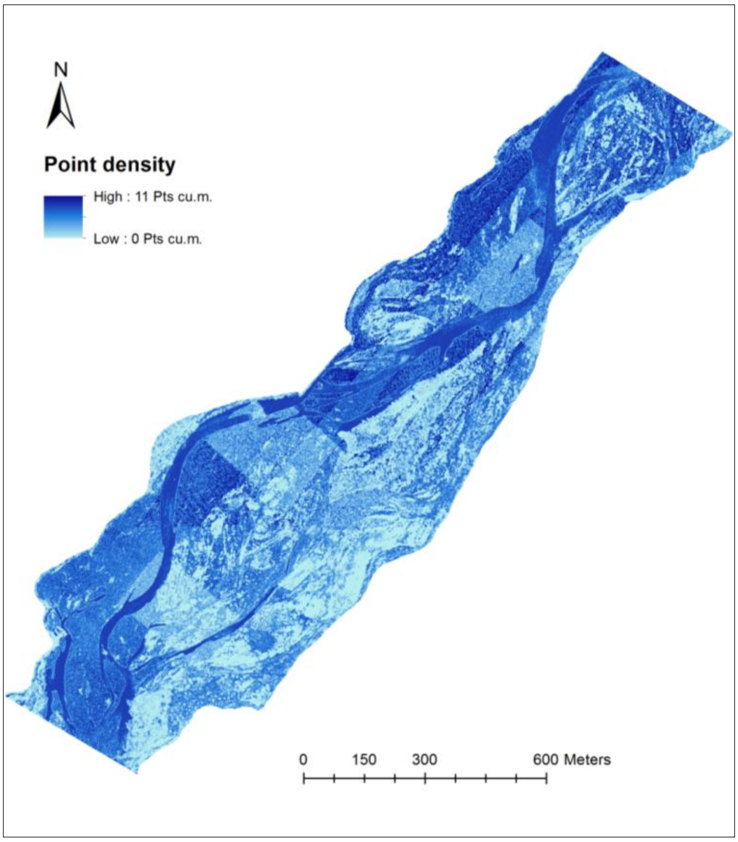


Figure 35: Point density input DEM of Belluno reach (Piave River).

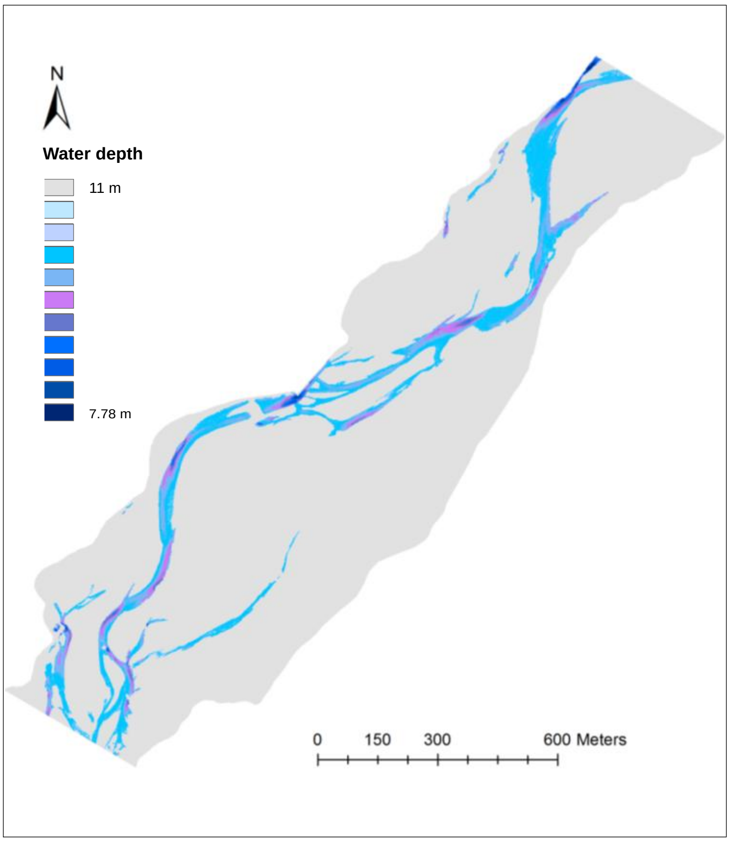


Figure 36: Input DEM of bathymetric quality (Belluno reach, Piave River).

6.1.2.4. Final output DoDs

At this stage, basic hybrid DEMs, FIS files (Piave, Tagliamento 2010 and Tagliamento 2011) and associated input DEMs (slope, point density and bathymetric quality) were ready to be run within the Geomorphic Change Detection (GCD) software 5.0 (Wheaton et al., 2010). This procedure has firstly produced associated uncertainty surfaces derived by the application of the FIS rules on the combined input DEMs. Subsequently, basic hybrid DEMs and error rasters of each reach in the two study years (2010 and 2011) were differenced to obtain precise DoD models. Geomorphic changes were detected following the literature (Wheaton et al., 2010), thus using a spatially-variable uncertainty thresholded of 95% C.I. and a Bayesian filter updating change estimates according to spatially-coherent units of erosion and deposition (5x5 mobile window). For details on GCD software we refer to Wheaton et al. (2010).

6.1.3. Geomorphic changes on channel components

6.1.3.1. Main channel processes

Geomorphic changes affecting main flowing branches afterwards 2010 flood events were isolated on the aerial images through manual digitalization of wet channels. The resulting shapefiles were then compared to the new DoD maps within the GCD application, in ArcGIS environment. Running the digitalized main channels over the DoD rasters has finally led to the characterization and quantification of erosion and deposition processes related to the activity of main flowing channels, helping to explain network reconfiguration.

6.1.3.2. Bank erosion processes

In ArcGIS environment, erosion and deposition dynamics highlighted by the DoD models were analysed, finding in Belluno reach (Piave River) the largest patterns of lateral erosion caused by 2010 floods. Two major bank erosions occurred similarly downstream of longitudinal bank protections were identified. Both lateral scour processes that removed stable vegetated areas were isolated and volumetrically quantified. Also remaining stable forested zones affected by erosion were edited to understand the incidence of these major bank erosion processes on total removal of stable vegetated areas.

6.2. SECTION II - King River (Australia)

6.2.1. Introduction

All field measurements were acquired using basic tools as measuring tape, topographic stadia and compass. In the following steps of data processing, aerial photos of the area and different softwares including Microsoft Package, ArcGIS, Statistica, R, were utilized.

Measurements have regarded tree as well as bank profile characteristics. To be surveyed, trees located on the twenty considered banks had to reach a minimum length of 1 m and a minimum diameter of 10 cm. Bank spaces between consecutive trees were categorized in: i) Convex, when the bank profile exceeds the straight line describing tree spacing, ii) Mixed, when the bank profile both exceeds and does not exceed in the same bank space the straight line describing tree spacing, iii) Concave, called scallops, when the bank profile does not exceed the straight line describing tree spacing. The depth of those bank features was measured only in case of a maximum apex of more than 0.5 m. Finally, the distance between consecutive trees was intended to be equal to the spacing of the analyzed bank profile features, as this was measured considering as external ends the points on the bank-top line that were closer and right behind tree trunks.

6.2.2. Measurements at tree-level

In detail, the measured characteristics of bank trees were: species, diameter, the three sides of the triangular empty space above the tree trunk (called horizontal H, vertical V and oblique O), the perpendicular distance of exposed roots between trunk base and bank face (tree undercutting), the average leaning angle of the trunk from the base until breast height (BH), tree canopy radius and the bearing angle with the following tree (Fig. 37).

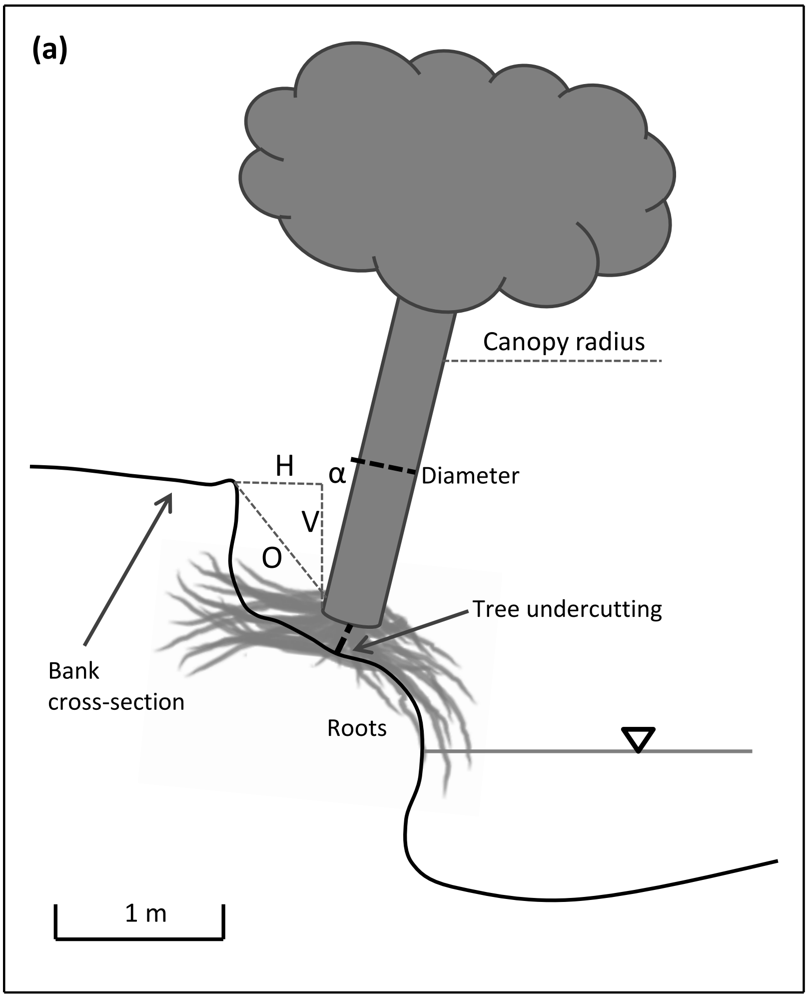


Figure 37: Tree characteristics measured in the field.

6.2.3. Measurements at scallop-level

Similarly, characteristics of the bank profile spaces between consecutive trees were acquired and divided in: total spacing considering as external ends the points on the bank-top line that were closer and right behind tree trunks, shape of bank profile spaces (convex, mixed or concave), presence and position along the total spacing of any apex greater than 0.5 m in depth and maximum depth (apex) (Fig. 38).

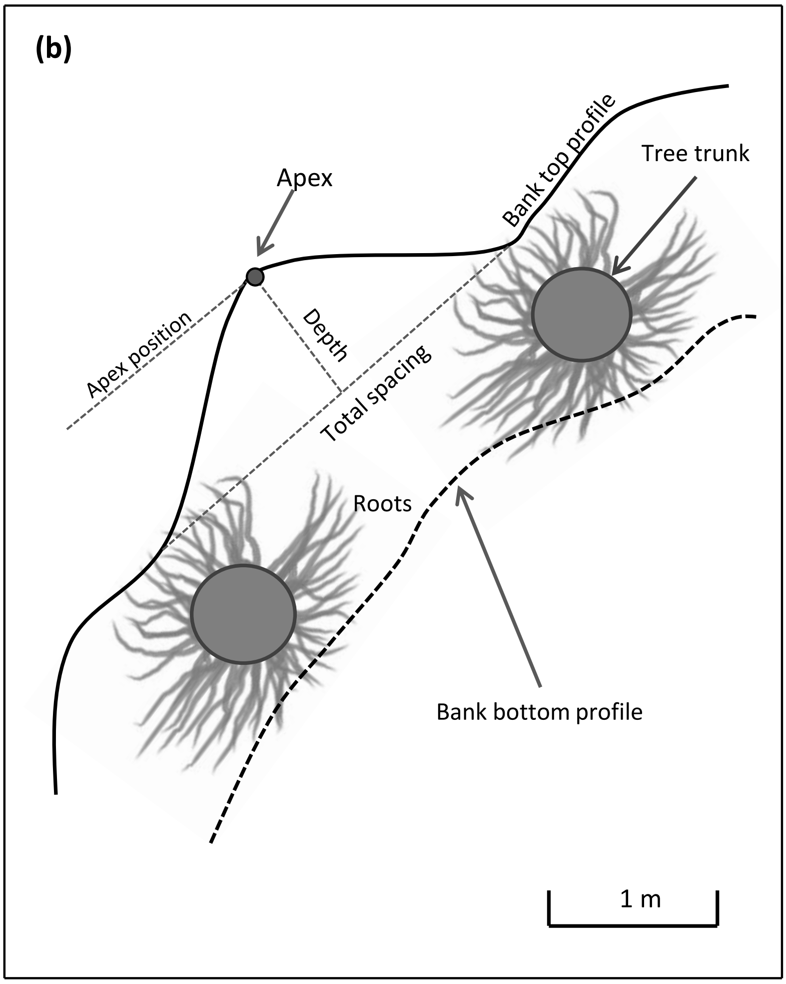


Figure 38: Scallop characteristics measured in the field.

6.2.4. Tree and scallop digitalization and categorization

The office work was firstly focused on separating trees and bank profile spaces in three categories following their position in the different morphological segments of the river: straight section (SS), inner bend (IB) and outer bend (OB). We consider this initial subdivision as fundamental since our analyzed components undergo very diverse hydraulic and erosional processes depending on their position along riverbanks. The categorization was carried out by reconstructing tree location in ArcGIS environment using bearing data and visual interpretation. Circle features built on the radius of bend arcs and break lines representing river inflection points were generated to appoint categories to trees and bank profile features (Fig. 39).

Figure 39: Tree and scallop separation according to river morphological sections.

Finally, data were ready to be elaborated using descriptive and quantitative statistical approaches. Possible relationships and dependencies among the analyzed characteristics of riparian trees and bank profile spaces were investigated through different softwares, as Microsoft (Excel), Statistica and R.

6.3. SECTION III - Bank retreat in the Piave River (Italy)

Bank retreat processes were investigated also on the Piave River and, more precisely, in Belluno reach. The different nature of this river system, characterized by a braided configuration, a gravel substrate and a more variable location of bank trees, has induced us to consider and measure less attributes of riparian trees and bank profiles. A slightly-modified field approach was utilized. Four arched bank profiles featuring lateral migration processes were chosen. For each tree, information of species, diameter at breast height (BH), position on the bank (bank-top or inner-bank), distance between tree and bank edge (in case of inner-bank trees) and canopy radius, were acquired. Additionally, bank tree location was surveyed with a dGPS for further digitalization purposes in ArcGIS environment. Bank profile spaces between consecutive scallops were then analysed, measuring the following paramenters: total spacing considering as external ends the bank-profile edges closest and in line to the trunk base, shape of bank profile spaces (convex, mixed or concave), presence and position along the total spacing of any apex greater than 0.5 m in depth and maximum depth (apex) (Fig. 40).

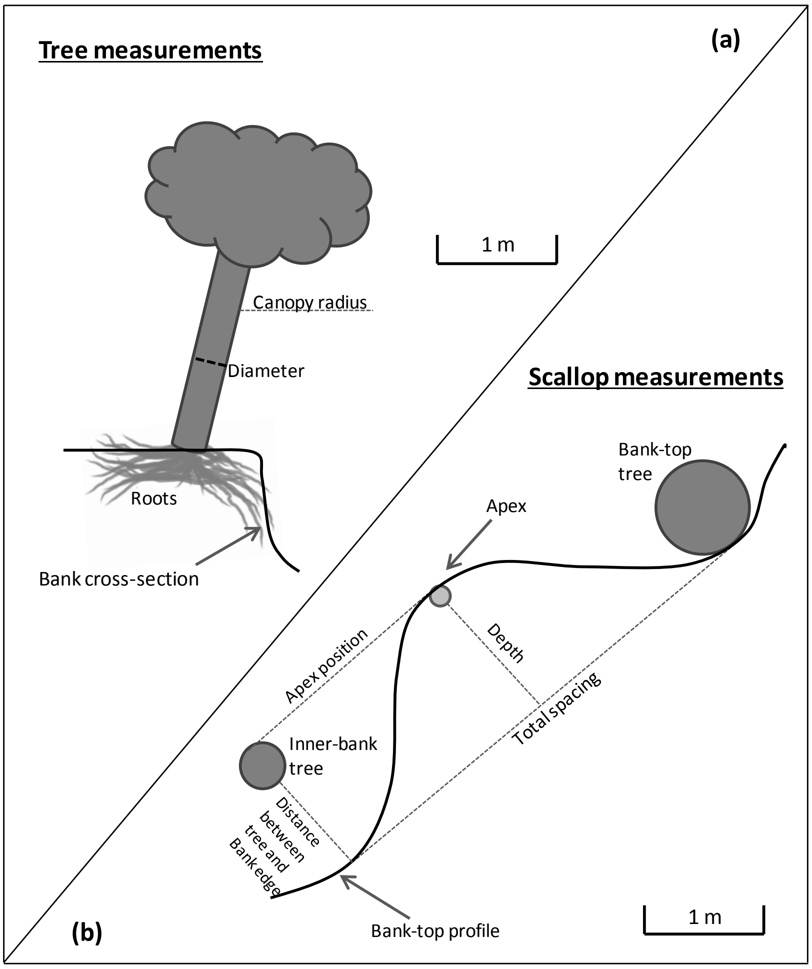


Figure 40: Tree (a) and scallop (b) characteristics measured on the Piave River.

7. RESULTS

7.1. Introduction

The results of this research start with the identification and estimation of short-term geomorphic changes occurred as a consequence of flood events that affected the Piave and Tagliamento Rivers (Italy) at the end of 2010. After reaching accurate and reliable amounts of sediment remobilization through enhanced surface differencing models, the attention has focused on the planimetric adjustments suffered by main flowing channels during the floods. In the development of newly scoured paths, the main branches of the rivers have eroded away stably forested banks, generally representing the most resistant areas to fluvial scour. Bank retreat evolution in forested cohesive riverbanks was then deeply analyzed on the King River (Australia), trying to explore relationships among different tree and spacing characteristics. Finally, the control of riparian vegetation on bank retreat was investigated in the Piave River: this river system, characterized by non-cohesive (gravel) sediment and very different characteristics in respect to the King River, has offered distinctive results and interesting insights for further comparison and discussion.

7.2. Impacts of 2010 floods on short-term geomorphic changes (Piave and Tagliamento rivers)

7.2.1. Accurate DEMs of Difference (DoDs) and volumetric estimates of change

The very first result that stands at the basis of reliable estimates of geomorphic changes is represented by the production of precise DEMs of Difference (DoDs). These surfaces were created within the application software Geomorphic Change Detection (GCD, Wheaton et al., 2010) using a multi-input approach which considers the evaluation of complementary accuracy derived by slope, point density and bathymetric quality. The choice of including the detection of bathymetric elevations derived from Moretto et al. (2012) method was developed to enhance the reliability of geomorphic changes as the majority of erosion and deposition processes occur within wet channels. LiDAR data alone were not able to reproduce underwater areas, so their combination with data obtained by colour bathymetry was an effective trade-off to build complete and precise surface elevation models. Moreover, the creation of “ad hoc” FIS (Fuzzy Inference System) files combining the inputs with rules based on literature, specific field data and experience to obtain a spatially-variable threshold of elevation uncertainty, has completed the creation of accurate DoD models.

Here below, the DoD models of Belluno (Fig. 41) and Praloran (Fig. 42) reaches (Piave River) are presented. As we can appreciate from the images, erosion and deposition processes seem to be well and fluent replicated. The most part of changes have occurred in the main flowing branches of the active channel, confirming the importance of reproducing precise elevations in wet areas. White pixels on the models represent either areas where no change has occurred or where uncertainty threshold is higher than real change. Despite a careful data filtering in the first steps of surface creation, few possible misleading elevations due to vegetation interference may be present.

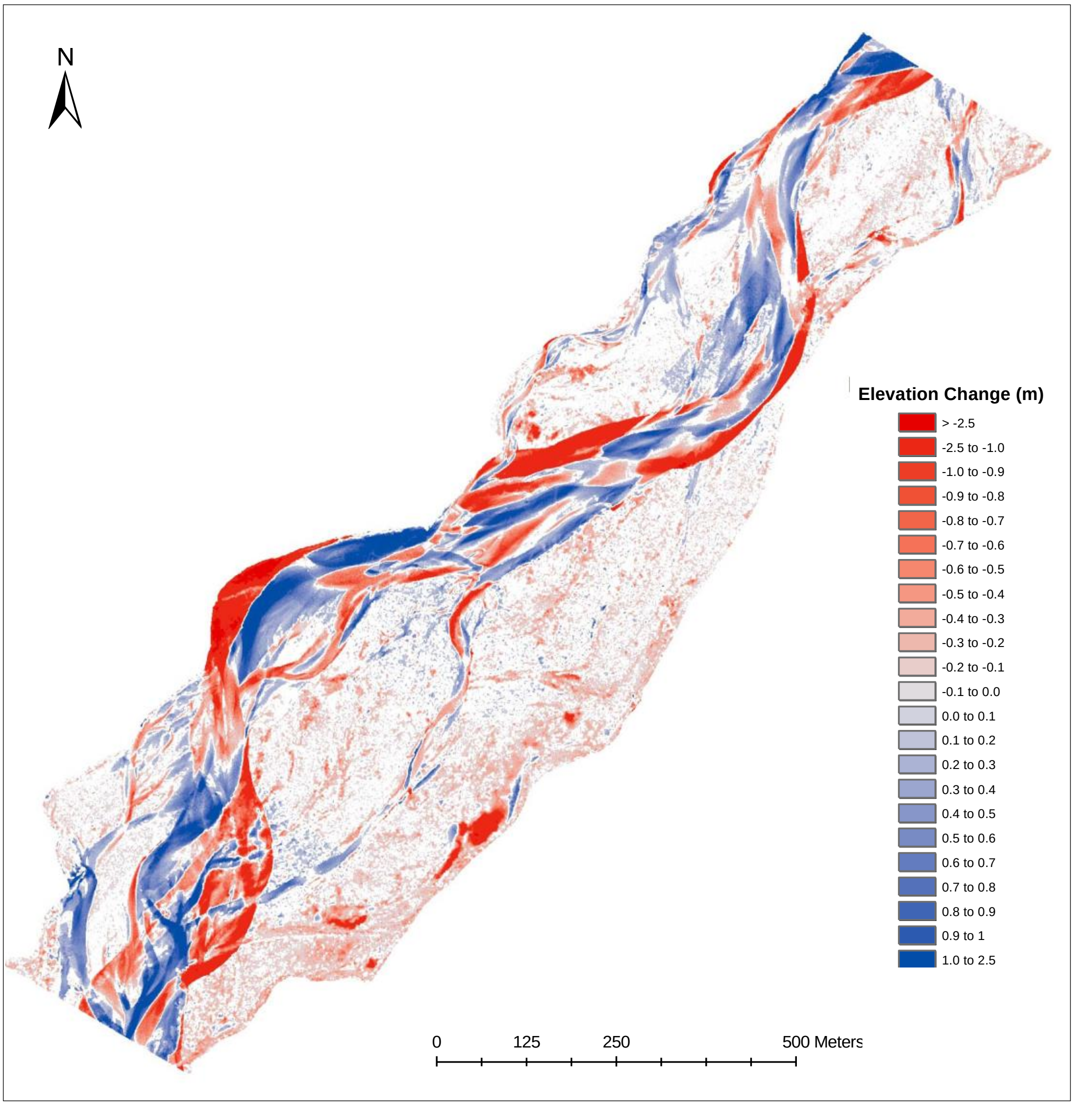


Figure 41: DoD model of Cornino (Piave River).

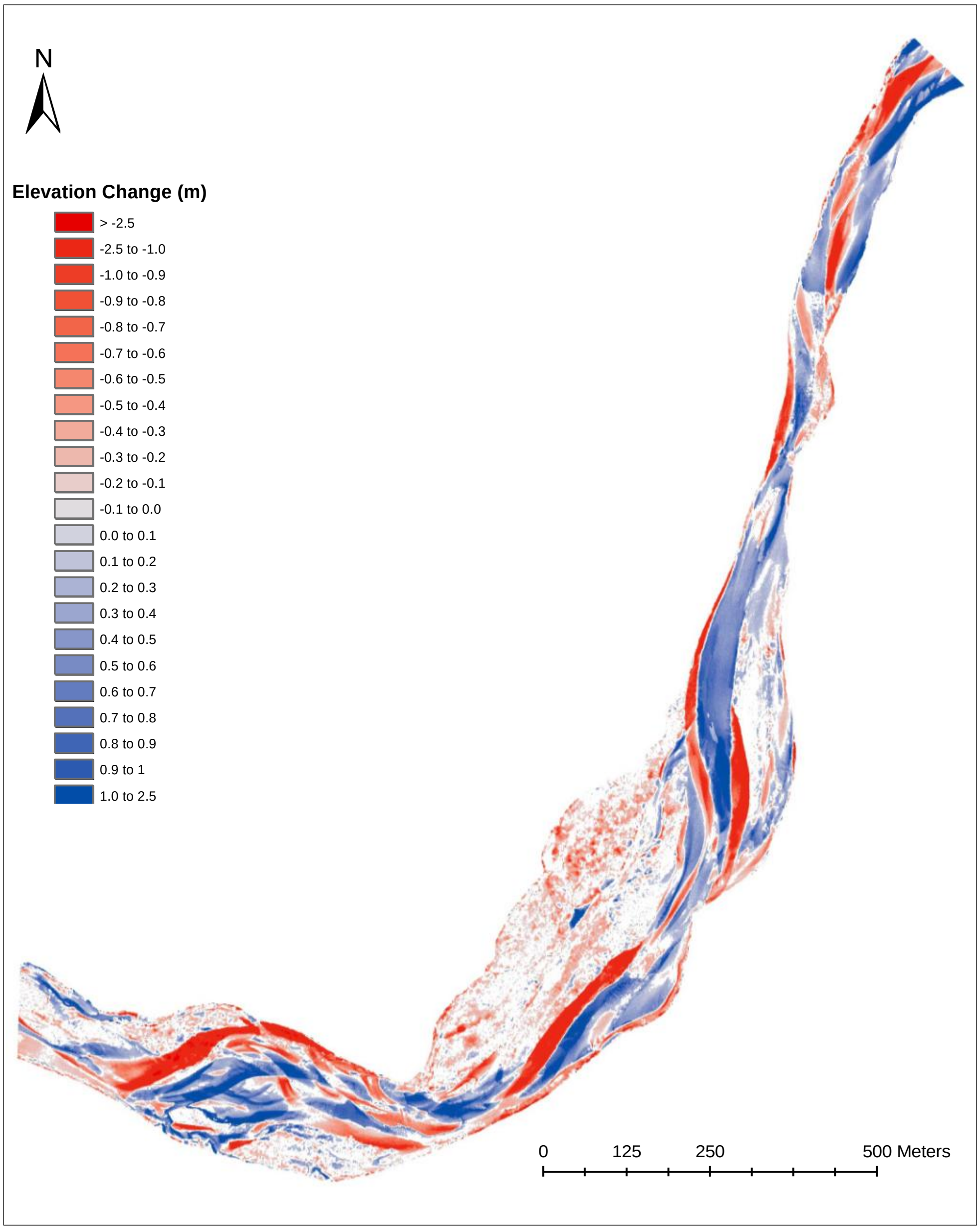


Figure 42: DoD model of Praloran (Piave River).

Volumetric estimates of geomorphic changes occurred after 2010 floods indicate a predominance of erosion processes in both reaches (Table 5). Eroded sediment clearly prevails in the uppermost reach Belluno (62% of the total), but going downstream the net difference decreases, featuring in Praloran an almost equilibrated situation (2% of difference). Uncertain volumes associated with real change embody all elevation differences below the variable threshold of detection and represent a consistent portion of the total.

Table 5: Volumetric estimates of geomorphic changes accounting for uncertainty on the Piave River.

Piave	**Belluno**			**Praloran**		
	Thresholded DoD Estimate	*± Error Vol.*	*% Error*	*Thresholded DoD Estimate*	*± Error Vol.*	*% Error*
Total Volume of Erosion (m^3)	164,449	± 65,893	40%	118,648	± 44,440	37%
Total Vol. of Deposition (m^3)	102,271	± 27,793	27%	109,156	± 29,094	27%
Total Net Vol. Difference (m^3)	-62,178	± 71,514	-115%	-9,492	± 53,116	-560%
Percent Erosion	62%			52%		
Percent Deposition	38%			48%		
Percent Imbalance	-12%			-2%		

The DoD models referred to the Tagliamento River are presented in Fig. 43 (Cornino reach) and Fig. 44 (Flagogna reach) and reveal, already from the first view, the greater magnitude of erosion and deposition processes in respect to the Piave River. Also within these surface models, the active channel seems to be well reproduced especially regarding the main flowing paths which generally show the highest degree of change. From the images we can also appreciate the different confinement level of the main channel in the two reaches, being Flagogna more constrained on its left side by topographic features.

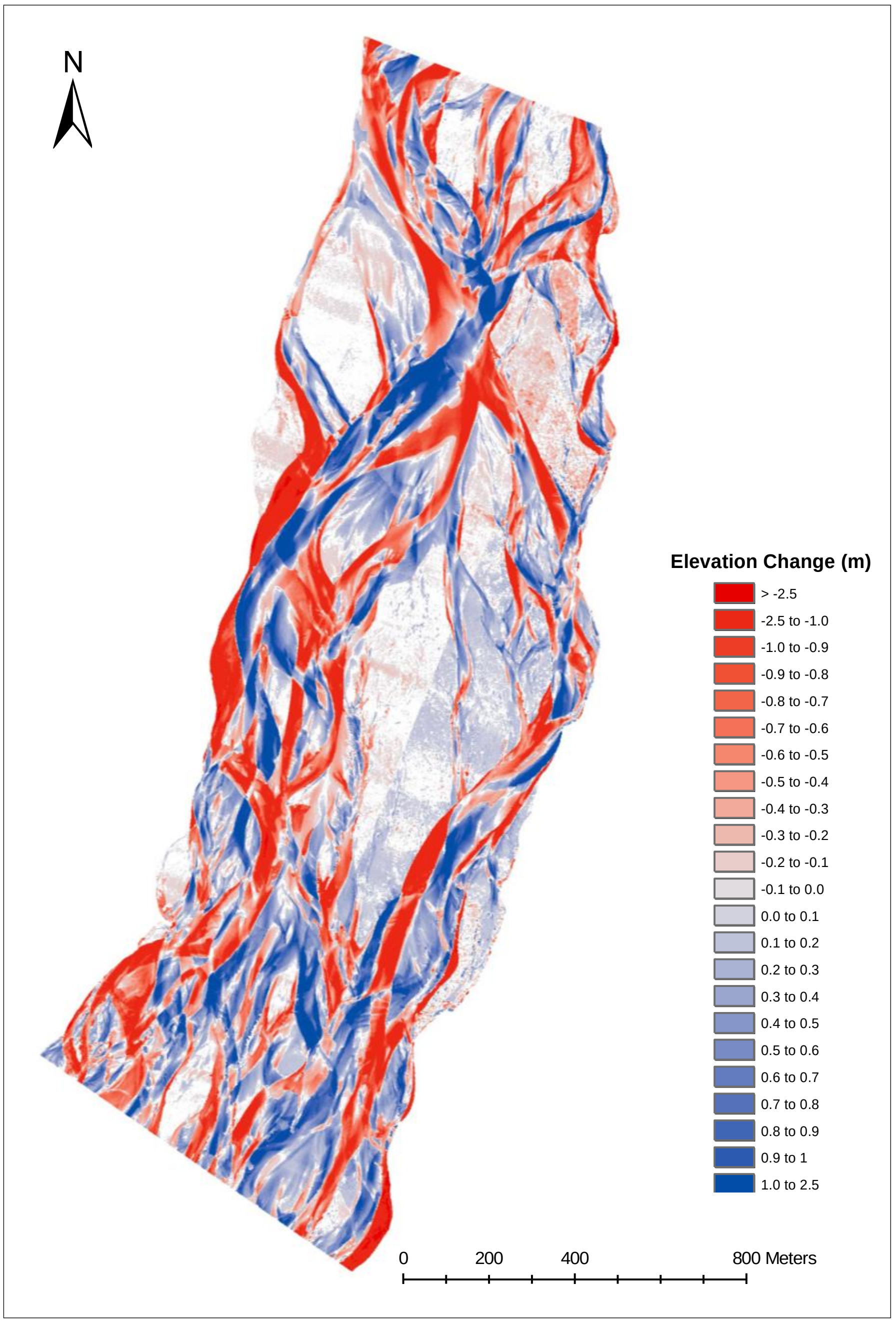


Figure 43: DoD model of Cornino (Tagliamento River).

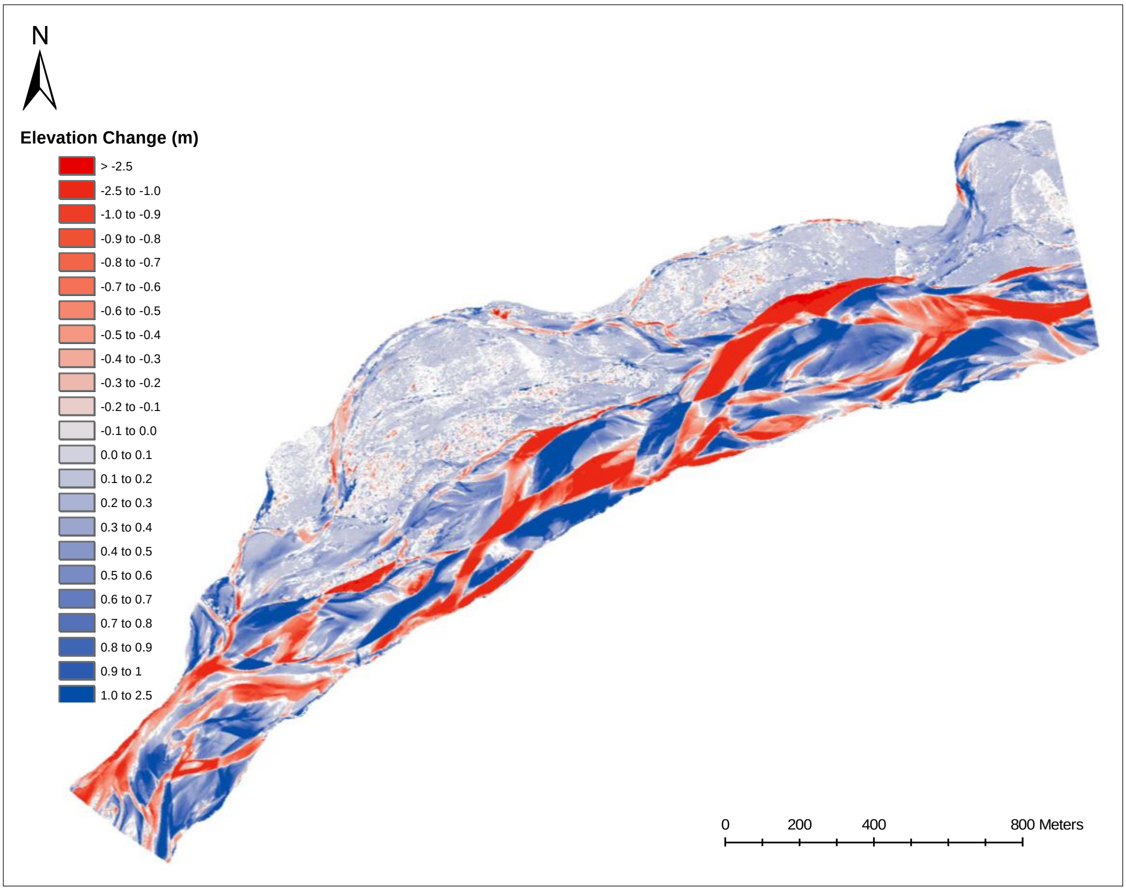


Figure 44: DoD model of Flagogna (Tagliamento River).

The volumetric effects of 2010 floods are summarized in Table 6. In contrast with Piave River reaches, the study sites of the Tagliamento River show different sediment magnitudes and dynamics. In fact, the uppermost reach Cornino registers a deficit in sediment balance, whereas the downstream Flagogna features a predominance of deposition. Sediment imbalance accounts for -9% in Cornino reach and +9% in Flagogna reach, respectively. Total mobilized sediment registers the highest amount in Cornino with a recirculation of over 1 million m^3. Associated error volumes result lower than in the Piave River, maybe due to more reliable topographic and survey characteristics of the study sites.

Table 6: Volumetric estimates of geomorphic changes accounting for uncertainty on the Tagliamento River.

Tagliamento	**Cornino**			**Flagogna**		
	Thresholded DoD Estimate	*± Error Vol.*	*% Error*	*Thresholded DoD Estimate*	*± Error Vol.*	*% Error*
Total Volume of Erosion (m³)	703,771	± 148,087	21%	335,377	± 73,514	22%
Total Vol. of Deposition (m³)	482,903	± 111,958	23%	489,729	± 131,964	27%
Total Net Vol. Difference (m³)	-220,868	± 185,646	-84%	154,352	± 151,059	98%
Percent Erosion	59%			41%		
Percent Deposition	41%			59%		
Percent Imbalance	-9%			9%		

7.2.2. Planimetric adjustments of main flowing channels

Main flowing channels (wet branches) were digitalized from 2010 and 2011 aerial images and their areal extent was compared to the DoD models in order to segregate sediment volumes and patterns. In Fig. 45, we can appreciate an example of main channel digitalization in Belluno reach (Piave River). It is visually evident a predominance of deposition processes for 2010 main branch and of erosion processes for 2011 main branch as a consequence of the analysed flood events. The shift of the main flowing channel seems to be clear leading to the formation of a new path.

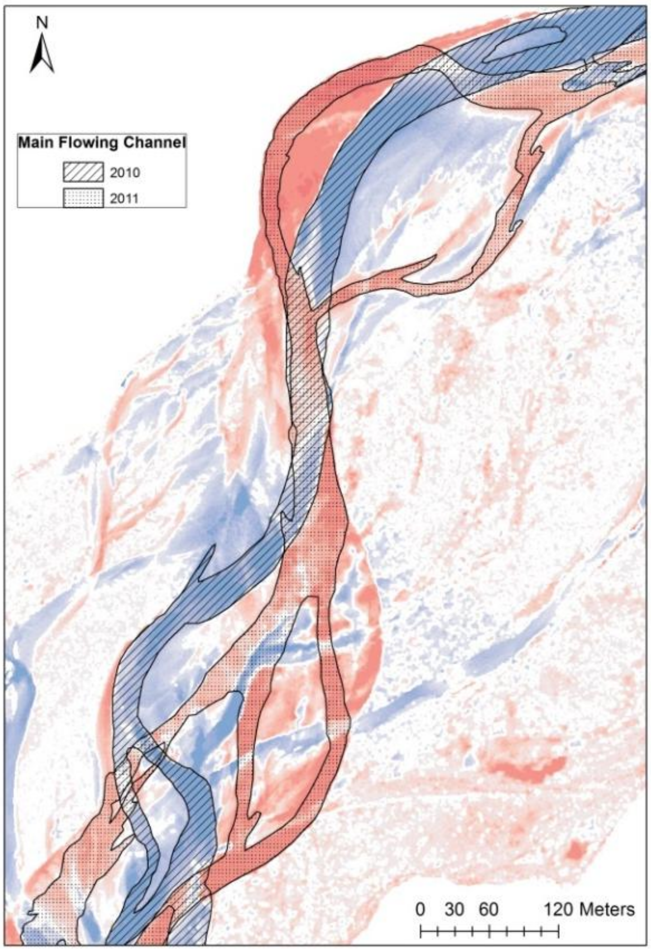


Figure 45: Digitalization of 2010 and 2011 main channels in the Piave River (Belluno reach).

The volumetric estimates of Belluno and Praloran reaches (Piave River) clearly indicate a totally reverse geomorphic trend before and after 2010 floods (Table 7). 2010 main flowing channels underwent prevalent deposition during flooding as underscored by the very high aggradation percentages, 91% for Belluno and 86% for Praloran respectively. On the other hand, 2011 main branches were almost totally newly scoured as they feature strongly predominant erosion processes, 98% in both reaches. This very sharp difference indicates that the effects of 2010 floods have led to a pronounced reconfiguration of main flowing channels that have strongly adjusted their planimetric structure.

Table 7: Volumetric segregation of 2010 and 2011 main channels in the Piave River.

PIAVE	**Belluno**		**Praloran**	
	2010	**2011**	**2010**	**2011**
Total Volume of Erosion (m³)	5,049	57,505	11,119	62,851
Total Volume of Deposition (m³)	53,855	1,368	68,802	968
Total Net Volume Difference (m³)	48,807	-56,137	57,683	-61,883
Percent Erosion	9%	98%	14%	98%
Percent Deposition	91%	2%	86%	2%
Percent Imbalance	41%	-48%	36%	-48%

In the Tagliamento River, similar patterns can be recognized. Main channel volumes derived from 2010 aerial images show a clear predominance of deposition processes with 85% for Cornino and 86% for Flagogna reaches, respectively (Table 8). In 2011, main flowing branches feature almost a total dominance of erosion processes, indicating also here the development of a new path of main flowing water after the flood events.

Table 8: Volumetric segregation of 2010 and 2011 main channels in the Tagliamento River.

TAGLIAMENTO	**Cornino**		**Flagogna**	
	2010	**2011**	**2010**	**2011**
Total Volume of Erosion (m³)	26,557	384,730	29,188	239,829
Total Volume of Deposition (m³)	149,166	16,869	177,712	7,545
Total Net Volume Difference (m³)	122,609	-367,861	148,524	-232,284
Percent Erosion	15%	96%	14%	97%
Percent Deposition	85%	4%	86%	3%
Percent Imbalance	35%	-46%	36%	-47%

7.2.3. Bank removal of stable and forested riverbanks

During the analysis DoD maps, we focused our attention on riverbank retreat, trying to interpret two significant bank erosions of stable vegetated areas that occurred downstream of two longitudinal bank protections (formed by boulders) in the Belluno reach (Piave River). As we can observe in Fig. 46, the three dimensional extent of the scour processes derived from the DoD model was isolated as well as the remaining stable zones affected by lateral erosion.

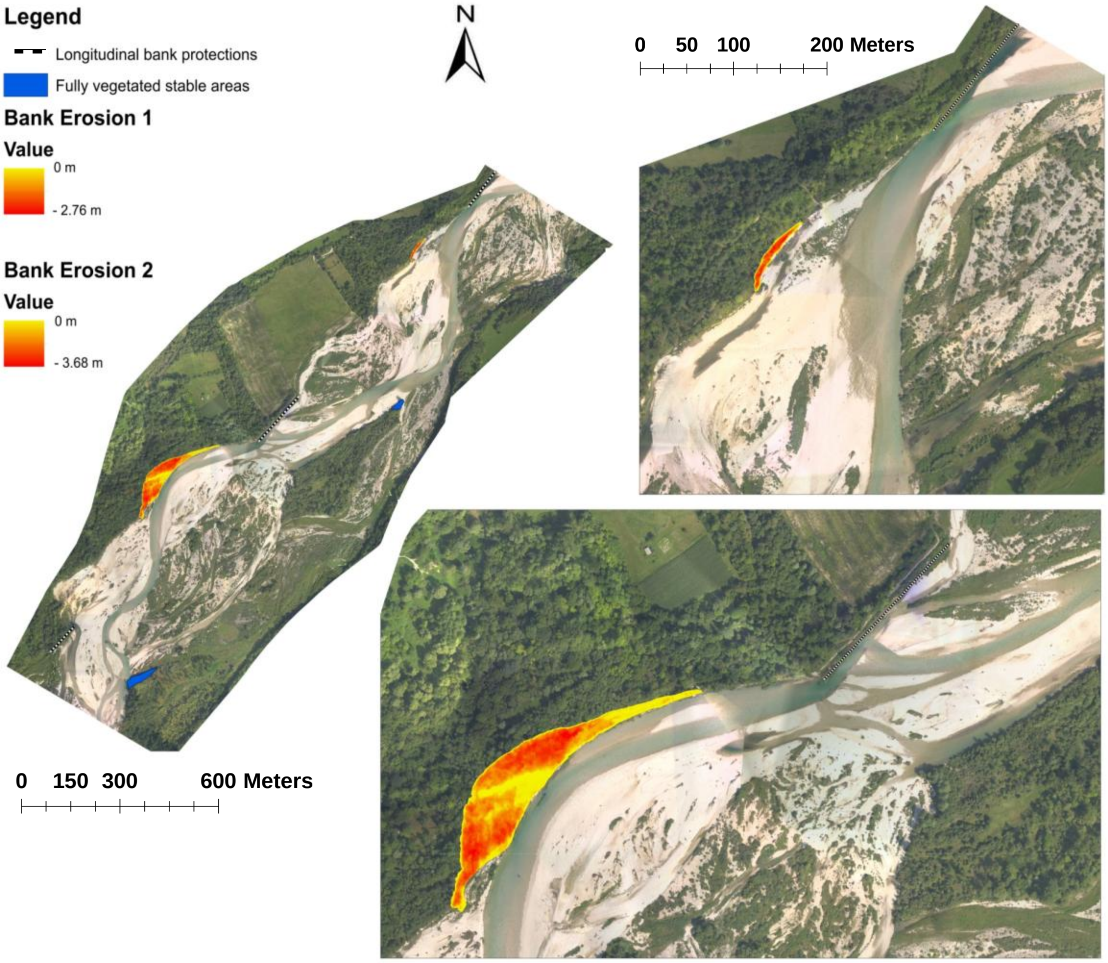


Figure 46: Erosion of stable areas in Belluno reach (Piave River).

Bank erosion n. 2 have registered the most significant change with a maximum depth of 3.68 m, a lateral shift of 60 m, a surface equal to 10,413 m^2 and a volume of 24,063 m^3 (Table 9).

Table 9: Characteristics of the major bank erosions of stable areas (Belluno reach).

	Bank erosion 1	**Bank erosion 2**	**Erosion in remaining stable areas**
Maximum depth (m)	-2.76	-3.68	-2.86
Maximum width (m)	11	60	25
Area (m²)	567	10,413	2,572
Volume (m³)	1,038	24,063	4,917

Another interesting consideration concerns the type of soil being eroded on banks as consequence of 2010 flood events: the two lateral scours have removed stable vegetated areas. These cohesive zones are normally the less prone to erosion and require not ordinary hydrodynamic conditions to be mobilized. Moreover, if we compare areal and volumetric incidence of the two bank erosions over the total amount of eroded stable areas, we can notice their strongly predominance, accounting for 81% and 84%, respectively (Table 10).

Table 10: Incidence of the two major bank erosions (Belluno reach).

	Total erosion in stable areas	**Incidence (%) of bank erosions 1 and 2 on total erosion of stable areas**
Area (m²)	13,550	81
Volume (m³)	30,017	84

7.3. Bank retreat evolution in forested cohesive riverbanks (King River)

7.3.1. Introduction

Bank retreat of cohesive forested riverbanks was analysed in 10 reaches of the King River (Australia), a low-land stream characterized by extensive root-plate abutments and scalloped bank profiles. The attributes of concave erosional features, called scallops, and consecutive bank trees were examined to find relations explaining the role of tree size and spacing in the development of scalloped riverbanks.

A fundamental point in the analysis of the role of riparian vegetation in bank retreat processes was represented by the subdivision of riparian trees and bank profile gaps into categories according to their position along the river channel. In fact, we have considered essential the membership of each tree and gap to a precise morphological section as different riverbank areas undergo very diverse hydraulic and erosional dynamics. In this sense, we divided the dataset into straight section (SS), inner bend (IB) and outer bend (OB) features according to their location in straight reaches and inner/outer bend portions of the channel.

The total number of surveyed bank trees reached 538 elements divided in 20 riverbank profiles (both sides of the 10 study reaches). Consequently, the total number of measured bank profile spaces was 518, also divided in 20 different bank lines. The bank with the lowest number of trees featured 13 plants with a great variance in respect to the one having the highest number which accounted for 49 plants.

7.3.2. Position and characteristics of bank trees

Bank trees were analyzed to define their starting position which represents a key point for all the further evaluations of bank retreat dynamics. From Fig. 47, we can observe as 80% of trees are directly growing on the bank face whereas only 20% is located on the top of the bank, on the floodplain. Specifically, the percentage of trees born or grown on the bank face reaches the highest value in the outer bends (OB) with 88%, followed by trees in straight sections (82%) and in inner bends (58%).

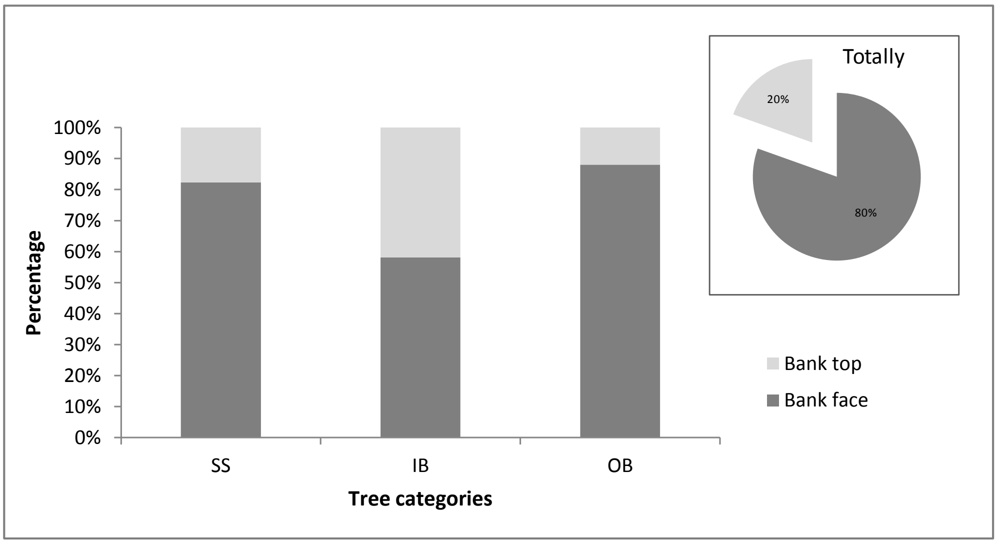


Figure 47: Tree position on banks: the pie chart shows the total distribution whereas the histogram the distribution of each category (SS = Straight Section, IB = Inner Bend, OB = Outer Bend).

Another interesting overview is given by the analysis of vertical depth at which trees on the bank face are located, as presented in Fig. 48. Trees grow down to nearly three meters below the floodplain surface, with the average position being around one meter from the bank top. Trees on outer bends have the highest variability together with the lowest position confirmed by a median of 0.9 m.

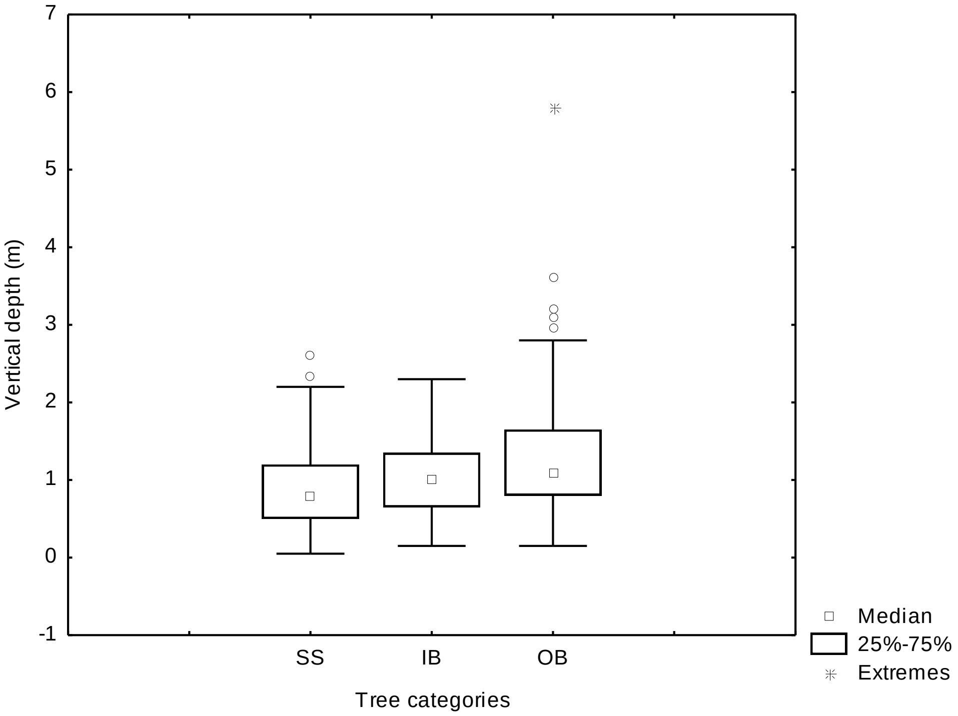


Figure 48: Variation in vertical depth of trees located on the bank face divided by categories (SS = Straight Section, IB = Inner Bend, OB = Outer Bend).

More than 80% of bank trees lean toward the channel, at an average angle of 17°. This angle does not vary much between the three categories of trees, straight section, inner and outer bends (Fig 49).

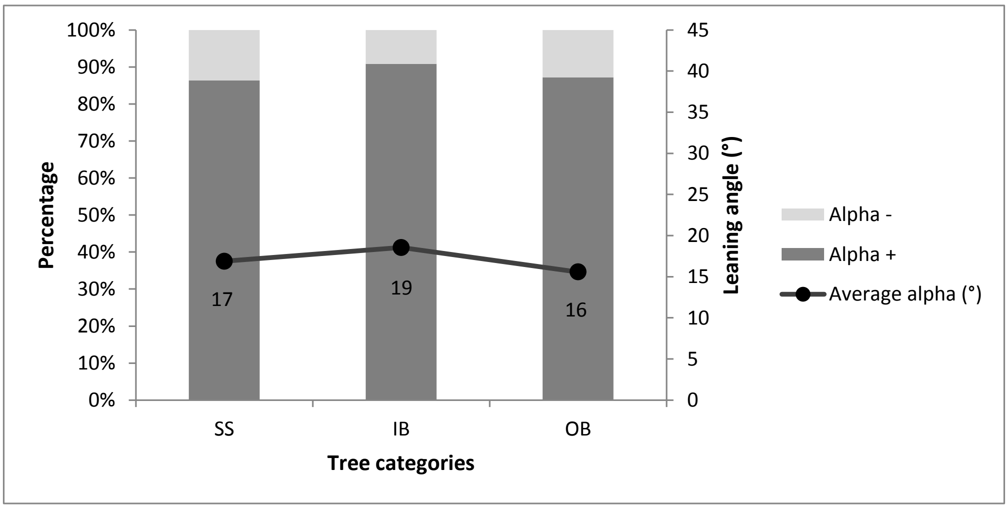


Figure 49: Leaning angle of trees among different categories (SS = Straight Section, IB = Inner Bend, EB = Outer Bend).

7.3.3. Erosion around trees: undercutting and overcutting

In this section, results on erosion processes occurring around trees located on the bank face are reported. Fig. 50 shows the incidence of undercutting below the base of bank trees. The presence of empty space characterized by exposed roots and caused by fluvial erosion seems to be restricted to a small number of plants. Straight section and outer bend trees feature the highest percentage of undercutting, both with 25%. Average undercutting depth greatly varies among categories and accounts 0.35 m for inner bend, 0.62 m for straight section and 0.97 m for outer bend trees.

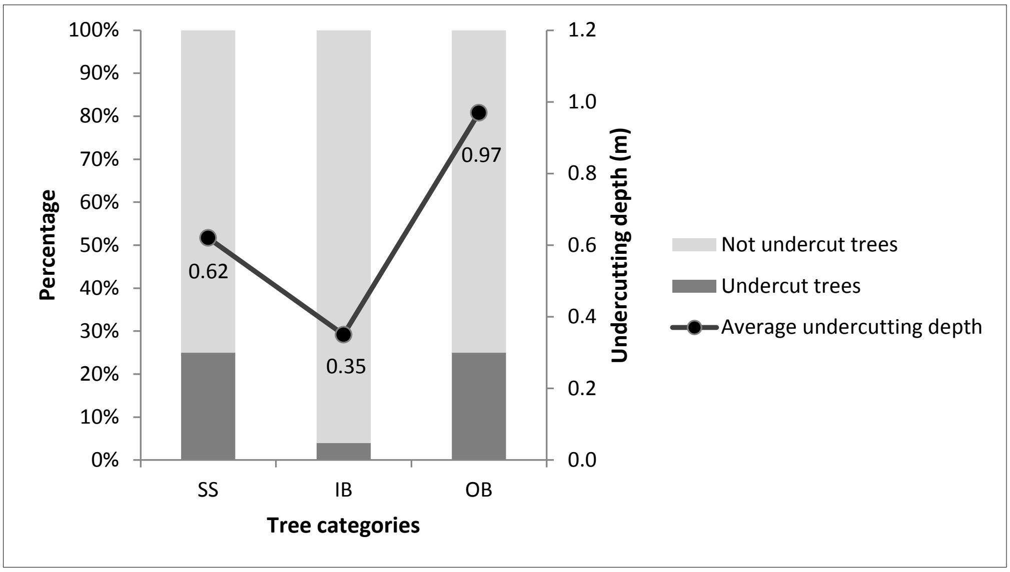


Figure 50: Incidence of undercutting below bank trees and average undercutting depth among categories (SS = Straight Section, IB = Inner Bend, OB = Outer Bend).

A triangle of sediment above the top edge of trees on the bank face has been eroded away, a process we call overcutting (Fig. 51). The amount of overcutting is greatest in outer bends where erosion dynamics are strengthen by flow properties; here the median area of 0.94 m^2. Surprisingly, inner bend trees feature a higher variability and magnitude of overcutting area in respect to straight section trees, with a median of 0.72 m^2.

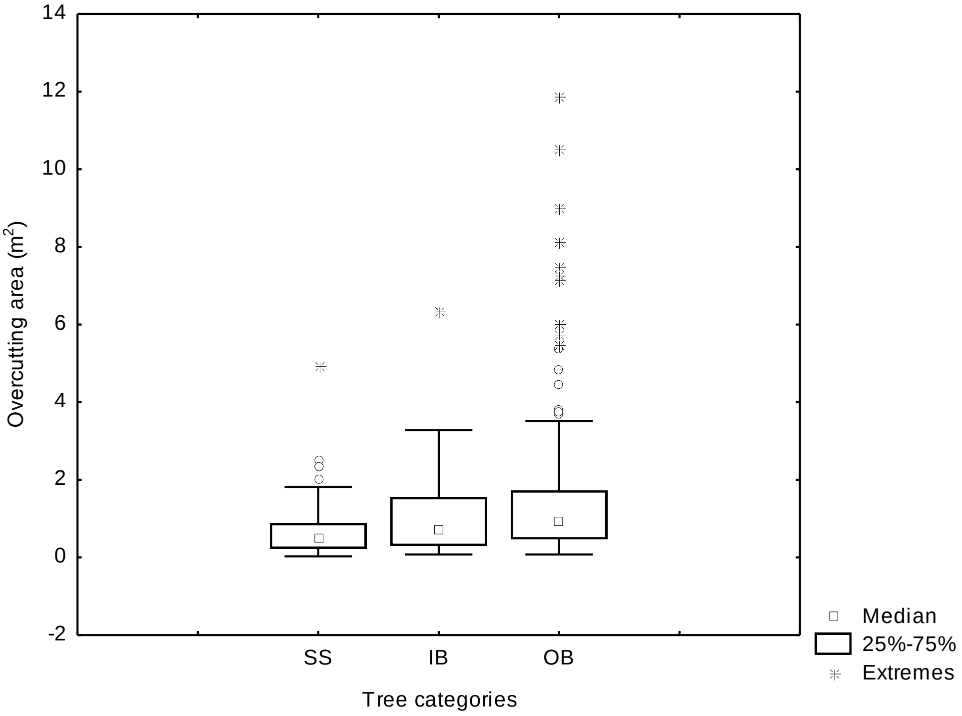


Figure 51: Overcutting area variation among categories derived from right-triangles above bank trees (SS = Straight Section, IB = Inner Bend, OB = Outer Bend).

The search for relationships explaining a possible dependency of overcutting area on tree diameter has produced a non-statistically significant result (p-value = 0.43), underscoring the inability of tree size to influence erosion above bank trees.

7.3.4. Incidence and magnitude of scallops

The analysis of bank profile spaces between consecutive trees has revealed a strong abundance of concave gaps, so called scallops, along the different morphological segments of the river (Fig. 52). Overall, mixed and concave gaps strongly prevail in the three bank types. In particular, scallops register a net predominance in outer bend areas with 59% over the total tree gaps.

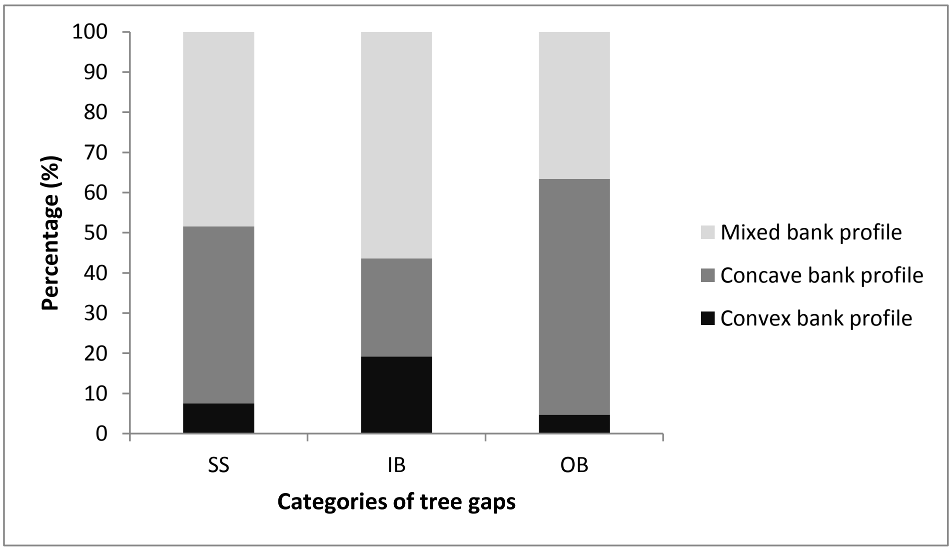


Figure 52: Configuration of bank profile spaces among categories (SS = Straight Section, IB = Inner Bend, OB = Outer Bend).

After identifying scallops as major components of bank profiles, especially in outer bends, an interesting focus on their depth among bank types is given in Fig. 53. Despite an initial hypothesis which believed outer bend scallops as characterized by deeper peaks, descriptive statistics has demonstrated a surprising trend. In fact, scallops in inner bends show the highest variance and median (1.5 m) of depth, substantially higher than outer bend scallops (median of 0.9 m). Scallops on straight sections of the stream register the lowest variance and median (0.8 m). Nevertheless, inner bend scallops account for the smallest number of observations over the three categories, source of possible interpretation errors.

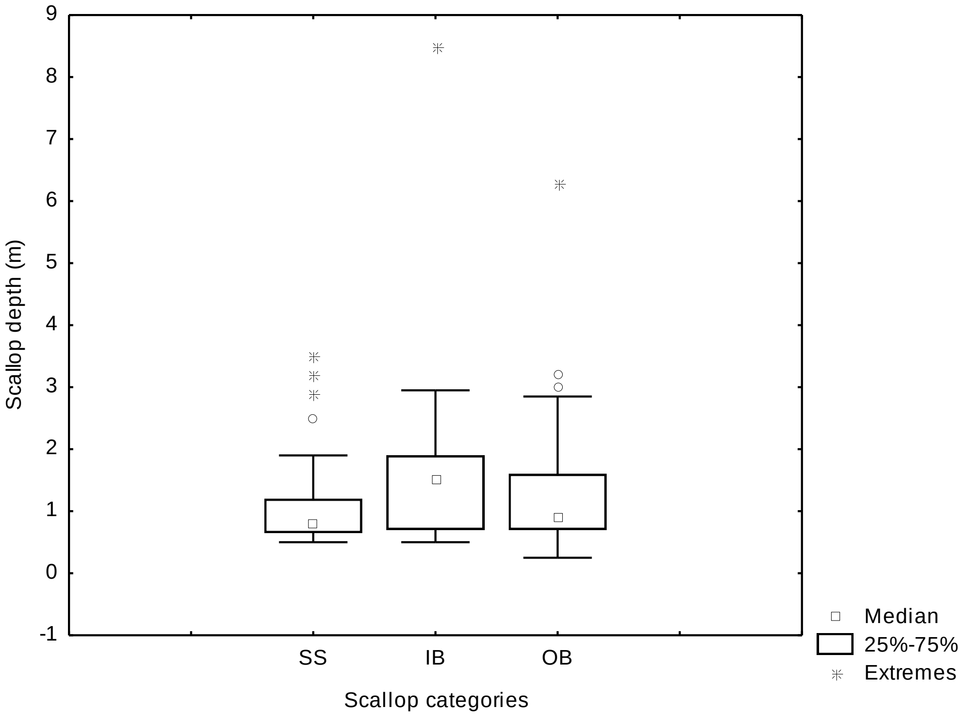


Figure 53: Variation of scallop depth among categories (SS = Straight Section, IB = Inner Bend, EB = Outer Bend).

7.3.5. The control of trees on outer bend scallops

The analysis of the impact of scallops on the different bank types of the King River has highlighted their strong contribution in shaping especially outer bend profiles. These areas are generally affected by the highest stream flow velocities and potential shear stresses, representing the most dynamic segments for the channel to migrate and remove bank soil. Therefore, we believe outer bends to have the greatest potential for exploring relationships between bank tree characteristics, in particular size and spacing, and scallop development. The search for dependencies along outer bends explaining the control of trees on bank retreat evolution is further supported by the highest number of scallop observations.

The influence of tree spacing on scallop depth has proved to be statistically significant along the outer bends of the river. As presented in Fig. 54, in almost half cases ($R^2 \approx 0.42$), the increase of the distance among bank trees seems to lead to an increase of scallop depth.

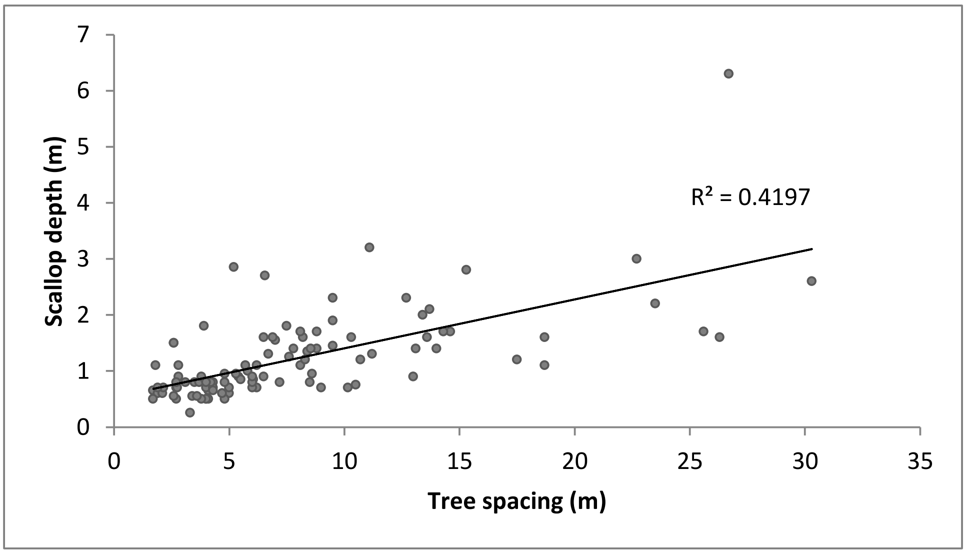


Figure 54: Influence of tree spacing on scallop depth in outer bends.

By contrast, the impact of tree size on scallop depth has showed a not statistically significant result (p-value = 0.28). Thus, the averaged diameter of the two trees on the external ends of scallops does not seem to have an influence on the extent of scallop depth.

7.4. Bank retreat evolution in forested non-cohesive riverbanks (Piave River)

7.4.1. Introduction

Bank trees and gaps investigated on the Piave River (Belluno reach) have accounted for a total number of 101 trees and 97 scallops that were surveyed along four arched bank profiles. The analysis of specific tree and scallop parameters was considered important also for further comparison between different types of fluvial systems (i.e. with the King River). Riparian vegetation presents a marked species variability on the Piave River with a predominance of black locust (*Robinia pseudoacacia*), ash (*Fraxinus excelsior*) and hop hornbeam (*Ostrya carpinifolia*) trees. All the dataset was acquired solely in the bank areas featuring scalloped longitudinal profiles, or rather riverbank portions characterized by lateral erosion processes between trees. Therefore, no subdivision of bank profile features into categories related to the membership to river morphological units was carried out. The main partition of data was in this case due to the presence of "bank-top" trees, right on the upper crest of the bank profile and of "inner-bank" trees located at some distance (up to 2 m) from the bank-top edge. Consequently, also scallops were divided according to the combined position of their side-trees in: "inner-bank" with both side-trees featuring at a distance from the bank crest, "mixed" with one side-tree at some distance and the other on the bank-top, and "bank-top" with both edge-trees located on the bank crest.

7.4.2. Scallop development

The analysis of data has revealed no statistically significant relationships indicating any dependency of scallop depth on combined distance or diameter of side-trees. Despite a lacking influence of side-trees characteristics on the development of bank retreat processes, an interesting result is provided by the variation of scallop depth among the above-mentioned categories. As depicted in Fig. 55, scallops delimitated by inner-bank trees feature the highest average scallop depth (median = 1.03 m), while mixed scallops register the greatest variance and the second highest scallop depth (median = 0.9 m). Finally, scallops characterized by trees located on bank-top feature the lowest average scallop depth with a median of 0.82 m.

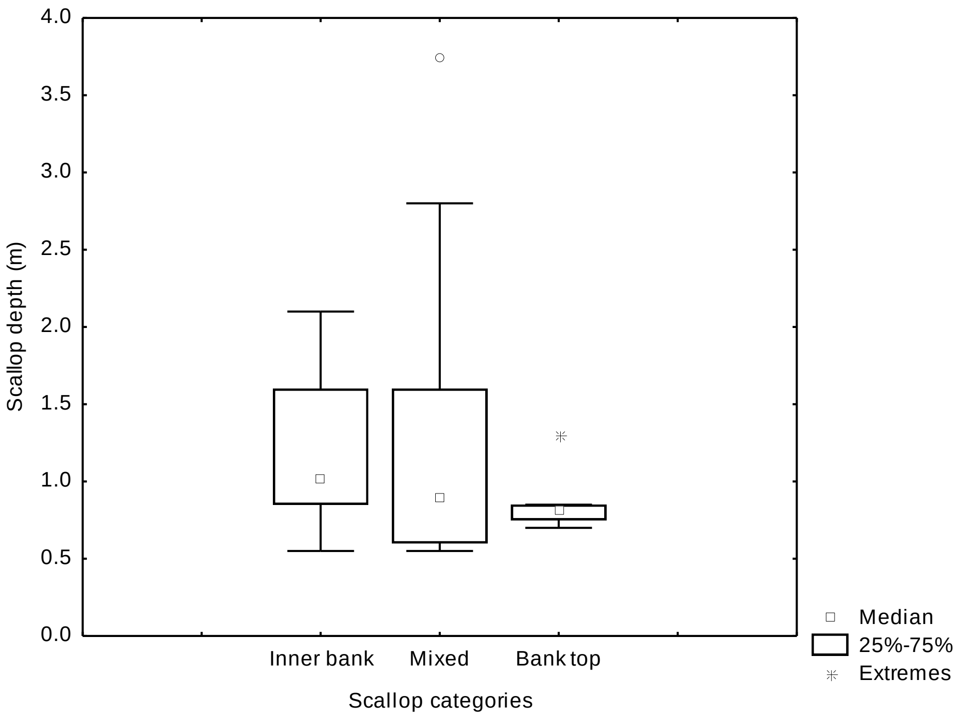


Figure 55: Variation of scallop depth among scallop categories: Inner-bank, mixed and bank-top.

The analysis on the influence of tree spacing on scallop depth has further revealed a statistically significant relationship. Fig. 56 shows how, with a R^2 = 0.69, tree spacing seems to be proportionally correlated to scallop depth. In more than half cases, scallop depth appears to be explain by variation in tree spacing, suggesting a fairly regular and progressive development of scallop erosion along riverbanks.

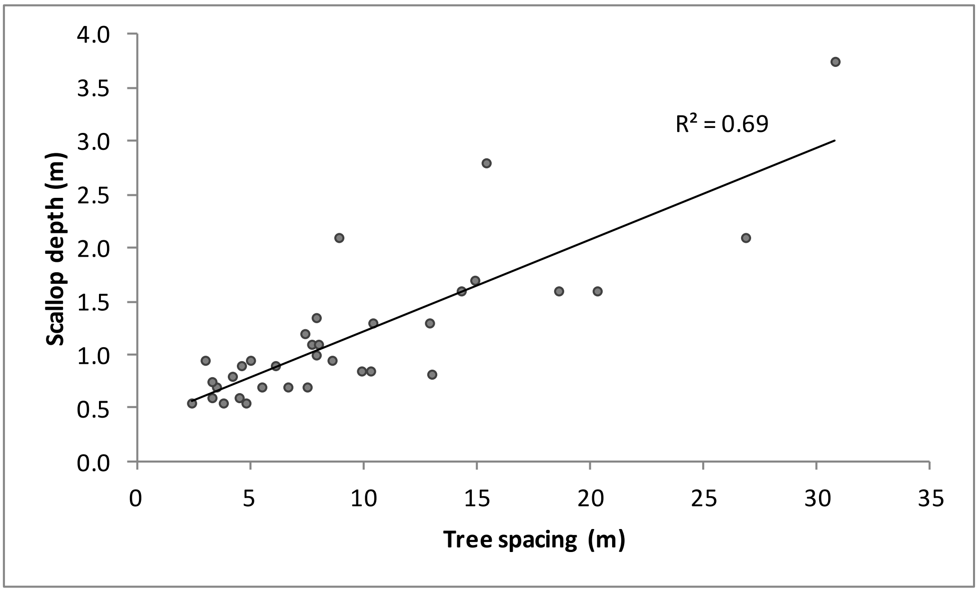


Figure 56: Influence of tree spacing on scallop depth.

8. DISCUSSION

8.1. Flooding and morphological trends on the Piave and Tagliamento rivers (Italy)

8.1.1. Are floods below bankfull discharge able to cause significant geomorphic changes?

The flood events that have affected the Piave and Tagliamento rivers in 2010 were classified as below or maximum equal to bankfull discharge. Despite past beliefs indicating only severe flood events well above bankfull stage as able to produce important morphological variations, the results of this research have pointed out that also fairly normal flood pulses can cause large geomorphic changes. In fact, visual interpretation and volumetric estimates reflect significant impacts induced by these flood events that, in several cases, have undermined stably vegetated areas of islands or riverbanks. This trend is confirmed by Bertoldi et al. (2010) and Surian et al. (2014) that show as flood pulses well below bankfull discharge have a crucial role on the morphological evolution of gravel-bed rivers.

8.1.2. Sediment patterns and influence of natural and artificial constrains

The balance of sediment remobilized during 2010 floods has delineated different trends in the study reaches of the Piave and Tagliamento rivers. In both cases, the net prevalence of erosion processes (sediment deficit) in the uppermost reaches (Belluno and Cornino) has decreased going downstream with Praloran (Piave River) featuring an almost equilibrated situation and Flagogna (Tagliamento River) accounting for a predominance of aggradation. These results seem to be in line with recent research about morphological changes occurred in these rivers in the last decades. In fact, Comiti et al. (2011) for the Piave River and Zanoni et al. (2008) for the Tagliamento River, have carried out multi-temporal analyses observing the change of various parameters, including active channel area and island dynamics. After a prolonged period of channel narrowing and incision probably due to now ceased mining activities that have created a deficit of sediment input in the area (especially in 1970-1990 time lapse), the two streams seem to experience, at this stage, a process of natural recovery. The last two decades have underscored a new phase of widening and aggradation that appears to last also thanks to the current reduced human impacts on these fluvial environments. Our estimates of geomorphic changes, even reporting a general imbalance in favour of erosion effects, generally confirm a trend towards sediment equilibrium that is achieved and also overtaken in the two downstream reaches (Praloran and Flagogna).

The magnitude and dynamics of geomorphic changes may be also influenced by peculiar characteristics at reach scale. Topographic heights, riparian vegetation and confinement degree of the channel may highly change areal and volumetric patterns of sediment mobilization. As we can observe in the surface differencing models, the two downstream reaches (Praloran and Flagogna) feature a higher degree of natural constrains in respect to the two uppermost sites (Belluno and Cornino). The channel is strongly confined on their left side from topographic reliefs and on the hydrographic right from stably vegetated areas, being no longer able to expand during flood events. This is further evidenced also by the volumetric estimates of change that present lower amounts of total mobilized sediment in respect to the uppermost reaches.

Geomorphic changes may be influenced also by human interventions. From the two major bank erosions analysed in Belluno reach we can derive a common trend: the areas interested by bank erosion processes appear to feature similar dynamics downstream of longitudinal protections. In this case, the installation of boulder structures to prevent lateral migration of the channel appears not effective or thought within a comprehensive strategy. In fact, the issue of eroding banks seems to have been shifted downstream and, potentially, upstream of the second longitudinal intervention a growing lateral erosion is threatening, beside the marginal field, also the own existence of the artificial structure. In this sense, we can infer that longitudinal bank protections could have led, during the floods, to an increase of water velocity through a "channelization effect" that, shifting flow and erosion processes downstream, has intensified the eroding potential enabling the mobilization of a larger amount of stable soil.

8.1.3. Main channel reconfiguration and restoration insights

The interpretation of DoD models and related volumetric estimates indicate an almost complete rearrangement of the main flowing channels after 2010 flood events. The flowing channels present in 2010 have undergone large deposition and newly scoured channels have formed in 2011. This sudden change of flowing path has led, in turn, to a slight increase in Sinuosity Index (SI) and also to the removal of stably vegetated riverbanks thus contributing to modestly enlarge the active channel area. The results on main channel reconfiguration and vegetation removal are in line with similar researches analysing the Tagliamento River, as Bertoldi et al. (2010) and Surian et al. (2014). The first study has confirmed the role of low-magnitude floods in generating a strong rearrangement of the channel network, further underscoring the unpredictable nature of these sudden changes that are among the greatest suffered by a river under flood conditions. The second research has instead emphasized the occurrence of significant vegetation erosion under relatively frequent and low potential floods (i.e. $1 \leq$ R.I. $\leq$ 2-3 years), identifying hydrological thresholds for vegetation removal and turnover. These findings seem to re-evaluate the current point of view on the role of flooding on geomorphic and vegetation dynamics: if, so far, most of studies have underlined the need of relatively large floods to induce important soil and vegetation erosion (Bertoldi et al., 2009b; Comiti et al., 2011; Mikus et al., 2013), these novel findings seem to support the idea of a significant control exerted by minor and frequent floods on geomorphic changes, especially in less-constrained and higher energy environments (i.e. Tagliamento River).

Sudden changes in main channel position seem to be highly unpredictable and consequently represent a threat in populated areas. Fluvial environments that are allowed to keep their evolutionary space (i.e. erodible fluvial corridor concept) can freely move without producing particular concerns. Nevertheless, especially in Europe, the most part of rivers feature artificially-reduced active channels as well as many infrastructural constrains that generate high hazard levels under flood conditions. Although the driving factors causing abrupt adjustments in main channel planform are still unknown, an explanatory guess could be the actual mobility of bed sediment in river systems, especially on gravel-bed rivers. In fact, marked main channels may feature bed conditions difficult to change maybe due to greater grain sizes or armouring effects. On the other hand, during flood events, the active channel undergoes a complete submersion and bars beside the old main branch may represent easier paths for sediment to be remobilized by fluvial scour. This removal could finally lead to the creation of a new and lower bed-level, diverting a large amount of flowing water and thus forming a novel main flowing channel at low stage.

Survey difficulties and unpredictability of this phenomenon may undermine its research; nevertheless more efforts are needed to increase the knowledge and prevision of channel configuration shifts. Increasing the understanding on channel planform dynamics would represent a benefit for most protection and restoration projects to effectively mitigate flood hazard and promote evolutionary space for river systems.

8.2. New perspectives towards a novel conceptual model of bank retreat evolution (King River)

8.2.1. Introduction

Results on the King River have revealed new and more complex processes and relationships on the evolution of forested riverbanks. These innovative perspectives should be included in future bank retreat modelling. The present study has tried to go beyond some limitations emerged from Pizzuto et al. (2010) model that has summarized bank retreat in three main stages:

1. Stage 1: Trees grow on the floodplain away from any erosion effects;
2. Stage 2: Erosion between the root plate of trees is accelerated producing scallops between abutments;
3. Stage 3: Over 5 to 15 years the scallops increase in depth until they generate "recirculating eddies" between the abutments which accelerate erosion of the abutment. Also in this stage, the tree abutment gradually slides from the top of the bank, down the bank face, and the tree leans toward the river, increasing the duration of fluvial scour until the tree is undermined and topples into the river bed.

In the following discussion, the main advances developed by this research on bank migration will be treated, forming integral parts of a more comprehensive conceptual model to describe bank retreat evolution in forested and cohesive riverbanks.

8.2.2. Position of trees on the banks

Pizzuto et al. (2010) found that riparian trees grew on the banktop. On the King River, most of the trees *(Eucalyptus camaldulensis)* grew on the bank face (Fig. 57). A possible explanation may be related to both the establishment process of red gums and the specific hydrological regime of South-Eastern Australian rivers. River red gums generally establish in the river bed. The highly variable hydrological regime of the King River, dominated by strong seasonal water-stage differences with winter flooding and spring-summer flood recession may promote high rates of seed germination. When prolonged winter floods retreat, bank soil is left moist and soft, allowing seedlings to establish along the summer months characterized by a stable low water stage, and thus supplying good survival conditions (Dexter, 1967; Di Stefano, 2002). Further, the strong dynamism of the channel may allow the King River to migrate toward forested floodplain or to re-occupy old channels with trees already located at a lower elevation in respect to the adjacent land. In any case, bank retreat models need to accommodate trees growing on the bank face as well as the bank top.

Figure 57: Example of trees located on bank face (King River).

8.2.3. Tree failure by fluvial scour

Erosion around trees on the bank face is more complex than described by Pizzuto et al. (2010). They described progressive undercutting until the tree gradually slumps down into the river. By contrast, on the King River, erosion occurs both above and below the root plate. The tree does not gradually slump into the river instead the root plate is gradually exhumed by erosion until it is completely exposed. Eventually it is outflanked by erosion and simply topples into the river. Failure is not by mass failure, but by fluvial scour of cohesive sediments.

Beside undercutting, the observed erosion above trees called overcutting strongly contributes to scour the root plate. Particularly on outer bends, the most susceptible areas for bank migration as high flow velocities are responsible of enhanced shear stresses (Pizzuto, 2009; Engel and Rhoads, 2012), fluvial scour may undermine root plate stability through flow hydrodynamic processes. In fact, the splitting up of the stream flow against static elements as tree trunks and root plates may create localized turbulence and, thus, enhance scour potential (Mcbride et al., 2007).

8.2.4. Scallop development

The analysis of bank profile spaces between riparian trees has revealed more complex characteristics and patterns in respect to those described by Pizzuto et al. (2010). Tree gaps can have three different planimetric configurations according to the relation between their profile and the straight line identifying tree spacing: convex, mixed and concave. Further, an important aspect to be considered is the bank segment where these features are located. In fact, different bank types associated with distinctive morphological units of the channel (straight section, inner and outer bends) have reported high variability in tree gaps typology and magnitude. Convex bank profiles, called scallops, have a major incidence in all three bank categories, nevertheless they strongly predominate in outer bend profiles. This may be related, as in the case of scour around trees, to the higher shear stresses affecting these sections on the channel.

Accounting for the highest number of observations and more pronounced erosional processes, outer bend scallops were chosen to test our hypotheses: the dependency of scallop depth on tree size and spacing. Tree size has demonstrated to be not statistically significant, excluding a direct influence of tree diameter on the development of scallop. By contrast, tree spacing has revealed a statistically significant relationship with scallop amplitude, explaining in almost half cases the growth of scallop depth. In this sense, for about half observations the greater the tree spacing, the higher the scallop depth.

Finally, the hydraulics of scour enlarging scallops seems to differ from flow recirculation patterns proposed by Pizzuto et al. (2010). In fact, recirculating eddies are unlikely able to induce effective sediment removal due to the reduced water velocity affecting these areas that may instead promote deposition (Sukhodolov et al., 2002; Vietz et al., 2012). By contrast, the impact of bankfull discharges on wooded elements (either trunk or root plate) may promote, through flow separation, water velocity increase beyond riparian vegetation and enhance scour potential around scallops. Thus, scallop enlargement may be due to increased near-bank velocities of the flow related to the presence of obstacles, similarly to hydrodynamical patterns observed in bendway weirs (Abad et al., 2008) or groyne fields (Sukhodolov et al., 2002).

8.2.5. A novel conceptual model of bank retreat in forested cohesive riverbanks

The analysis of bank profile processes on the King River has revealed new elements and relationships to be considered in the description of bank retreat evolution in forested cohesive riverbanks, especially focusing on outer bends. The conceptual model proposed by Pizzuto et al. (2010) can be improved by: i) Adding a case where the trees grow on bank face, ii) Adding fluvial scour (including overcutting) as major process leading to tree toppling and scallop enlargement, iii) Adding relationship between tree spacing and scallop dimensions.

In this context, a novel and more comprehensive conceptual model describing bank retreat development in forested cohesive riverbanks is presented. The model illustrates bank migration of outer bends, nevertheless its design can be useful also to interpret riverbank behavior in straight sections of rivers. Banks located on inner bends are excluded from this model as they present few scallops and undergo extremely different hydrological and sediment transport processes.

The model consists of three stages where bank trees slowly become isolated from the bank face creating abutments that will eventually fall into the channel due to scour around their root plates (Fig. 58). In the first stage, most trees feature on the bank face at a certain distance from the banktop line, with few exposed roots toward the channel due initial phases of fluvial scour. Tree gaps on the bank profile are characterized by arch-shaped erosional features, called scallops, that present a higher deviation (depth) in respect to the linear distance between bank edges behind consecutive trees. After prolonged bankfull stages and flooding periods, fluvial entrainment due to high flow velocity and consequent shear stress along the outer section of bends, removes soil above (overcutting) and below (undercutting) the root plates, exposing more and more root systems. During this stage (Stage 2), trees start to lean and destabilize, condition that is enhanced by the progressive greater number of exhumed roots that contribute, in turn, to promote turbulence and scour. When root plates become too much exposed to hold tree structure, bank trees will eventually fall at different stages into the channel depending on their resistance to progressive instability (Stage 3). Tree failure will also cause the detachment of the bank material hooked by the remaining roots and previously attached to the bank face. Scallops that were enlarged by subsequent flood periods, will suffer now a reshaping that will create a long smooth arch regulating the entire bank profile, now free from abutments resistance. In the case new seedlings were able to establish and germinate, or migrating banks are encountering new trees on bank top, the cyclic evolution of bank retreat will keep shaping outer bends.

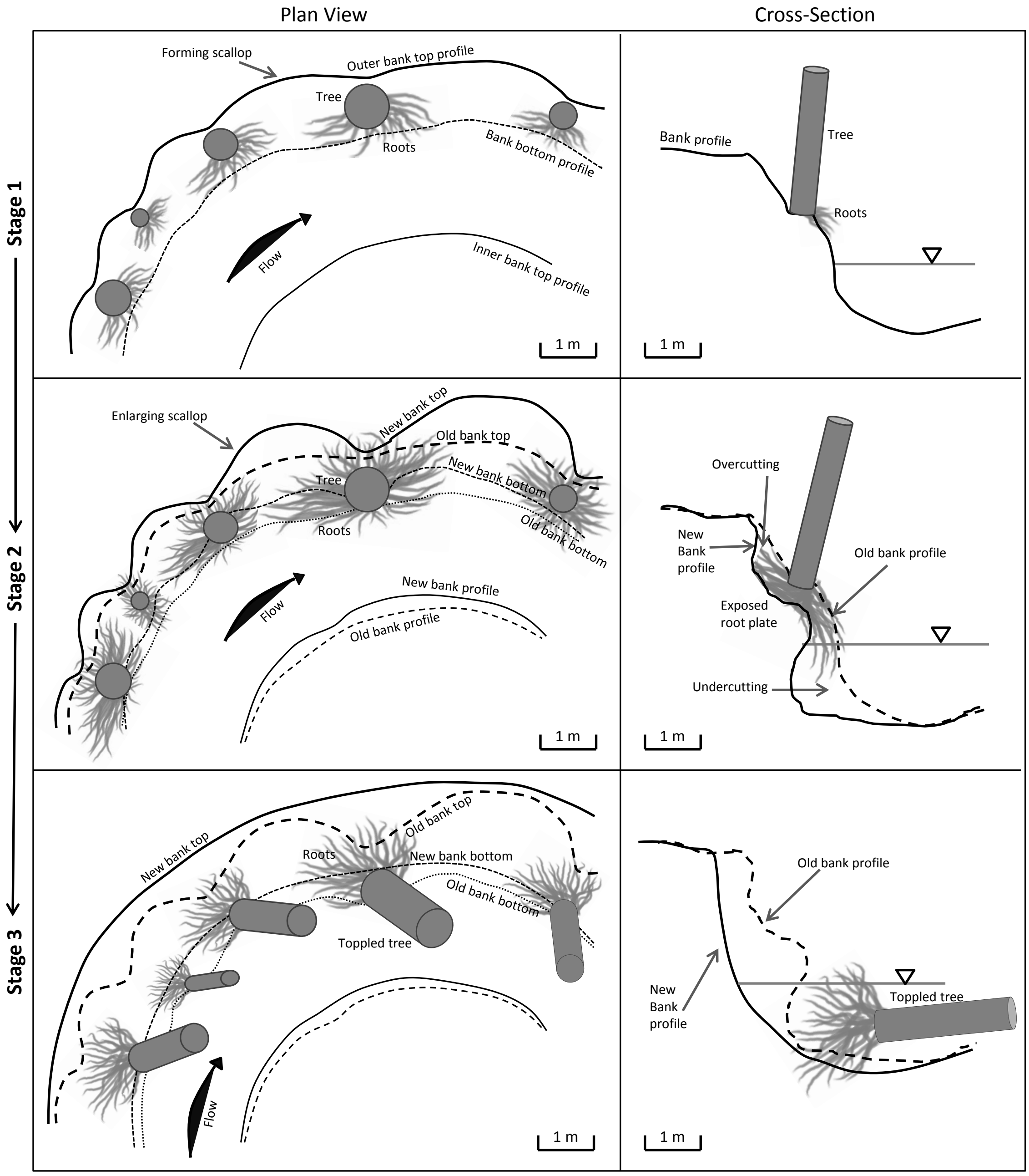


Figure 58: Planform- and cross-sectional views of bank retreat evolution in outer bends characterized by forested and cohesive riverbanks.

The conceptual model does not pretend to explain extensively bank retreat processes in all forested riverbanks, but it was thought to better describe bank migration in outer bends characterized by fine sediment and the presence of large and spaced trees. Fluvial environments featuring seasonally variable hydrological regimes will benefit at most from this bank evolutionary model that offers anyway new interesting insights for further research opportunities.

8.3. Bank retreat evolution on the Piave River and final comparisons

The results have reported few dependencies among the considered tree and scallop characteristics. Considering the scarcity of scalloped bank profiles on the Piave River, the analysis of the variation of scallop depth among categories describing the location of bank trees (bank-top, mixed or inner-bank) has demonstrated suitable to investigate the control of riparian vegetation on bank retreat development. Significant findings have confirmed the higher influence of trees located on the bank-top to prevent bank removal probably due to the enhanced cohesion given by root plates. In the study, trees located up to 2 m far from the bank crest were considered, as their roots may be able to interact and affect bank face dynamics. Moreover, the development of scallops has showed to be fairly strong influenced by tree spacing that in more than half cases explain their growth.

Many differences on bank retreat dynamics can be observed between the King and the Piave rivers. Starting from their riparian vegetation structure, a first basic discrepancy regards the position of trees on banks. If in the King River, trees feature on the top or face of the banks with root plates generally exposed at some degree, in the Piave River they are located on the top, or more frequently, at an inner distance from the bank crest and little or no root exposure is present (Fig. 59). This characteristic influences in turn the impact of hydraulic processes affecting bank vegetation and sediment that seem to suffer very different removal processes in respect to those exposed in the novel conceptual model targeted for low-gradient streams characterized by cohesive soils.

The search for relationships linking scallop depth to bank tree characteristics has allowed to identify common patterns in the two fluvial systems. In both rivers, tree size is not affecting the development of scalloped bank profiles. By contrast, tree spacing has demonstrated to explain at some degree the evolution of scallops along riverbanks. Specifically, the distance of riparian trees appears to influence more scallop depth on the Piave River ($R^2 = 0.69$) in respect to the King River ($R^2 = 0.42$). This might be due to the less structural stability of non-cohesive sediment that with a low degree of adherence can easily be scoured away or fall down the bank face. Further, the characteristics of the root plates on the Piave River might reduce at a higher degree their cohesion effect at a certain distance from the trees. By contrast, at the same distance the root configuration and cohesive soil of the King River are likely to provide banks with an enhanced resistance, producing more variability in the development of scallops.

In any case, these results are in line with studies on vegetation mechanics that illustrate a progressive decrease of soil cohesion given by roots with increasing spacing from tree trunks (Wynn et al., 2004; Docker and Hubble, 2009).

Figure 59: Example of scallop and inner tree in the Piave River.

Despite the difference in amount of data collected and functioning dynamics, the King and the Piave rivers offer interesting possibilities of comparison. In Fig. 60 we can appreciate the comparison of scallop depth between the outer bends of the King River and the four arcs in active bank erosion of the Piave River. King River's scallops show a greater variance maybe enhanced also by the higher number of observations. Both rivers present the same average scallop depth with a median of 0.95 m. The difference in variance might express again the ability of cohesive bank profiles (King River) to contrast more efficiently a hypothetical geometric development of scallops depending on tree spacing.

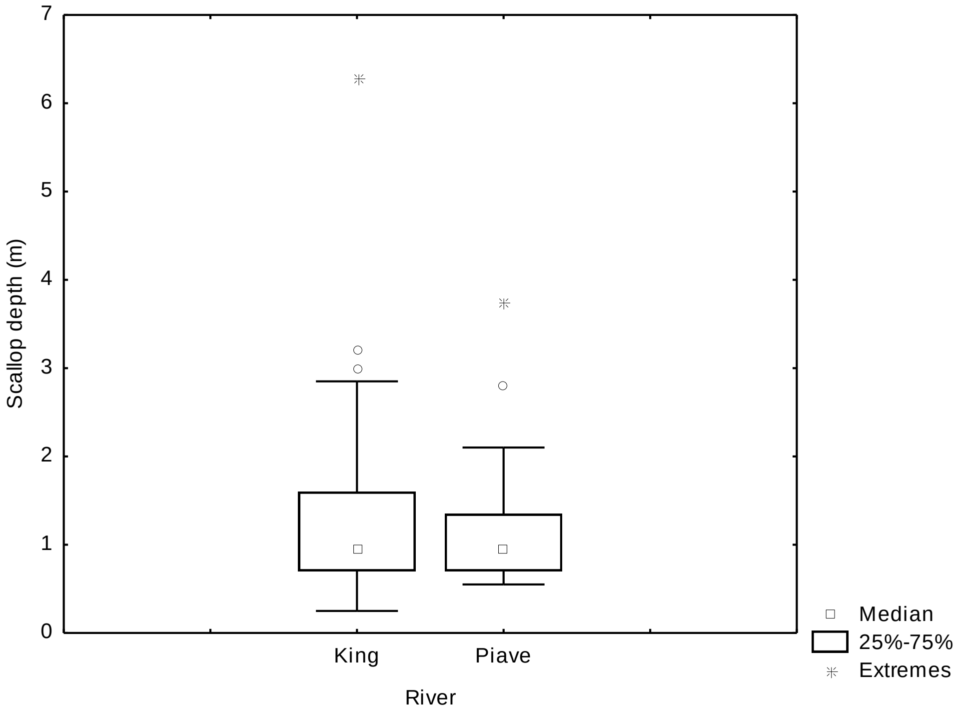


Figure 60: Comparison of scallop depth between the King and the Piave rivers.

A further comparison has the purpose of connecting two apparently different bank sections of the two river systems that we thought to be comparable in terms of scour patterns. In fact, even considering the proper scale and configuration assumptions, outer bends of the King River and the arched bank profiles found on the Piave River have the potential to reveal comparable dynamics. In Fig. 61, the average tree spacing at bend- (King River) and arc- (Piave River) level is plotted to explain the average scallop spacing. Outer bends and arched banks are thought as individual elements, assuming that their measured scallops (depth > 0.5 m) are ordered in a sequence. Total tree spacing for each bend/arc is divided by the number of acting trees and then compared to the average scallop depth of that bend/arc. Despite the evident lower number of elements for the Piave River, the two fluvial systems confirm to have fairly comparable magnitude of scallop processes. King River's bends show a similar degree of influence produced by tree spacing ($R^2 = 0.45$) to that resulted by considering all scallops together (Fig. 54). By contrast, Piave River's arcs report a significantly higher relationship explaining scallop depth ($R^2 = 0.82$) than that featured without this morphological subdivision (Fig. 56). Reaching almost the double degree of correlation in respect to King River's case, scallop processes on the Piave River seem to need to be handled at arc-scale to provide more meaningful results.

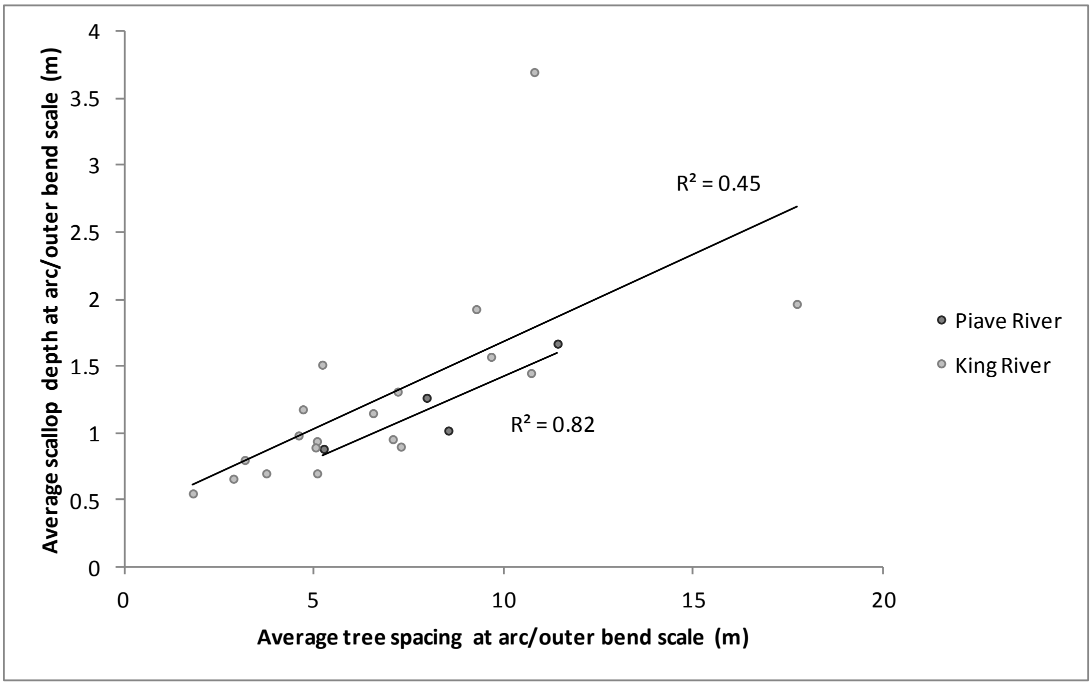


Figure 61: Impact of average tree spacing on average scallop depth at arc/outer bend scale (King and Piave rivers).

The more comprehensive and clear explanation of the common and distinctive patterns of bank retreat expressed by these two fluvial systems is probably included in their different functioning dynamics. The larger spatial extent, topographic gradient, flow regime of the Piave River along with its non-cohesive sediment composition, seem to strongly influence the morphological response of this system to flood events that can be very impacting also at discharges below the bankfull. For this reason, especially during floods, the role of bank trees in reducing bank retreat processes can be outclassed by the force of fluvial scour that can erode large portions of riverbanks, as occurred in Belluno reach (lateral shift of 60 m, see in results).

Despite the lower control exerted during floods, the study of the interaction between riparian vegetation and bank retreat processes in gravel-bed rivers represents a key aspect in the understanding of lateral adjustments in these very dynamic environments. Recent research on such fluvial systems has focused more the attention on planimetric variations and island removal (i.e. Comiti et al., 2011), neglecting to consider the development of bank retreat in forested non-cohesive riverbanks. Future research opportunities could take advantage from high-resolution topographic surveys, as TLS (Terrestrial Laser Scanning) mapping, to verify empirical findings and enhance our knowledge of bank retreat evolution with non-cohesive sediment conditions.

9. CONCLUSIONS AND FINAL REMARKS

9.1. Key research findings and messages

The PhD research has reached the overall goal of precisely estimating and interpreting short-term geomorphic changes caused by below-bankfull floods on the Piave and Tagliamento rivers. The evaluation of bathymetric accuracy in the enhanced DoD models has allowed to effectively isolate real topographic changes that have mostly affected perennial underwater areas as main flowing channels. Associated sediment estimates have underscored a general balance deficit; even though more equilibrated trends towards sediment equilibrium seem to take place in the most downstream reaches. Moreover, the most significant processes affecting main channel shifting and lateral erosion of forested areas have been successfully analysed, showing the potential of floods below bankfull condition to markedly adjust the main channel network, even removing stable portions of the river corridor. The study on the King River, an Australian stream characterized by marked scalloped riverbanks, has then given us the chance to focus and explore bank retreat processes in vegetated banks. The identification of novel characteristics and processes affecting bank retreat evolution has deepened our understanding of retreating riverbanks characterized by cohesive sediment and large spaced trees. The study has delineated the following main innovative aspects: the predominant position of trees on bank faces, the role of fluvial scour as main erosional process undermining tree stability and the major contribution of scallops in shaping retreating bank profiles. Tree spacing has demonstrated to moderately influence the extent of scallop depth. All these elements should be included in bank retreat modeling as they depict crucial processes which exclusion can lead to misleading description of bank dynamics as well as erosion rates.

The results reached in this study have further tried to fill some gaps identified in the research of Pizzuto et al. (2010), encouraging us to create a more comprehensive conceptual model to explain bank retreat evolution in forested cohesive riverbanks. The model fits the best to outer bend profiles of riverbanks characterized by strong migration dynamics and highly variable hydrological regimes. Further improvements to the model are possible, maybe considering additional physical aspects as, for example, the variation of erosion pattern along the bend due to the change of curvature radius. Despite its empirical foundation, this model may represent a great help for river managers to handle with fluvial controversial issues as bank retreat processes.

New findings have finally been confronted with riverbank processes on the Piave River. Even accounting for a lower extent of erosional bank profiles and several physical differences as non-cohesive sediment composition, bank tree spacing has confirmed to influence also in this case scallop depth. Comparisons between King and Piave rivers have showed similarities in the magnitude of bank retreat processes, underscoring a stronger dependency on tree spacing at bend/arc scale by the Piave River.

The results of this study have pointed out crucial aspects in the process of enhancing our understanding of river systems. Key research findings are represented by the verified potential of floods below bankfull discharge to consistently impact river channel morphology, producing multi-scale changes and remobilizing large amount of sediment. Further, the role of riparian vegetation in reducing bank retreat through bank tree spacing has been confirmed. These advances may represent a great help for river experts that, thanks to this additional fragment of knowledge, can have at their disposal meaningful and accurate tools to target more effective river protection and management strategies, within the delicate task of dealing with fluvial systems.

In detail, the main conclusions of this research can be summarized and outlined as follows:

Piave and Tagliamento Rivers (Italy)

- Flood pulses below or equal to bankfull discharge have caused considerable geomorphic changes;
- The evaluation in GCD modelling, among the inputs, of in-channel elevations derived by colour bathymetry has allowed to achieve more accurate estimates of true change, especially within channel wet areas where most of the sediment has been remobilized;
- Trends concerning sediment balance have underscored a predominance of erosion processes during 2010 flood events, expect for Flagogna reach (Tagliamento River), decreasing going downstream. This has confirmed a still ongoing sediment deficit at reach scale even within a slight recovery phase, in line with other recent studies;
- Main flowing channels (active at low-flow stage) have undergone an almost total rearrangement after the flood events, increasing their sinuosity index;
- The floods have caused major bank erosions of stably vegetated areas (Belluno reach, Piave River), possibly amplified by the effect of upstream longitudinal protections;
- Bank retreat dynamics in forested non-cohesive (gravel) riverbanks (Piave River) have showed a higher influence of trees located right on bank crest and closely spaced to reduce scallop depth.

King River (Australia)

- The process of bank retreat and the role of vegetation contrasting fluvial scour has been effectively isolated and quantified;
- A new perspective, never considered before, related to the starting position of trees on bank top was found;
- Tree toppling was found to be caused by fluvial scour around bank trees both above (overcutting) and below (undercutting) root plates;
- Significant relationships between tree and scallop characteristics have confirmed tree spacing as an important factor in influencing the magnitude of bank retreat;
- A novel and more comprehensive conceptual model describing bank retreat of forested and cohesive riverbanks was successfully developed.

9.2. Recommendations for future research

The significant findings reported in this research have deepened the comprehension of crucial aspects related to river systems; nevertheless they have also uncovered some theoretical and operational limitations as well as new opportunities for future research. In the first phase of the study, despite the use of integrated topographic surveys have allowed to accurately reproduce the entire active channel including below-water areas, some vegetated patches, lately manually filtered, have registered erroneous and misleading elevations due to their compactness. This error type as well as other uncertainty sources developed in the progressive phases of interpolation and modelling need to be carefully evaluated if meaningful estimates of geomorphic changes are pursued. Volumetric estimates delineating sediment remobilization during flooding have reported significant geomorphic trends. Such patterns are crucial to understand the actual condition of fluvial systems; nevertheless they represent only a static picture that requires sediment transport (input and output) information to be comprehensive. Few attempts to describe a total sediment budget of a river reach have been published in the recent years; anyway their very high uncertainty suggests that more efforts are needed to reach trustful approximation of sediment dynamics. The focus and understanding of bank retreat dynamics in vegetated riverbanks have added essential knowledge to a process that represents one of the major issues in fluvial geomorphology. A viable opportunity to better describe its complexness might be the integration of digitalized riverbank profiles thanks to very detailed topographic devices. Laser Scanning possibly represents one of the best instruments to reach this goal, uncovering vast opportunities for future research. A final comment is dedicated to the issue of comparing different fluvial environments. Conventionally, the analysis and confrontation of empirical theories and physical results between different river systems stand for a unique chance of discovering surprising patterns towards more comprehensive scientific findings. If this consideration is extremely true, it is also real the fact that comparing river components and processes directly or indirectly affected by a wide range of side variables represents a risk that can lead to misleading results. For this reason, the research of analogies between fluvial patterns and dynamics needs to be carefully meditated, highlighting with deep considerations all the aspects influencing common and individual results.

10. ACKNOWLEDGEMENTS

"Important thing in science is not so much to obtain new facts as to discover
new ways of thinking about them."

- Sir William Bragg

My PhD path has represented an incredibly rewarding experience, leading to discover how fascinating science and research are, even though facing some initial issues and doubts as natural. Becoming aware that all issues have multiple ways to be thought and solved, and becoming more critical with the reality around me, are the two main teachings that I have learned from this life's chapter. Sure of the tremendous enrichment, both academic and personal, that this adventure has meant to me, I deeply hope to have the opportunity of cultivating my passion on river research in the future.

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Fabio

11. REFERENCES

Abad, J.D., Rhoads, B.L., Güneralp, I., Garcia, M.H., Asce, M., 2008. Flow structure at different stages in a meander-bend with bendway weirs. Journal of Hydraulic Engineering 134 (8), 1052-1063.

Abbe, T.B., Montgomery, D.R., 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers: Research and Management 12, 201-221.

Abernethy, B., Rutherfurd, I.D., 2000. The effect of riparian tree roots on the mass-stability of riverbanks. Earth Surface Processes and Landforms 25, 921-937.

Abernethy, B., Rutherfurd, I.D., 2001. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. Hydrological Processes 15, 63-79.

Allmendinger, N.E., Pizzuto, J.E., Potter Jr., N., Johnson, T.E., Hession, W.C., 2005. The influence of riparian vegetation on stream width, eastern Pennsylvania, U.S.A. Geological Society of America Bulletin 117, 229-243.

Arscott, D.B., Tockner, K., Ward, J.V., 2000. Aquatic habitat diversity along the corridor of an Alpine floodplain river (Fiume Tagliamento, Italy). Archiv für Hydrobiologie 149, 679-704.

Arthington, A.H., Bunn, S.E., Poff, N.L.R., Naiman, R.J., 2006. The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications 16 (4), 1311-1318.

Ashmore, P.E., 2001. Braiding phenomena: statics and kinetics. In: Mosley, M.P. (Eds.), Gravel-bed Rivers V. New Zealand Hydrologic Society, Wellington, pp. 95-121.

Ashmore, P.E., Church, M.A., 1998. Sediment transport and river morphology: a paradigm for study. In: Klingeman, P.C., Beschta, R.L., Komar, P.D., Bradley, J.B. (Eds.), Gravel-Bed Rivers in the Environment. Water Resources Publications, Highlands Ranch, Colorado, pp. 115-148.

Bathurst, J.C., Graf, W.H., Cao, H.H., 1987. Bed load discharge equations for steep mountain rivers. In: Thorne, C.R., Bathurst, J.C., Hey, R.D. (Eds.), Sediment Transport in Gravel-Bed Rivers. Wiley, Chichester, pp.453-477.

Bertoldi, W., Zanoni, L., Tubino, M., 2009a. Planform dynamics of braided streams. Earth Surface Processes and Landforms 34, 547-557.

Bertoldi, W., Gurnell, A.M., Surian, N., Tockner, K., Zanoni, L., Ziliani, L., Zolezzi, G., 2009b. Understanding reference processes: linkages between river flows, sediment dynamics and vegetated landforms along the Tagliamento River, Italy. River Research and Applications 25, 501-516.

Bertoldi, W., Zanoni, L., Tubino, M., 2010. Assessment of morphological changes induced by flow and flood pulses in a gravel bed braided river: the Tagliamento River (Italy). Geomorphology 114, 348-360.

Billi, P., 1994. Morfologia dei corsi d'acqua. Verde Ambiente 5, 61-70.

Bischetti, G.B., Bonfanti, F., Greppi, M., 2003. Misura della resistenza alla trazione delle radici: apparato sperimentale e metodologia d'analisi. Quaderni di Idronomia Montana 21 (1), 349-360.

Bischetti, G.B., Chiaradia, E.A., Epis, T., Morlotti, E., 2009. Root cohesion of forest species in the Italian Alps. Plant and soil 324 (1-2), 71-89.

Brasington, J., Rumsby, B.T., Mcvey, R.A., 2000. Monitoring and modelling morphological change in a braided gravel-bed river using high-resolution GPS-based survey. Earth Surface Processes and Landforms 25 (9), 973-990.

Brasington, J., Langham, J., Rumsby, B., 2003. Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. Geomorphology 53 (3–4), 299–316.

Brewer, P.A., Passmore, D.G., 2002. Sediment budgeting techniques in gravel-bed rivers. Geological Society, London, Special Publications 191, 97-113.

Cavalli, M., Tarolli, P., Marchi, L., Dalla Fontana, G., 2008. The effectiveness of airborne LiDAR data in the recognition of channel-bed morphology. Catena 73 (3), 249-260.

Chaplot, V., Darboux, F., Bourennane, H., Leguedois, S., Silvera, N., Phachomphon, K., 2006. Accuracy of interpolation techniques for the derivation of digital elevation models in relation to landform types and data density. Geomorphology 77, 126–141.

Chappell, A., Heritage, G.L., Fuller, I.C., Large, A.R.G., Milan, D.J., 2003. Geostatistical analysis of ground-survey elevation data to elucidate spatial and temporal river channel change. Earth Surface Processes and Landforms 28 (4), 349-370.

Charlton, M.E., Large, A.R.G., Fuller, I.G., 2003. Application of airborne LiDAR in river environments: the River Coquet, Northumberland, UK. Earth Surface Processes and Landforms 28 (3), 299-306.

Comiti, F., 2012. How natural are Alpine mountain rivers? Evidence from the Italian Alps. Earth Surface Processes and Landforms 37 (7), 693-707.

Comiti, F., Da Canal, M., Surian, N., Mao, L., Picco, L., Lenzi, M.A., 2011. Channel adjustments and vegetation cover dynamics in a large gravel bed river over the last 200 years. Geomorphology 125, 147 – 159.

Constantine, C.R., Dunne, T., Hanson, G.J., 2009. Examining the physical meaning of the bank erosion coefficient used in meander migration modeling. Geomorphology 106 (3-4), 242-252.

Costa, J.E., O'Connor, J.E., 1995. Geomorphically effective floods. In: Costa, J.E., Millar, A.J., Potter, K.W., Wilcock, P.R. (Eds.), Natural and Anthropogenic Influences in Fluvial

Geomorphology. Geophysical Monograph, vol. 89. American Geophysical Union, Washington DC, pp. 45-56.

Coulthard, T.J., 2005. Effects of vegetation on braided stream pattern and dynamics. Water Resources Research 41 (4), W04003. DOI: 10.1029/2004WR003201.

Delai, F., Moretto, J., Picco, L., Rigon, E., Lenzi, M.A., 2014. Analysis of morphological processes in a disturbed gravel-bed river (Piave River): integration of LiDAR data and colour bathymetry. Journal of Civil Engineering and Architecture 8 (5), 639-648.

Del Favero, R., Lasen, C., 1993. La Vegetazione Forestale del Veneto. Progetto Editore, Padova, Italy, pp. 312.

Devereux, B., Amable, G., 2009. Airborne LiDAR: instrumentation, data acquisition and handling. In: Heritage, G.L., Large, A.R.G. (Eds), Laser Scanning for the Environmental Sciences. Wiley-Blackwell, Chichester, UK, pp. 49-66.

Dexter, B.D., 1967. Flooding and regeneration of river red gum, *Eucalyptus Camaldulensis*, Dehn. Forests Commission of Victoria, Melbourne, Bulletin 20, 1-35.

Dietrich, W.E., 1987. Mechanics of flow and sediment transport in river bends. In: Richards, K.S. (Eds.), River Channels Environment and Process. Basil Blackwell, Oxford, pp. 179-224.

Di Stefano, J., 2002. River red gum (*Eucalyptus camaldulensis*): a review of ecosystem processes, seedling regeneration and silvicultural practice. Australian Forestry 61, 14-22.

Docker, B.B., Hubble, T.C.T., 2009. Modelling the distribution of enhanced soil shear strength beneath riparian trees of south-eastern Australia. Ecological Engineering 35, 921–934.

Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266, 753-762.

Engel, F.L., Rhoads, B.L., 2012. Interaction among mean flow, turbulence, bed morphology, bank failures and channel planform in an evolving compound meander loop. Geomorphology 163-164, 70-83.

Erwin, S.O., Schmidt, J.C., Wheaton, J.M., Wilcock, P.R., 2012. Closing a sediment budget for a reconfigured reach of the Provo River, Utah, United States. Water Resources Research 48 (10), W10512. DOI: 10.1029/2011WR011035.

Fitzpatrick, F.A., Knox, J.C., 2000. Spatial and temporal sensitivity of hydrogeomorphic response and recovery to deforestation, agriculture, and floods. Physical Geography 21 (2), 89-108.

FLOODsite Consortium, 2005. Language of Risk, Project definitions. FLOODsite Report T32-04-01, www.floodsite.net.

Formann, E., Habersack, H.M., Schober, S., 2007. Morphodynamic river processes and techniques for assessment of channel evolution in alpine gravel bed rivers. Geomorphology 90, 340-355.

Frothingham, K.M., Rhoads, B.L., 2003. Three dimensional flow structure and channel change in an asymmetrical compound meander loop, Embarras River, Illinois. Earth Surface Processes and Landforms 28 (6), 625-644.

Fryirs, K.A., Brierley, G.J., 2012. Geomorphic analysis of river systems: an approach to reading the landscape. Wiley-Blackwell, Chichester, UK, pp. 360.

Fuller, I.C., Large, A.R.G., Milan, D.J., 2003. Quantifying development and sediment transfer following chute cutoff in a wandering gravel-bed river. Geomorphology 54, 307–323.

Fuller, I.C., Large, A.R.G., Heritage, G.L., Milan, D.J., Charlton, M.E., 2005. Derivation of reach-scale sediment transfers in the River Coquet, Northumberland, UK. In: Blum, M., Marriott, S., Leclair S. (Eds.), Fluvial sedimentology VII. : International Association of Sedimentologists Special Publication. Wiley-Blackwell, Chichester, UK, pp. 61–74.

Graf, W.L., 2001. Damage control: restoring the physical integrity of America's rivers. Annals of the Association of American Geographers 91 (1), 1-27.

Griffin, E.R., Kean, J.W., Vincent, K.R., Smith, J.D., Friedman, J.M., 2005. Modeling effects of bank friction and woody bank vegetation on channel flow and boundary shear stress in the Rio Puerco, New Mexico. Journal of Geophysical Research 110, F04023. DOI: 10.1029/2005JF000322.

Gurnell, A., 2014. Plants as river system engineers. Earth Surface Processes and Landforms 39 (1), 4-25.

Gurnell, A., Surian, N., Zanoni, L., 2009. Multi-thread river channel: a perspective on changing European alpine river systems. Aquatic sciences 71 (3), 253-265.

Hancock, G.R., 2006. The impact of different gridding methods on catchment geomorphology and soil erosion over long timescales using a landscape evolution model. Earth Surface Processes and Landforms 31, 1035–1050.

Hassan, M.A., Egozi, R., Parker, G., 2006. Experiments on the effect of hydrograph characteristics on vertical grain sorting in gravel bed rivers. Water Resources Research 42 (W09408), 1–15.

Henshaw, A.J., Thorne, C.R., Clifford, N.J., 2012. Identifying causes and controls of river bank erosion in a British upland catchment. Catena 100, 107 – 119.

Heritage, G., Hetherington, D., 2007. Towards a protocol for laser scanning in fluvial geomorphology. Earth Surface Processes and Landforms 32 (1), 66–74.

Heritage, G.L., Milan, D.J., 2009. Terrestrial laser scanning of grain roughness in a gravel-bed river. Geomorphology 113, 4 -11.

Heritage, G.L., Milan, D.J., Large, A.R.G., Fuller, I., 2009. Influence of survey strategy and interpolation model upon DEM quality. Geomorphology 112, 334–344.

Hodge, R., Brasington, J., Richards, K., 2009. In situ characterization of grain-scale fluvial morphology using Terrestrial Laser Scanning. Earth Surface Processes and Landforms 34, 954–968.

Hodge, R., Brasington, J., Richards, K., 2009. Analysing laser-scanned digital terrain models of gravel bed surfaces: linking morphology to sediment transport processes and hydraulics. Sedimentology 56 (7), 2024-2043.

Holmes, K.W., Chadwick, O.A., Kyriakidis, P.C., 2000. Error in a USGS 30-meter digital elevation model and its impact on terrain modeling. Journal of Hydrology 233, 154–173.

Hopkinson, L., Wynn, T., 2009. Vegetation impacts on near bank flow. Ecohydrology 2, 404-418.

Hubble, T.C.T., Docker, B.B., Rutherfurd, I.D., 2010. The role of riparian trees in maintaining riverbank stability: a review of Australian experience and practice. Ecological Engineering 36, 292 – 304.

Jang, J.S.R., Gulley, N., 2007. Fuzzy Logic Toolbox 2: User Guide, Matlab. Matlab, Natick, MA, pp. 299. Available at: http://www.mathworks. com/access/helpdesk/help/pdf_doc/fuzzy/fuzzy.pdf

James, L.A., Hodgson, M.E., Ghoshal, S., Latiolais, M.M., 2012. Geomorphic change detection using historic maps and DEM differencing: the temporal dimension of geospatial analysis. Geomorphology 137, 181 – 198.

Kean, J.W., Smith, J.D., 2006. Form drag in rivers due to small-scale natural topographic features: 1. Regular sequences. Journal of Geophysical Research 111, 1-13.

Kirkman, L.K., Sharitz, R.R., 1994. Vegetation disturbance and maintenance of diversity in intermittently flooded Carolina bays in South Carolina. Ecological Applications 41, 177-188.

Knighton, D., 2014. Fluvial forms and processes: a new perspective. Routledge, New York, NY, pp. 400.

Kochel, R.C., 1988. Geomorphic impact of large floods: review and new perspectives on magnitude and frequency. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. John Wiley & Sons, New York, pp. 169-187.

Kondolf, G.M., Piégay, H., Landon, N., 2007. Changes in the riparian zone of the lower Eygues River, France, since 1830. Landscape Ecology 22, 367–384.

Lallias-Tacon, S., Liébault, F., Piégay, H., 2014. Step by step error assessment in braided river sediment budget using airborne LiDAR data. Geomorphology 214, 307-323.

Lane, E.W., 1955. Design of stable channels. Transactions of the American Society of Civil Engineers 120 (1), 1234-1260.

Lane, S.N., 1998. Hydraulic modelling in hydrology and geomorphology: a review of high resolution approaches. Hydrological Processes 12 (8), 1131-1150.

Lane, S.N., Westaway, R.M., Hicks, D.M., 2003. Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. Earth Surface Processes and Landforms 28 (3), 249–271.

Lane, S.N., Tayefi, V., Reid, S.C., Yu, D., Hardy, R.J., 2006. Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. Earth Surface Processes and Landforms 32, 429 – 446.

Lazzarini, A., 2002. Il dibattito sul diboscamento montano nel Veneto fra Sette e Ottocento. In: Lazzarini A. (Eds.), Diboscamento montano e politiche territoriali. Franco Angeli, Milan, Italy, pp. 57–97.

Leopold, L.B., Wolman, M.G., 1957. River channel patterns - braided, meandering and straight. U.S. Geological Survey Professional Paper 282B, pp. 39-85.

Lloyd, C.D., Atkinson, P.M., 2001. Assessing uncertainty in estimates with ordinary and indicator kriging. Computers and Geosciences 27, 929–937.

Lyons, J., Trimble, S.W., Paine, L.K., 2000. Grass versus trees: Managing riparian areas to benefit streams of Central North America. Journal of the American Water Resource Association 36 (4), 919-930.

Marcus, W.A., Fonstad, M.A., 2008. Optical remote mapping of rivers at sub-meter resolutions and watershed extents. Earth Surface Processes and Landforms 33 (1), 4–24.

Marren, P.M., 2005. Magnitude and frequency in proglacial rivers: a geomorphological and sedimentological perspective. Earth-Science Reviews 70, 203–251.

McBride, M., Hession, W.C., Rizzo, D.M., Thompson, D.M., 2007. The influence of riparian vegetation on near-bank turbulence: a flume experiment. Earth Surface Processes and Landforms 32, 2019-2037.

Mikus, P., Wyzga, B., Kaczka, R.J., Walusiak, E., Zawiejska, J., 2013. Islands in a European mountain river: linkages with large wood deposition, flood flows and plant diversity. Geomorphology 202, 115-127.

Milan, D.J., Heritage, G.L., Hetherington, D., 2007. Application of a 3D laser scanner in the assessment of erosion and deposition volumes and channel change in a proglacial river. Earth Surface Processes and Landforms 32 (11), 1657–1674.

Milan, D.J., Heritage, G.L., Large, A.R.G., Fuller, I.C., 2011. Filtering spatial error from DEMs: Implications for morphological change estimation. Geomorphology 125, 160 – 171.

Mitchell, J.K., 2003. European river floods in a changing world. Risk Analysis 23 (3), 567-574.

Montgomery, D.R., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. G.S.A. Bulletin 109, 596-611.

Montgomery, D.R., Piégay, H., 2003. Wood in rivers: Interactions with channel morphology and processes. Geomorphology 51 (1-3), 1-5.

Moretto, J., Rigon, E., Mao, L., Delai, F., Picco, L., Lenzi, M.A., 2012. Assessing morphological changes in gravel bed rivers using LiDAR data and colour bathymetry. In: Collins, A.L., Golosov, V., Horowitz, A.J., Lu, X., Stone, M., Walling, D.E., Zhang, X.B. (Eds.), Erosion and Sediments Yields in the Changing Environment, IAHS Publication

356. IAHS Press, Centre for Ecology and Hydrology, Wallingford, Oxfordshire, UK, pp. 419-427.

Moretto, J., Delai, F., Picco, L., Lenzi, M.A., 2013. Integration of colour bathymetry, LiDAR and dGPS surveys for assessing fluvial changes after flood events in the Tagliamento River (Italy). Agricultural Sciences 4 (8A), 21-29.

Moretto, J., Rigon, E., Mao, L., Delai, F., Picco, L., Lenzi, M.A., 2014. Short-term geomorphic analysis in a disturbed fluvial environment by fusion of LiDAR, colour bathymetry and dGPS surveys. Catena 122, 180-195.

Nardi, L., Rinaldi, M., 2014. Spatio-temporal patterns of channel changes in response to a major flood event: the case of the Magra River (central-northern Italy). Earth Surface Processes and Landforms. Article first published online, DOI: 10.1002/esp.3636.

Nelson, J.M., Smith, D.J., 1989. Evolution and stability of erodible channel bends. In: Ikeda, S., Parker, G. (Eds.), River Meandering. AGU, Washington D.C., pp. 321-377.

Notebaert, B., Verstraeten, G., Govers, G., Poesen, J., 2009. Qualitative and quantitative applications of LiDAR imagery in fluvial geomorphology. Earth Surface Processes and Landforms 34, 217-231.

O'Neal, M.A., Pizzuto, J.E., 2011. The rates and spatial patterns of annual riverbank erosion revealed through terrestrial laser-scanner surveys of the South River, Virginia. Earth Surface Processes and Landforms 36, 695 - 701.

Osterkamp, W.R., Hupp, C.R., Schening, M.R., 1995. Little River revisited - thirty-five years after Hack and Goodlett. Geomorphology 13, 1-20.

Owens, P.N., Batalla, R.J., Collins, A.J., Gomez, B., Hicks, D.M., Horowitz, A.J., Kondolf, G.M., Marden, M., Page, M.J., Peacock, D.H., Petticrew, E.L., Salomons, W., Trustrum, N.A., 2005. Fine-grained sediment in river systems: environmental significance and management issues. River Research and Applications 21, 693 – 717.

Picco, L., Mao, L., Rainato, R., Lenzi, M.A., 2014. Medium-term fluvial island evolution in a disturbed gravel-bed river (Piave River, Northeastern Italian Alps). Geografiska Annaler, Series A, Physical Geography 96 (1), 83-97.

Piégay, H., 2003. Dynamics of wood in large rivers. American Fisheries Society Symposium 37, 109-133.

Piégay, H., Darby, S.E., Mosselman, E., Surian, N., 2005. A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion. River research and applications 21 (7), 773-789.

Pizzuto, J.E., 2009. An empirical model of event scale cohesive bank profile erosion. Earth Surface Processes and Landforms 34, 1234-1244.

Pizzuto, J.E., Meckelnburg, T.S., 1989. Evaluation of a linear bank erosion equation. Water Resource Research 25 (5), 1005-1013.

Pizzuto, J., O’Neal, M., Stotts, S., 2010. On the retreat of forested, cohesive riverbanks. Geomorphology 116, 341-352.

Printer, N., Heine, R.A., 2005. Hydrodynamic and morphodynamic response to river engineering documented by fixed-discharge analysis, Lower Missouri River, USA. Journal of Hydrology 302, 70 – 91.

Prosser, I.P., Hughes, A.O., Rutherfurd, I.D., 2000. Bank erosion of an incised upland channel by subaerial processes: Tasmania, Australia. Earth Surface Processes and Landforms 25, 1085-1101.

Raven, E.K., Lane, S.N., Ferguson, R., 2010. Using sediment impact sensors to improve the morphological sediment budget approach for estimating bedload transport rates. Geomorphology 119, 125 - 134.

Reusser, L., Bierman, P., 2007. Accuracy assessment of LiDAR-derived DEMs of bedrock river channels: Holtwood Gorge, Susquehanna River. Geophysical Research Letters 34 (23), L23S06. DOI: 10.1029/2007GL031329.

Rinaldi, M., Darby, S.E., 2008. Modelling river-bank-erosion processes and mass failure mechanisms: progress towards fully coupled simulations. In: Habersack, H., Piégay, H., Rinaldi, M. (Eds), Gravel-Bed Rivers 6 – From Process Understanding to River Restoration, Series Developments in Earth Surface Processes, Vol. 11. Elsevier, Amsterdam, pp. 213–239.

Rumsby, B.T., Brasington, J., Langham, J.A., McLelland, S.J., Middleton, R., Rollinson, G., 2008. Monitoring and modelling particle and reach-scale morphological change in gravel-bed rivers: applications and challenges. Geomorphology 93 (1–2), 40–54.

Rutherfurd, I., 2007. The influence of riparian management on stream erosion. In: Lovett, S., Price, P. (Eds.), Principles for Riparian Lands Management. Land and Water Australia, Canberra, pp. 85-116.

Rutherfurd, I.D, Grove, J.R., 2004. The influence of trees on stream bank erosion: evidence from root-plate abutments. In: Bennett, S.J., Simon, A. (Eds.), Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union, Washington D.C., pp. 141-152.

Samarakoon, M.B., Tanaka, N., Yagisawa, J., 2013. Effects of local scouring and saturation of soil due to flooding on maximum resistive bending moment for overturning *Robinia pseudoacacia*. Landscape and Ecological Engineering 9, 11-25.

Samuels, P., Klijn, F., Dijkman, J., 2006. An analysis of the current practice of policies on river flood risk management in different countries. Irrigation and Drainage 55, 141-150.

Schnauder, I., Moggridge, H.L., 2009. Vegetation and hydraulic-morphological interactions at the individual plant, patch and channel scale. Aquatic Sciences 71, 318-330.

Schumm, S.A., 1977. The fluvial system. Wiley, New York, NY, pp. 338.

Schumm, S.A., Erskine, W.D., Tilleard, J.W., 1996. Morphology, hydrology, and evolution of the anastomosing Ovens and King Rivers, Victoria, Australia. Geological Society of America Bulletin 108 (10), 1212-1224.

Sear, D.A., Newson, M.D., Thorne, C.R., 2003. Guidebook of applied Fluvial Geomorphology. Department of Environment and Rural Affairs and Environment Agency, Swindon, UK, pp. 229.

Seminara, G., 2006. Meanders. Journal of Fluid Mechanics 554, 271-297.

Shields, A., 1936. Anwedung der Aehnlichkeitmechanik und der turbulenzforschung auf die geschiebebewegung (English Translation). Mitteilung der Preussischen versuchsanstalt fuer Wasserbau und Schiffbau, Heft 26, Berlin, Germany.

Simon, A., Hupp, C.R., 1992. Geomorphic and vegetative recovery along modified stream channels of west Tennessee. U.S. Geological Survey, Open-File Report 91-502, Nashville, TN, pp. 142.

Simon, A., Rinaldi, M., Hadish, G., 1996. Channel evolution in the loess area of the midwestern United States. Proceedings, Sixth Federal Interagency Sedimentation Conference, Las Vegas, NV, pp. 345-357.

Simon, A., Curini, A., Darby, S.E., Langendoen, E.J., 1999. Streambank mechanics and the role of bank and near-bank processes in incised channels. In: Darby, S.E., Simon, A. (Eds.), Incised Channels: Processes, Forms, Engineering and Management. John Wiley and Sons Inc., Chichester, UK, pp. 123 – 152.

Simon, A., Collison, A.J.C., 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27 (5), 527-546.

Siska, P.P., Hung, I.K., 2001. Propagation of Errors in Spatial Analysis. Papers and Proceedings of the Applied Geography Conferences, Vol. 24, University of North Texas, TX, pp. 284–290.

Sukhodolov, A., Uijttewaal, W.S.J., Engelhardt, C., 2002. On the correspondence between morphological and hydrodynamical patterns of groyne fields. Earth Surface Processes and Landforms 27, 289-305.

Surian, N., 2002. Dowstream variation in grain size along an Alpine river: analysis of controls and processes. Geomorphology 43, 137-149

Surian, N., Cisotto, A., 2007. Channel adjustments, bedload transport and sediment sources in a gravel-bed river, Brenta River, Italy. Earth Surface Processes and Landforms 16, 1641 – 1656.

Surian, N., Ziliani, L., Comiti, F., Lenzi, M.A., Mao, L., 2009. Channel adjustments and alteration of sediment fluxes in gravel-bed rivers of north-eastern Italy: potentials and limitations for channel recovery. River Research and Applications 25, 551-567.

Surian, N., Barban, M., Ziliani, L., Monegato, G., Bertoldi, W., Comiti, F., 2014. Vegetation turnover in a braided river: frequency and effectiveness of floods of different magnitudes.

Earth Surface Processes and Landforms. Article first published online, DOI: 10.1002/esp.3660.

Taylor, J., 1997. An introduction to error analysis: the study of uncertainties in physical measurements, 2nd ed. University Science Books, Sausalito, CA, pp. 327.

Tockner, K., Malard, F., Ward, J., 2000. An extension of the flood pulse concept. Hydrological Processes 14, 2861-2883.

Tockner, K., Uehlinger, U., Robinson, C., 2008. Rivers of Europe. Academic Press Inc., Oxford, UK, pp. 728.

Vandenberghe, J., De Moor, J.J.W., Spanjaard, G., 2012. Natural change and human impact in a present-day fluvial catchment: the Geul River, Southern Netherlands. Geomorphology 159-160, 1-14.

Van de Wiel, M.J., Darby, S.E., 2007. A new model to analyse the impact of woody riparian vegetation on the geotechnical stability of riverbanks. Earth Surface Processes and Landforms 32 (14), 2185-2198.

Vietz, G.J., Rutherfurd, I.D., Stewardson, M.J., Finlayson, B.L., 2012. Hydrodynamics and sedimentology of concave benches in a lowland river. Geomorphology 147-148, 86-101.

Wechsler, S.P., 2003. Perceptions of digital elevation model uncertainty by DEM users. URISA Journal 15 (2), 57–64.

Wechsler, S.P., Kroll, C.N., 2006. Quantifying DEM uncertainty and its effect on topographic parameters. Photogrammetric Engineering and Remote Sensing 72 (9), 1081–1090.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. The Journal of Geology 30 (5), 377-392.

Westaway, R.M., Lane, S.N., Hicks, D.M., 2003. Remote survey of large-scale braided, gravel-bed rivers using digital photogrammetry and image analysis. International Journal of Remote Sensing 24 (4), 795–815.

Wheaton, J.M., 2008. Uncertainty in morphological sediment budgeting of rivers. Unpublished Ph.D. Thesis, University of Southampton, Southampton, UK, pp. 412. Available at: http://www.joewheaton.org/Home/ research/projects-1/phdthesis

Wheaton, J.M., Brasington, J., Williams, R.D., 2004. Modelling fluvial sediment budgets under uncertainty. EOS Transactions AGU 85 (47), Fall Meeting Supplement, Abstract H53C-1264.

Wheaton, J.M., Brasington, J., Darby, S.E., Sear, D.A., 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth Surface Processes and Landforms 35, 136-156.

Wohl, E., 2005. Compromised rivers: understanding historical human impacts on rivers in the context of restoration. Ecology and Society 10 (2), 2. Available at: http://www.ecologyandsociety.org/vol10/iss2/art2/

Wolfert, H.P., 2001. Geomorphological change and river rehabilitation: case studies on lowland fluvial systems in the Netherlands. Alterra Scientific Contributions 6, Alterra Green World Research, Wageningen, The Netherlands, pp. 200.

Wynn, T.M., Mostaghimi, S., Burger, J.A., Harpold, A.A., Henderson, M.B., Henry, L.A., 2004. Variation in root density along stream banks. Journal of Environmental Quality 33, 2030-2039.

Wynn, T.M., Mostaghimi, S., 2006. Effects of riparian vegetation on stream bank subaerial processes in southwestern Virginia, USA. Earth Surface Processes and Landforms 31 (4), 399-413.

Zanoni, L., Gurnell, A., Drake, N., Surian, N., 2008. Island dynamics in a braided river from analysis of historical maps and air photographs. River Research and Applications 24, 1141-1159.

Ziliani, L., Surian, N., 2012. Evolutionary trajectory of channel morphology and controlling factors in a large gravel-bed river. Geomorphology 173-174, 104-117.