The Influence of Physical and Anthropogenic Factors on a Channel's Geomorphic Diversity

By

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Memorandum

The following composition is the result of eight months of independent research in the School of Geosciences at the University of Sydney, under the supervision of Scott Rayburg and Mel Neave.

Where the work of others, whether published, unpublished or otherwise has been referred to or made use of, the fullest acknowledgement has been given.

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Abstract

The geomorphic diversity (or the natural variability within and between geomorphic structures) of fluvial systems provides an indication of river health and biological activity as well as their resilience to change. Despite this, few studies have investigated the controls on geomorphic diversity and, as a result, our understanding of this fundamental aspect of rivers is incomplete. Similarly, investigations into the controlling factors on channel morphology tend to be limited in scope. For example, the influence of physical and anthropogenic external factors on the morphology of fluvial systems has typically been examined through the study of the effects of a single factor (e.g., woody debris) on either the cross-sectional form, the shape of the long-profile, the bed structure or the channel pattern of a river system. As rivers have been shown to adjust their channel morphologies to external controls (Knighton 2000) over all four of these degrees of freedom, isolating individual degrees of freedom may miss out on the complex interactions that occur between them. The aim of this study, therefore, is to examine the multi-scale and multi-factor influences of physical and anthropogenic external factors (particularly confinement, riparian vegetation, woody debris, obstructions and anthropogenic impoundment) on the geomorphic structure and diversity of river systems at a range of scales, using the Turon River in Central West New South Wales as a case study.

In this study, river channels were examined at four scales (i.e., cross-section, long-profile, bedform and bar unit) to assess the influence of five external factors (confinement, riparian vegetation, woody debris, obstructions (i.e., islands and in-channel bars) and anthropogenic impoundment (i.e., a causeway)) on the geomorphic diversity of the Turon River. To accomplish this, a total of 231 cross-sections were surveyed over a 600 m reach. These data were then used to calculate the size and variability of cross-sections, long-profiles, bedforms and bar units within the study reach. Morphology and diversity at each scale (and for each factor) were tested for statistical differences using non-parametric uni-variate approaches.

The results presented in this study suggest that the presence of obstructions is the most influential external factor on channel size in the Turon River, affecting the size and shape of cross-sections, long-profiles and, to a lesser extent, bedforms and bar-units. That is, obstructed channels were found to be significantly different to channels devoid of obstructions insofar as they were smaller, shallower, contained steeper channel gradients had more vertical variation in their long-profiles, had longer pool-riffle sequence spacing and were of a different channel form to channel reaches devoid of obstructions. Obstructions, in association with the presence and type of woody debris, were also observed to be the most influential factors on the diversity of river channels. For example, the presence of either obstructions or woody debris increased the variability of cross-sectional and bedform parameters, while the type of woody debris present influenced the variability of the long-profile's vertical and angular variations (i.e., the vertical and angular variations in long-profiles containing in-channel woody debris were less variable than those with on-bank woody debris).

Importantly, cross-sections are impacted upon more than long profiles, with their size and variability affected by both large-scale external factors (e.g., confinement and riparian vegetation) and small-scale influences (e.g., obstructions and impoundments). For example, cross-sections within confined reaches were found to be larger but less diverse than cross-sections in unconfined channels, while the reverse is true for obstructed cross-sections (i.e., obstructed cross-sections were smaller and more diverse than unobstructed channels). Conversely, pool-riffle sequences were the least affected river components, only being influenced by obstructions and, to a lesser extent, woody debris. That is, bar-units within obstructed channels were smaller, longer and more asymmetric than bar-units within channels devoid of obstructions.

The results presented in this study also indicate that the variability of channel characteristics was affected more by the influence of external factors than channel dimensions. Additionally, the findings of this study indicate a reversal in the influence external factors have on the size and shape of a channel and its diversity. That is, smaller channels were found to be more diverse than larger channels.

This is the first study to examine the influence of multiple factors on multiple scales within a river reach. The results of this investigation illustrate that river systems have complex responses to *a combination* of different physical and anthropogenic external factors that are evident at multiple scales (from cross-sections through to bar units). Additionally, it has shown that interactions between the external factors in a reach can result in a highly geomorphically diverse environment.

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1 Introduction

1.1 Geomorphic diversity

Geomorphic diversity refers to the natural variety of geomorphic features in a particular area (Semeniuk 1997). The geomorphic diversity of rivers is of great importance as it can be used as an indicator of river health (i.e., diverse morphologies usually equate with healthy rivers) and is a key driver of biological diversity within river systems (Semeniuk 1997; Burnett et al. 1998; Bartley & Rutherford 2005). Despite its importance to river systems, however, not much is currently known about the drivers of geomorphic diversity. Indeed, exactly what constitutes a diverse geomorphic assemblage in a river is only poorly understood and it is unknown how external factors, both natural and/or anthropogenic, influence the physical diversity of fluvial systems. The objective of this study, therefore, is to assess how physical and anthropogenic external factors affect the geomorphic diversity of river systems at a range of scales.

1.1.1 Identifying geomorphic diversity

There are a variety of ways in which geomorphic diversity has been classified. According to Semeniuk (1997), for example, there are two main types of geomorphic diversity, depending on the scale at which the diversity occurs. *Small scale geomorphic diversity* refers to local scale complexity occurring in a regional setting of relative homogeneity. On the other hand, *large scale geomorphic diversity* refers to diversity taking place over an entire region (Semeniuk 1997). Rayburg & Neave (2008) also identified two types of diversity and complexity that can be used to classify the geomorphic diversity of fluvial systems. These are 1) *external variability*, which refers to the variety of morphologic structures found within a river system (e.g., Bartley & Rutherford 2005); and 2) *internal variability*, which refers to the variety of forms within each type of morphologic structure.

Although the concept of geomorphic diversity is relatively new, geomorphologists have been indirectly looking at geomorphic diversity for many years. This has taken the form of river classification techniques, which seek to classify rivers at a variety of scales based on the morphologic structure of the rivers themselves or the features found within them. Hence, river classification can be viewed as the precursor of geomorphic diversity assessments and can provide a foundation for considering geomorphic diversity through a consideration of how rivers have been classified in the past.

River classification requires the organisation of numerous observations into meaningful groups based on their similarities and/or differences (Thoms et al. 2007). Thus, it requires us to identify different types of features within a landscape. The earliest forms of river classification involved defining rivers according to their planforms (e.g., straight, meandering, braided or anastomosing). One such classification was proposed by Leopold and Wolman (1957) which identified three key river planforms: braided, meandering and straight. However they later stated that meanders were a prominent feature in all river channels, regardless of size (Leopold & Wolman 1960). Rust (1978) also developed a river classification scheme which divided river systems into four different types: single channel or multi-channel systems with low and high sinuosity types separated by a sinuosity of 1.5 (Gregory 1977). Rivers may also be classified by the surface waterbodies they have (lotic, semi-lotic or lentic waters) or the type of in-channel structures they exhibit (e.g., pool-riffle, stepped-bed, cascading channel). Ward et al. (2002) have also established a way of classifying floodplains (i.e., disequilibrium, equilibrium or low-gradient floodplains); whilst others (e.g., McKenney et al. 1995; Gurnell 1997) have classified rivers using the characteristic processes occurring along channels with different energy gradients. For example, low-gradient (low energy) channels are characterised by unidirectional channel migration and bar deposition whilst high-gradient (high energy) channels exhibit high levels of channel avulsion (McKenney et al. 1995).

Each of these geomorphic structures can be thought of, from a biological perspective, as a species, enabling us to identify the diversity of features within the landscape. For example, a river system displaying straight, meandering and braided reaches is more geomorphically diverse than one that is only meandering. Without geomorphic classifications, therefore, it would not be possible to discuss geomorphic diversity as there would be no distinct geomorphic features or structures upon which to base the assessment. However, even though river classification still serves a useful analytical role since end members of the continuum remain morphologically unique, it is becoming increasingly apparent that transitional patterns and broad sedimentary forms and processes exist (Rhoads 1992) leading to the possibility of highly geomorphically diverse river channels.

In summary, geomorphic diversity has been identified in a number of ways, both directly and indirectly. For example, a direct approach to defining geomorphic diversity is through the examination of the scale at which the diversity is occurring (e.g., Semeniuk 1997; Rayburg & Neave 2008), while an indirect approach is through the use of river classification schemes (e.g., Leopold & Wolman 1957; Rust 1978). However, although there are an array of techniques to identify geomorphic diversity (using a wide range of classification schemes for fluvial systems), few studies have actually examined what constitutes a geomorphically diverse assemblage.

1.1.2 What Determines Geomorphic Diversity

The level of geomorphic diversity in a river reach, and associated biological responses to that diversity, are believed to be a function of processes operating at a range of scales (Poole 2002; Yarnell et al. 2006). According to Bartley and Rutherford (2005), there are three scales over which these processes occur. At the largest scale, a river is controlled by basin planform and regional geology, both of which affect the channel gradient and determine whether a reach is erosional or depositional. At the intermediate scale, geomorphic variability is predominantly influenced by catchment area and hydrology which produce variations in in-channel structures. Finally, small-scale variations are believed to be influenced by external factors (e.g., woody debris) and localized geological structures (e.g., rocky outcrops). Bartley and Rutherford's (2005) idea of multiple scales over which processes occur supports the widely held view of fluvial landscapes existing as "multi-scaled nested hierarchies of interactive terrestrial and aquatic elements (Frissell et al. 1986; Townsend 1996) where elements are defined as the basic, relatively homogenous units observable within a landscape at a given scale" (Poole 2002, p. 642). According to these hierarchical principles, the physical nature of river systems at any level or scale in the hierarchy is restricted by larger scale structures and processes and is influenced by the processes and structures operating at smaller scales (Thoms et al. 2007).

There are others, however, who argue that the geomorphic features within river systems and their floodplains reflect complex relationships between climate, catchment geology, topographic relief and hydrodynamics, mediated by vegetation (Ward et al 2002; Thoms et al. 2007). This means that under stable climatic conditions, channel geometry must be in equilibrium with streamflow characteristics, local valley-floor slope and sediment type (Ferguson 1981). In comparison, some studies indicate that spatial attributes of channel change are driven by discharge and variations in sediment supply, but are further modified by spatial feedbacks associated with in-channel structures (Lane et al. 1996; Yarnell et al. 2006). For example, Yarnell et al. (2006) suggest that reaches with a moderate sediment supply may exhibit the largest geomorphic diversity by creating channel conditions that contain a variety of geomorphic features and surface textures. In addition, Sweet et al. (2003) state that variations in sedimentation rates (including sediment supply) reflect an array of factors including valley floor geometry, channel dimensions, flood regime and floodplain characteristics.

In-channel structures (also referred to as channel units or bedforms) play a key role in determining a channel's geomorphic diversity. In-channel structures are defined as morphologically distinct sections of a channel, generally one to a few channel widths in length

(Halwas & Church 2002). They have also been defined as any irregularity produced on a channel bed by the interaction between water flow and sediment movement (Simons & Richardson 1966; Keller & Melhorn 1973). Many studies have shown that the type and nature of in-channel structures are dependent upon sediment size (e.g., Keller & Melhorn 1973; Gregory et al. 1994; Chin 1999). For example, pool-riffle sequences are commonly found in gravel-bed alluvial channels (Keller & Melhorn 1973) while step-pool morphologies tend to dominate regions with large bed material (i.e., boulders) and are therefore found mostly in steep mountain streams (Chin 1999). Noble (1989), on the other hand, states that pool-riffle sequences are a basic component of river channel geomorphology that form independent of sediment type. That is, pool-riffle sequences have been found to occur in sand bed rivers as well as in gravel bed channels.

The nature and assemblage of in-channel structures within a river reach also tend to be dependent on channel slope, with cascades, rapids and chutes generally found in channels with high gradients, and pools, glides and riffles observed in streams with low to moderate gradients (Montgomery & Buffington 1997; Halwas & Church 2002). Some studies (e.g., Montgomery & Buffington 1997) have found channels with gradients less than 0.015 are likely to contain pool-riffle sequences; reaches with gradients between 0.015 and 0.030 are likely to contain plane bed structures; channels with gradients of 0.030 to 0.065 are likely to have step-pool sequences; and reaches with gradients greater than 0.065 should exhibit cascade structures. However, other studies (e.g., Chartrand & Whiting 2000) have suggested that, due to an overlap in the different slopes that contain certain channel structures, factors in addition to stream gradient play an important role in determining channel morphology. These factors include confinement, riparian vegetation, large woody debris accumulation and debris flows (Montgomery & Buffington 1997; Chartrand & Whiting 2000).

Two of the more commonly observed bed structures in moderately sloped gravel or larger bed material streams are pool-riffle sequences and step-pools. These quasi-periodic bedforms are key components of geomorphic diversity (especially when internal variability is considered) in the rivers in which they are found. Pool-riffle sequences comprise areas of topographic highs and lows. Pools are defined as the topographic lows in a river channel that are produced by scour and generally contain relatively fine-grained sediments (Gregory et al. 1994). In comparison, riffles are topographic highs that are produced by the accumulation of coarse-grained deposits (Keller 1971). The typical spacing of pool-riffle sequences is measured along the channel from the deepest point to deepest point of consecutive pools (Keller & Melhorn 1973) and is commonly reported as five to seven channel widths (Leopold et al. 1964; Keller 1972). This spacing can vary depending on whether the river is associated with resistant floodplain and valley deposits (Hudson 2002), the presence of woody debris jams (Noble 1989) or whether or not there are anthropogenic factors in the vicinity of the river channel (Gregory et al. 1994). However, the study of a river displaying pool-riffle sequences at a single point in time only provides us with a static view of the river's morphology, and does not give any indication of the connections and changes that occur between the longitudinal and planform morphology (Hudson 2002).

Within step-pool morphologies, there are alternating segments of steeply and moderately sloping channel bed (Bowman 1977). The steep segments (also referred to as rapids) are classified as step risers and consist of cobbles and boulders that are transverse to river flow (Chartrand & Whiting 2000). The moderately sloping segments (or regular segments) are classified as pools and are made up of well-sorted gravel (Bowman 1977; Chartrand & Whiting 2000). Unlike pool-riffle sequences, step-pool sequences do not exhibit an average longitudinal spacing of five to seven channel widths (Leopold et al. 1964; Keller 1972); instead, studies suggest an average spacing of 1.4 channel widths for regular segments and 2.2 channel widths for rapids (Bowman 1977). The alternation of steps and pools produces a characteristic sequence of bedforms that produce a longitudinal profile resembling a staircase (Chin 1999; Chin 2002).

The structure and complexity (i.e., geomorphic diversity) of river channels, therefore, is controlled by a hierarchy of processes, with each process being restricted by the larger scale processes above them and influenced by the smaller scale processes and structures below them. For example, intermediate scale catchment area and hydrology are restricted by regional geology and influenced by local variations caused by small-scale external factors (e.g., woody debris). Bedform structures are one of the scales at which processes occur and are of particular importance in determining the geomorphic diversity of river channels as they can be influenced by a myriad of external factors including confinement, riparian vegetation, large woody debris accumulation and debris flows. However, the exact effects of these factors on the structure and complexity of different scales within fluvial systems is still poorly understood.

1.2 External factors and the way they influence geomorphic diversity

Disturbances (particularly those created by external factors) are a major contributor to spatial heterogeneity (or geomorphic diversity) and for creating conditions under which niche overlap can occur (Ward et al. 2002). As previously mentioned, there are a number of factors that can influence the morphology, and therefore the geomorphic diversity, of a river channel. These factors may be physical (e.g., riparian vegetation, valley impingement, woody debris and channel confluences) or anthropogenic (e.g., impacts from mining and impoundments such as dams, weirs and causeways). Each of these factors are known to alter channel morphology and can affect a channel's geomorphic diversity in different ways (Church 1992). For example, studies have shown that features increasing local scour and deposition also increase pool depth and frequency, thereby increasing channel diversity (Abbe & Montgomery 1996; Yarnell et al. 2006).

1.2.1 Riparian Vegetation

Riparian vegetation is important to river systems as it provides a buffer to lateral flows and limits the volumes of water, sediment and nutrients entering a river. Additionally, riparian vegetation moderates ecological processes within river channels by influencing temperature and light regimes, producing organic matter structuring a river's physical environment at multiple scales, and providing habitat/shelter for aquatic, amphibious and terrestrial life forms (Ward et al. 2002). Riparian vegetation also provides bank stabilisation (Gurnell 1997; Charron et al. 2008) and the stabilisation of recently deposited floodplain sediments (Martin & Johnson 1987). Ferguson (1981) states that even a single row of trees along a channel's banks can have a stabilising effect on the river. However, vegetation growing on the channel bed (as opposed to the banks) can increase channel instability and initiate channel migration (Graeme & Dunkerley 1993).

It has been shown that there is a close association between the pattern of riparian vegetation and the processes affecting the physical nature of the river channel (Gurnell 1997). For example, riparian vegetation and river valley geology can influence channel morphology by creating constraints to the river's movements (i.e., degrees of freedom) (Knighton 2000). Some studies have indicated that encroachment of vegetation into a channel, including vegetative growth in abandoned segments of a channel, is accompanied by the contraction of channel width (Hickin 1984; Martin & Johnson 1987). Conversely, Ward et al. (2002) have argued that as a result of channel migration, a constrained river may begin to undercut the banks in areas where riparian vegetation is present. If this form of erosion continues, the potential for a slump of bank material to enter the river increases. In fact, Andrews (1982) discovered that the primary mechanism for bank retreat was the erosion of a bank's gravel and sand base, resulting in the undercutting of the upper part of the bank that then slumped into the river channel. As such, tree root exposure, the presence of bent tree trunks and the position of trees on river's banks can be used to identify eroding banks (Gregory & Davis 1992). If a slump were to occur any riparian vegetation growing within the overcut bank material will also enter the river, and thereby increase the volume of large woody debris in the river channel.

The importance of riparian vegetation, due to the role it plays in maintaining healthy river systems, is well documented and many studies have identified a link between riparian vegetation and the processes that shape riverine ecosystems (e.g., Gurnell 1997; Knighton 2000). It is still unclear, however, as to how riparian vegetation affects the overall geomorphic diversity of rivers.

1.2.2 Woody Debris

There are many types of woody debris accumulations in rivers, all of which can have an impact on a river's geomorphology and thus its geomorphic diversity. Forms of woody debris accumulations, which themselves represent an element of geomorphic diversity, are extensively described by Abbe and Montgomery (2003). Bank input debris generally consists of tree boles that have entered the channel directly from their growth locations due to undercutting of banks, windthrow or mass movement (Abbe & Montgomery 2003). This type of debris tends to have only local effects on the morphology of the channel although over time it can affect greater segments of cross-sectional area if additional debris collects on or near the original piece (Abbe & Montgomery 2003).

Log-steps form when a tree bole crosses a river channel, completely or partially blocking the channel but still allowing the water to flow over the top. These steps can have a wide range of orientations, although they most commonly lie normal to flow, and are believed to decay rapidly thereby having a negligible impact upon a river's geomorphology (Abbe & Montgomery 2003). Mao et al. (2008), however, found that all of the log-steps they studied caused a downstream scour pool for at least for the duration of the log's presence in the channel.

Large woody debris jams have a significant influence on river channel morphology (Gregory & Davis 1992; Gregory et al. 1994; Abbe & Montgomery 1996) as they can act as minor impoundments that directly impinge on the dissipation of stream energy (Gurnell 1997) and potentially cause scour around the jam. For instance, jams that completely cross the river channel (e.g., valley jams or debris-flow jams) redirect a large portion of a river's flow, resulting in bank erosion, channel widening and local bed scour (Abbe & Montgomery 2003). Local bed scour can cause a pool to form upstream of the woody debris which in turn can cause pool-riffle sequences to become more complex than in channels lacking such woody debris structures (Gregory et al. 1994). This phenomenon of complex pool spacing has been found to strongly correlate with the loading of large woody debris in small to moderately sized gravel-bed rivers (Montgomery et al. 1995; Abbe & Montgomery 1996). Myers and Swanson (1997) found the pools formed by accumulations of large woody debris are shallower than free-formed pools (i.e., pools formed in fine material due to oscillations in flow direction) suggesting that deposition or less optimal scour flow conditions occur around these randomly located features. In contrast, Abbe and Montgomery (1996) state that, on average, pools related to woody debris jams are deeper and display larger variance in depths than free-forming pools. Hence, depending on the nature of the woody debris jam and the channel character, there is the potential for a complex response to wood, with forced pools occurring within the channel that may be either deeper or shallower than those which occur in the same stream but away from the woody obstructions.

Partial damming of a channel (e.g., by flow-deflection jams) may lead to sufficient water build-up to allow for overbank flow and the creation of a new channel where the bank is least stable (Keller & Melhorn 1973). Alternatively, instead of creating an entirely new channel, the increase in overbank flow may either widen (Abbe & Montgomery 2003), sometimes by a factor of two or more channel widths (Keller et al. 1995), or narrow the existing channel (e.g., Mao et al. (2008) found that around 36% of the flow-deflection jams they studied produced obvious channel narrowing). With respect to channel morphology, flow-deflection jams can cause large pools to form directly upstream of them while slack water or eddies promote deposition that leads to the development of an arcuate bar downstream of them. Because the sediments that create the arcuate bar downstream of the woody debris jam come from the erosion of the river banks the surface of these bars tends to resemble that of the flood plain (Abbe & Montgomery 2003).

Woody debris jams that form at the head of an island or in-channel bar (i.e., bar-apex jams), on the other hand, have been found to favour one channel over another, eventually closing the least favoured channel and thus eliminating the original bifurcation (Hickin 1984). There are three characteristic alluvial conditions that are created by bar-apex jams: an arcuate bar formation upstream of the jam created by flow divergence and deceleration; a deep crescentic pool formed around the upstream margin of the jam created by vortex flow, flow convergence and acceleration into the bed, and lateral acceleration of flow; and a central bar made up of fine sediments along the bole of the key member created by the deceleration of flow within the flow-separation envelope in the wake of the accumulated members (Abbe & Montgomery 2003). These accumulations of large woody debris may also act as nuclei for the development of vegetated islands (Abbe & Montgomery 1996; Ward et al. 2002) by trapping fine sediments that are ideal for vegetative growth (Pettit et al. 2005).

Finally, there is mobile woody debris that is deposited on the flood plain and along river banks during floods, and on the tops of bars as the flood waters recede. This form of woody debris tends to have an insignificant effect on bed texture or geomorphology since they are likely to be moved further downstream in the next high flow event (Abbe & Montgomery 2003). However, as it moves downstream, mobile woody debris may get caught on a component of a large woody debris jam and thus become incorporated into the jam.

In spite of all of these findings, the influence of woody debris on channel morphology has been found to be strongest in smaller sized, low gradient streams (Beschta and Platts 1986) that are unable to move the large features, even in times of high flow (Myers & Swanson 1997), although Chen et al. (2008) found that woody debris in intermediate sized rivers played a greater role in pool formation than in small or large sized channels. In addition, the level of influence woody debris will have on pool formation is governed by the ratio of woody debris size to channel size (Webb & Erskine 2005). The effects woody debris have on channel processes can also be counteractive, depending on the size, orientation and density of the debris, the scale at which the effects are observed, and the characteristics of the river (Lisle 1995). There is believed to be a strong correlation between the distribution, size, number and characteristics of woody debris accumulations and river geomorphology and flooding frequency (Pettit et al. 2005). Nevertheless, at the reach scale, stable woody debris jams can decrease depth and slope, increase width, and create major in-channel obstructions, potentially causing a single-thread channel to take on a braided form (Abbe & Montgomery 2003).

In summary, the effect woody debris has on a channel's complexity and structure can be perceived as being a factor of the type of accumulation or the size of the river channel the debris has accumulated in. For instance, debris that has entered the channel from the banks directly opposite an accumulation is more likely to only have localised effects. Log-steps and woody debris jams, on the other hand, are prone to dam river channels and can cause overbank flows, channel widening and scour pools both up- and down-stream of the obstruction. However, even though there have been a large number of studies into the impacts of woody debris on channel morphology, the influence of this common physical feature on channel geomorphic diversity has not been expressly considered.

1.2.3 Valley confinement and channel geology

Confined river channels (i.e., channels that are constrained by adjacent valley slope) generally contain a single-thread channel bordered by a narrow band of riparian vegetation (Ward et al. 2002). Their flow depth is also proportionally greater than that in unconfined channels and these flows therefore, tend to overwhelm bed features that would remain partially emergent in a wider channel (Zimmermann et al. 2006). Additionally, if lateral confining valley walls are present along a river, it will be reflected in the channel form, especially in the planform (Milne 1983). Meanwhile, a steep and narrow valley profile could be indicative of recent uplift, which creates changes in the long profile, sinuosity, and valley height relative to valley depth (Rhea 1993) thus, the geology and geomorphology of a reach strongly influences the nature of sediments entering the river channel (Bond 2004).

Narrow, deep valleys are known to create limitations on the lateral migration of individual meanders and the meander belt as a whole which can lead to low sinuosity (Milne 1983). For example, Ferguson (1981) found that confinement leads to the local restriction or prevention of "normal" identified processes of meander development (i.e., lateral extension and downvalley translation). However, confined meander bends have been found to display a variety of sinuosities depending on the angle at which the channel meets the valley wall while less well-developed cross-sectional asymmetries have been observed in areas where tight meanders are imposed due to the coarse sediments introduced from nearby erosion scars (Milne 1983).

Rockslides can be common in confined river valleys and can have major impacts on the river channel form. Korup et al. (2006) state that catastrophic rock-slope failures (i.e., excessive rock-falls) can lead to the input of substantial volumes of sediment into the river channel, potentially causing significant channel instability. In addition, if the river valley is naturally unstable a single rock-fall event could trigger other rock-falls further downstream by deflecting flow or causing local channel fill (Nolan & Marron 1995) while the focus of fluvial erosion may shift due to contact erosion caused by major rock-falls (Korup 2004; Korup et al. 2006). Landslides are also a major contributor of woody debris into river channels (Young et al. 2006), particularly in areas with relatively steep valley walls (Keller et al. 1995).

Large cobbles and boulders within the channel are known to control the local gradient of small streams (Halwas & Church 2002). If channel flow is low, these extremely large pieces of sediment are unable to be removed from the channel, except through basal undercutting followed by rolling (Bowman 1977). Thus, they can form steps in the river channel and can ultimately change the morphological classification of a river channel (e.g., from a pool-riffle river to a step-pool river for example). Additionally, the combined effect of individual channel constrictions may dominate reach-averaged channel morphology in bedrock-influenced and gravel-bed (i.e., coarse-grained) rivers (Thompson 2001). Wohl and Legleiter (2003) argue that the downstream spacing of pools along a bed-rock controlled river channel is strongly influenced by, and correlated to, the downstream spacing of lateral bedrock constrictions, including bedrock outcrops. This is thought to occur because these random disturbances cause bed resistance to vary, creating irregular channel geometries (i.e., geomorphic diversity) (Milne 1983).

Valley impinged channels are more likely to be less geomorphically diverse than their unconfined counterparts because they generally consist of a single thread with little to no lateral migration and because their greater flow depths are likely to overpower bedform features and create a more uniform bed. However, rockslides commonly occur within confined river valleys which can cause large boulders to enter the river system, creating obstructions to the flow. As a result, it is hypothesised that a river which only impinges on one side of the valley would be more geomorphically diverse than a confined river channel as it would still be able to undertake some degree of lateral migration. Similarly, it is expected that a channel with bedrock outcrops in some places but not in others would have a greater geomorphic diversity than a river that has little or no bedrock outcrops.

1.2.4 Channel confluences

Channel confluences are observed in drainage basins worldwide (Best 1988). They can be areas where one river meets another or more simply, where branches of the same channel converge after an obstruction, such as an island or woody debris. Channel confluences are sites that cause considerable changes in downstream hydraulic geometry to occur (Best 1988). For instance, studies have revealed channel width adjustments (Richards 1980; Roy & Roy 1988) and changes in sediment size occurring downstream of river confluences (Best 1988). The overall effect that channel confluences have on channel morphology, however, is a product of the angle at which the convergence occurs (Best 1988).

The backwater effect (where water from one tributary branch backs up into the other tributary branch) is relatively common in rivers with very gentle slopes, as is the case where two rivers converge on a wide floodplain (Roy and Roy 1988). This could lead to a reduction in channel capacity below a confluence and the storage of flow above the confluence. Best (1988) hypothesised that some sediment movement may be inhibited due to slower velocity flows in the backwater region at the upstream junction, in addition to the increased flow depth-to-particle size ratios at the channel mouth, causing both channels to have similar particle sizes.

To summarise, channel convergences not only occurs at the confluence of two rivers, but at the junction of a main and secondary channel after an island. Backwater effects may occur upstream of channel convergences, leading to reduced channel capacity. It is therefore theorised that a river that has channel confluences occurring after obstructions, such as islands, would exhibit channel changes downstream from the confluence. It is also suspected that possible backwater effects may be observed directly upstream of the convergence of the channels.

1.2.5 Anthropogenic impacts

Human activities can influence channel morphology through the construction of artificial channels or weirs and causeways (direct structural interference) or through impacts on runoff and/or sediment fluxes due to regional land uses (Burnett & Schumm 1983; Kellerhals & Church 1989; Church 1992; Price & Leigh 2006). Our ability to detect the effect of human activities on fluvial ecosystems depends upon our ability to quantify a river's natural diversity (Li & Reynolds 1994; Palmer et al. 1997), although it is well known that anthropogenic activities on or along river channels can lead to a simplification of the physical, or geomorphological, structure of a river system (Bartley & Rutherford 2005) and thus a reduction in geomorphic diversity (Parsons & Gilvear 2002).

It is expected that changes in valley floor vegetation and habitat diversity may occur in areas where human activity has altered the fluvial dynamics or the connectivity between a channel and its floodplains (Parsons and Olivier 2002). In addition, Park (1995) states that anthropogenic factors often create channel instability and promote rapid and complex channel changes. Dam construction, urban sprawl, and many other anthropogenic activities can disrupt the natural equilibrium of a river system whose catchment has been impacted upon and this may lead to changes, possibly even drastic ones, within the channel (Ferguson 1981) while the diversion of river water, channelisation, impoundment and inundation of upstream channels inevitably changes runoff patterns and fluxes to downstream segments and removes distinctive habitats (Freeman et al. 2007).

Agricultural practices, particularly cattle grazing, can drastically impact the riparian zone, mainly by reducing the level of vegetation and by the trampling of the banks (Magilligan & McDowell 1997). The introduction of European agricultural practices in Australia has resulted in an increase in runoff due to the elimination of catchment vegetation (Gordon & Meentemeyer 2006) leading to drastically increased levels of upland erosion, increased sediment supply (Rhoads 1992) and floodplain aggradation (James 1989). Magilligan and McDowell (1997) found that channel narrowing of both bankfull and low flow widths occurred after the removal of cattle from the riparian zone.

In-stream mining directly alters the channel geometry and bed elevation as it involves the removal of sediment from a riverbed (Sandecki 1989). Many studies have documented the consequences of in-stream mining which include: i) channel incision, ii) flood reduction and iii) channel degradation (Rovira et al. 2005). In other words, in-stream mining can lead to the deterioration of channel structures and water quality. James (1989) observed that, after the closure of in-stream mines within the Bear River Basin in America, channels had aggraded, migrated southward and incised through the sediment produced during mining operation into the pre-mining substrate. In addition to the large number of open shafts and tailings accumulations, erosion by river channels is the most noticeable geomorphic consequence of mining (Graf 1979). Although some may expect that mining undertaken adjacent to the river channel will have little to no effect as there is no dredging of the river bed (as is the case for in-stream mining), it has been documented that this type of practice still significantly increases sediment load (Park 1995). Although this increase may only be temporary it can trigger a series of channel changes that can continue for more than a century after mining operations cease (Rhoads 1992). Consequently, gold mining of fluvial sediments, both in-stream and on the banks, has been known to trigger significant channel instability and change (James 1989, 1991).

The construction of roads, commonly built during mining operations, has been associated with the destabilisation of slopes (Reid & Dunne 1984; Price & Leigh 2006) and the rapid development of gullies (Neller 1989, cited in Park 1995). Graf (1979) states that some gullies became stable sixty to seventy years after they began forming. However, gullies containing constrained channels have been known to remain unstable for more than 100 years (Graf 1979).

Humanmade impoundments are known to influence channel morphology by impeding river flows and reducing the supply of sediment to downstream channels (Gaeuman et al 2005; Thoms et al. 2007). The trapping of sediment behind dams lowers the downstream sediment load which is likely to encourage channel incision (James 1991; Gordon & Meentemeyer 2006) and possibly remove gravel-based features (Parsons & Gilvear 2002). The accelerated erosion caused by sediment retention behind reservoirs can extend for hundreds of kilometres below the impoundment and may continue to occur for more than a century (Williams and Wolman (1984) cited in James 1991) although such impacts are less obvious in coarse-grained reaches with well vegetated banks (Ferguson 1981). In addition, channel incision and widening immediately below a dam may be no more important than that occurring further downstream due to the far-reaching influence of the dam structure (Assani & Petit 2004) and some river channels have been found to be narrower than their original channel width downstream of impoundments (Rovira et al. 2005). This variety in responses to dams reflects differences in factors such as the regional environment, location, substrate and the system of sediment and water release (Petts 1980; Brandt 2000; Assani & Petit 2004). For example, in semi-arid rivers, impoundments often result in downstream degradation because of the lack of large, flushing flows.

A wide array of anthropogenic impacts on riverine environments has been identified including increased run-off caused by the trampling of riparian vegetation, increased erosion and gully formation created by mining and the construction of roads, and channel incision downstream of humanmade impoundments. It is difficult to determine, however, what the resultant morphology, and thus geomorphic diversity, of a river channel would be if all of the aforementioned anthropogenic activities had taken place within or alongside a particular river channel at some point in time, since each activity has a different influence on the channel.

1.3. Channel response to external factors

River channels across the globe have different characteristics and behaviours. For example, a channel's width, depth, slope, planform and flow velocity are all influenced by sediment load, sediment type, valley slope and discharge (Hey 1976). Furthermore, Ferguson (1981) identifies that differences in channel slope are likely to occur because rivers vary in size, geology and hydrology. As such, different rivers are bound to respond to disturbances (external factors) in varying ways (Thoms et al. 2007). These responses can be both biological (e.g., increases in vegetation and thus create resistance to flow in the riparian zone) and physical (e.g., adjustments in channel morphology) (Magilligan & McDowell 1997). Some of these responses are subdued and look similar to those that occur within the natural range of river system functions whereas others are more obvious and result in major changes to the character and functioning of the river (Thoms et al. 2007). For example, downstream changes in channel morphology are generally more noticeable in ephemeral rivers, due to factors such as infrequent flooding, flow transmission losses and typically few tributary inflows beyond those observed in the headwater regions (Tooth 2000).

Knighton (2000) suggests that natural rivers have four degrees of freedom in adjusting their channel morphology to external controls. These include cross-sectional form, bed configuration, channel pattern and channel slope. These changes in channel morphology and longitudinal profile (i.e., changes in a channel's geomorphic diversity) can have major impacts on bank stability and riparian corridors (Charron et al. 2008). Therefore, once we have acquired a better understanding of the mechanics and consequences of channel adjustments, it will be possible to model these adjustments using simulation methods (Gregory 1980).

1.3.1 Cross-sectional change

There are two main types of cross-sections used in the study of rivers. The first, known as the valley floodplain cross-section, consists of the channel bed, channel bars, the channel shelf, the floodplain, and terraces (Figure 1(a)) (Hupp & Osterkamp 1996; Gurnell 1997). The second, known as the in-channel cross-section, simply contains the channel bed and channel bars. The channel bed is defined as the part of the channel that is under water at mean discharge, while channel bars are found at the level of approximately 40% flow duration and can support herbaceous plants (Hupp & Osterkamp 1996; Gurnell 1997). The channel shelf is located at around 5-25% flow duration and is covered by riparian shrubs; the floodplain occurs at the level of the 1-3 years flood frequency and supports floodplain woodlands; and terraces are representative of past floodplains (Hupp & Osterkamp 1996; Gurnell 1997). Channels exhibit three distinct zones within their in-channel cross-sectional topography: a point-bar platform along the inner bank; a relatively deep thalweg located along the outer concave cut bank; and the point-bar slope, which makes up the central portion of the channel and connects the other two segments (Figure 1(b)) (Leopold & Wolman 1960; Anthony & Harvey 1991).

Floodplain cross-sections are generally thought to result from existing and previous transitions between fluvial geomorphological processes (governed by the discharge and sediment regime) and hillslope processes (dominated by the relative importance of overland and subsurface flows) and morphological adjustments to these regimes (Gurnell 1997). Conversely, in-channel cross-sections reflect the consequence of morphological adjustments to fluvial processes (Knighton 1982). Anthony and Harvey (1991), for example, report that the most significant effect on cross-sectional adjustment was variations in flow level. In times of high flow (i.e., bankfull and overbank flow), the thalweg is at its maximum depth, the point-bar is at its maximum capacity (i.e., at its steepest) and channel cross-sections display a high asymmetry (Anthony & Harvey 1991). In comparison, during low flows cross-sections tend to be more symmetric. This concept of cross-sectional morphology being dependent on flow frequency and discharge is supported by Tooth (2000) who states that areas where there are little or no tributary inflows, and in the absence of splays, downstream decreases in the in-channel cross-sectional area are likely to reflect decreases in flow frequency and discharge.

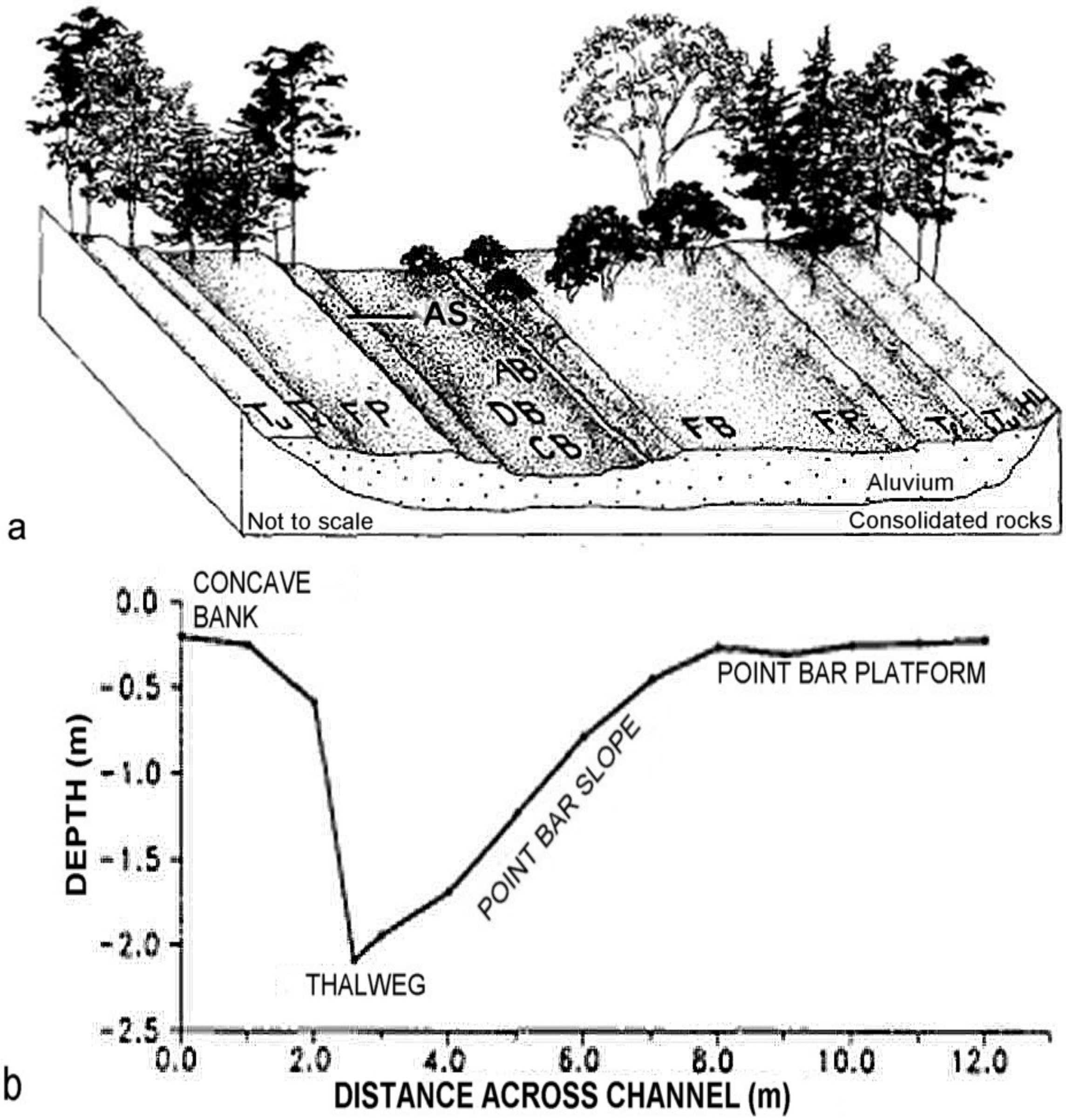


Figure 1: Schematic diagrams of the two main types of cross-sections used in studies of fluvial systems. (a) The valley floodplain cross-section, where AB = channel-shelf bank, AS = channel shelf, CB = channel bed, DB = depositional bar, FB = flood-plain bank, FP = flood plain, HL = hillslope, T_L = lower terrace, T_u = upper terrace (Source: Hupp & Osterkamp 1996). (b) In-channel cross-section (Source: Anthony & Harvey 1991)

Channel widening and narrowing is another form of cross-sectional change. If a channel is too narrow for the given sediment and flow conditions, the rate of bank material erosion will be greater than the rate of deposition due to the high levels of shear stress placed on the banks (Andrews 1982). As a consequence of this, the channel will widen. In comparison, if a river channel is too wide for the given sediment and flow conditions, the rate of suspended sediment deposition will be greater than the rate of erosion, resulting in channel narrowing (Andrews 1982). Gregory (1979) reports that regional climate may also play an important role in the widening and narrowing of river channels. Channels in temperate regions that have been widened by floods with recurrence intervals of between 50 to 200 years may return to their former width in a manner of months or years, compared to rivers in semi-arid regions that may take decades to recover (Wolman and Gerson 1978).

1.3.2 Bed Configuration

Bed configuration refers to the type, structure and spacing (which is usually expressed in units of channel width) of bedforms along a channel (Chin 1999). The relative spacing of bedform structures is thought to maximise flow resistance and hence, moderate bedload transport rate (Richards & Clifford 1991). Anthony and Harvey (1991) suggest that bed configuration is stage-dependent because at low flows pool-riffle spacing bore no relationship to channel planform and little resemblance to high flow morphology. Rhoads (1992) supports this view, reporting that bedforms change with flow depth and respond rapidly to changes in discharge.

In addition, Keller (1972) states that the number of bedform elements within rivers increases with increased channel sinuosity to preserve the average spacing. Ferguson (1981) also argues that these induced channel changes may simply be accelerated versions of adjustments that could occur naturally, provided the same changes in sediment supply, channel slope or hydrologic regime occur. Bowman (1977) also noted changes in channel slope (often believed to cause changes in bed configuration) are often not accompanied by cyclic alternation in channel form, indicating that channel steps do not relate to changes in channel morphology.

As previously mentioned, a river may respond to external influences by altering its bed configuration. A good example of this is when an obstruction, such as woody debris or bedrock outcrops, impedes river flow upstream causing local scour and resulting in the formation of a pool. Numerous studies have been undertaken into the occurrence of such forced bedforms. Keller and Tally (1979), for example, report that accumulations of woody debris can influence the spacing, development and characteristics of pool-riffle sequences in woodland channels. Similarly, Abbe and Montgomery (1996) observe that woody debris jams influenced the formation of scour pools and bars in large rivers while Gregory et al. (1994) found that some channelized rivers have lower interriffle spacings in proportion to channel width than non-channelized rivers.

1.3.3 Channel Pattern

Channel pattern, also known as a channel's planform, is believed to be controlled by bank stability, by reduced sediment transport, and, in low to medium order rivers, by locally enhanced overbank flows created by woody debris dam sites (Gurnell 1997). However, planform may also be controlled by discharge, bed and bank sediment composition, sediment load, and valley slope (Knighton 1987; Park 1995). Timár (2003), for example, concludes that the sinuosity of the Tisza River correlates strongly with the position of subsidence anomalies and faults (i.e., changes in slope). Likewise, flume experiments performed by Schumm and Khan (1972) demonstrated that the sinuosity of the thalweg increased with increasing gradient until it reached a maximum beyond which the sinuosity quickly fell and braiding began to occur. As a result, it is likely that a straight river stretch will transform to a meandering planform as slope increases and the maximum thread of velocity (thalweg) runs alongside one of the riverbanks, allowing selective bank erosion to occur (Richards 1978). Additionally, anabranching may occur when flow is concentrated near the margin of the floodplain (Rhoads 1992).

Some studies (e.g., Vandenberghe 1995; Timár 2003) have even suggested that channel pattern can change in response to historical climatic changes. Gilvear and Bravard (1996) have found that much lower lateral migration rates occur in temperate rivers, but this is believed to reflect, at least in part, the suppression of natural dynamics by human-built structures (Ward et al. 2002).

1.3.4 Long profile and channel slope

Essentially, a stream's long profile is seen as a long-term form element, reflecting the diverse influences of basin geology, watershed evolution, and water discharge and sediment load conditions operating over long periods of time (Knighton 2000). In spite of this, the long profile of a river can change over a period of years and, therefore, can reflect recent adjustments made by the river (Keller et al. 1995) in response to tectonic, geologic and climatic conditions (Cherkauer 1972). Hence, long profile characteristics are believed to be the result of spatially-distributed feedbacks between a variety of form and process variables operating over a range of spatial and temporal scales (Harmar & Clifford 2007). As such, the stream long profile can provide information about short- and long-term aggradation and degradation and, therefore, river stability (Mossa & Kowinski 1998).

Fluctuations observed within long profiles may be caused by the distribution of in-channel structures, particularly pools and riffles. A regular pattern of fluctuations would be expected to be seen in the long profile of a river containing freely formed pools (i.e., rivers exhibiting natural pool-riffle sequences) whereas a random pattern of bed topography would be expected in a stream with many forced pools (Madej 1999).

It is believed that the long profiles of ephemeral streams are no different to perennial streams in that they also adjust to changes in sediment load, roughness and discharge (Cherkauer 1972).

However, Schumm (1961) reported that rivers located in semi-arid areas often exhibit straight or convex long profiles due to downstream decreases in discharge resulting from infiltration and evaporative losses (cited in Goldrick & Bishop 2007). It has also been found that a steep longitudinal gradient can reduce the effects of lateral bedslope with momentum effects governing topographic controls (Lane& Richards 1995).

A channel's slope can vary depending upon the river's planform. For example, a stable, straight channel may have a larger slope than a stable, sinuous channel (Keller & Melhorn 1973). However, the slope of a channel, along with channel area, represents a first-order approximation of the physical conditions at which processes are active (Brardinoni & Hassan 2006). Channel slope is most strongly correlated with discharge, decreasing at a rapid rate as discharge increases (Knighton 2000). In addition, a sharp change in slope may be the result of the river flowing over a region of uplift but could also be caused by flow across a lithologic boundary or an inactive fault (Rhea 1993).

The concavity of a long profile can be affected as a result of lithologic variability, tectonic uplift or downstream decreases in discharge (Morisawa 1968). An uplift of a few millimetres per year may cause minor changes in valley floor slope, which is known to cause significant changes in channel pattern (Burnett & Schumm 1983). However, a river channel may maintain its gradient with gradual increasing valley slope by increasing sinuosity. On the other hand, if the change is more drastic, a meandering river channel may braid with accompanying river channel metamorphosis and possible channel incision (Burnett & Schumm 1983).

1.4 Purpose of study

Although numerous studies have investigated how the aforementioned external factors influence channel morphology (e.g., Abbe & Montgomery 1996, Bartley & Rutherford 2005, Chen et al. 2008) few have looked at more than one external factor at a time. A notable exception to this is the work of Brainwood et al. (2008) who looked at the influences of geologic setting (i.e., valley confinement and channel geology) and impoundments, although their work focused on the influences of these factors on mussel populations rather than geomorphology. In addition, few studies have attempted to measure geomorphic diversity and at present, few studies have looked for the potential controlling factors which influence geomorphic diversity. It is intended that the methods used in this study may be applied to studies of other rivers to further increase our understanding of geomorphic diversity within channels. It is also anticipated that this study will identify surrogates for the biodiversity and overall health of this and other study sites.

1.5 Study objectives

The overall aim of this study is to determine how physical and anthropogenic factors, acting at a range of spatial scales, influence geomorphic diversity within a river reach. This will be done by determining the key external factors that affect channel morphology and investigating how these factors influence variations in the shape and in-channel structure of a river at the cross-sectional, longitudinal and bedform scales. As such, the study questions are: 1) what is the river's geomorphic diversity; 2) how do external factors influence the size, shape and diversity of river systems; and, 3) how do these factors influence changes within the river system?

2 Site description

2.1 Site location, physiography and size

Geomorphic diversity was assessed for the Turon River in the Central West of New South Wales, Australia. The Turon River begins in the hills near Portland and flows in a north-west direction to its convergence with the Macquarie River, near Hill End (Figure 1; Walker 1998). It exhibits traditional pool-riffle morphology (Figure 2), has a mean annual flood of 9,798 ML and a record high flood of 96,191 ML (recorded on 6 August 1986; Figure 3). A considerable number of entrenched meanders occur along the length of the Turon River, allowing for thick deposits of alluvium to build up on the inside banks of the meander bends (Marshall 1969). The Turon River Basin, located to the west of the Great Dividing Range, has an area of approximately 651 km^2, experiences an average annual rainfall of 633 mm with no discernible monthly pattern (Figures 4a & b), and has mean minimum and maximum temperatures of approximately 6.8 and 20.1°C, respectively (Figure 5).

The physiography of the Turon River has been largely determined by regional lithology and geologic structure. In its upper reaches, the Turon River flows through steep sided, V-shaped valleys characterised by razorback ridges, scree-covered slopes and numerous graded tributaries (Marshall 1969). These features are created by the river eroding steeply into Silurian strata (c.f. Marshall 1969). Where the river passes through the Sofala Volcanics, the valleys are wide and U-shaped and it is in these wider valley regions that extensive clearing has taken place to make land available for agricultural purposes.

Rocky outcrops occur along the length of the Turon River, the majority of which consist of large rounded boulders that have been formed by water seeping into their cracked surfaces and freezing (Walker 1998). The other outcrops that can be observed along the river channel are likely to be the remains of historic water races (discussed in section 2.2). Rockfalls are also common along the length of the river.

The study site examined for this investigation is situated on a short reach of the Turon River (Figure 6), approximately 6.5 km east of the town of Sofala (250 km North-West of Sydney). More specifically, the study site is located between latitude and longitudes of 33° 6' 1"S, 143° 45' 1" E and 33° 6' 13" S, 143° 45' 14"E. The study reach has a meandering planform with several mid-channel bars and islands present (Figure 7) and consists of confined and unconfined stretches, vegetated and un-vegetated gravel bars, a large woody debris jam (Figure 8) and a causeway (Figure 9). The banks of the study reach are heavily vegetated by *Casuarina* or grass and reeds although some areas have been overgrown with blackberries. The study reach is approximately 600 m long and has a sinuosity (meander wavelength) of 1.7, a radius of curvature of 705 m and an overall channel gradient of 0.0015.

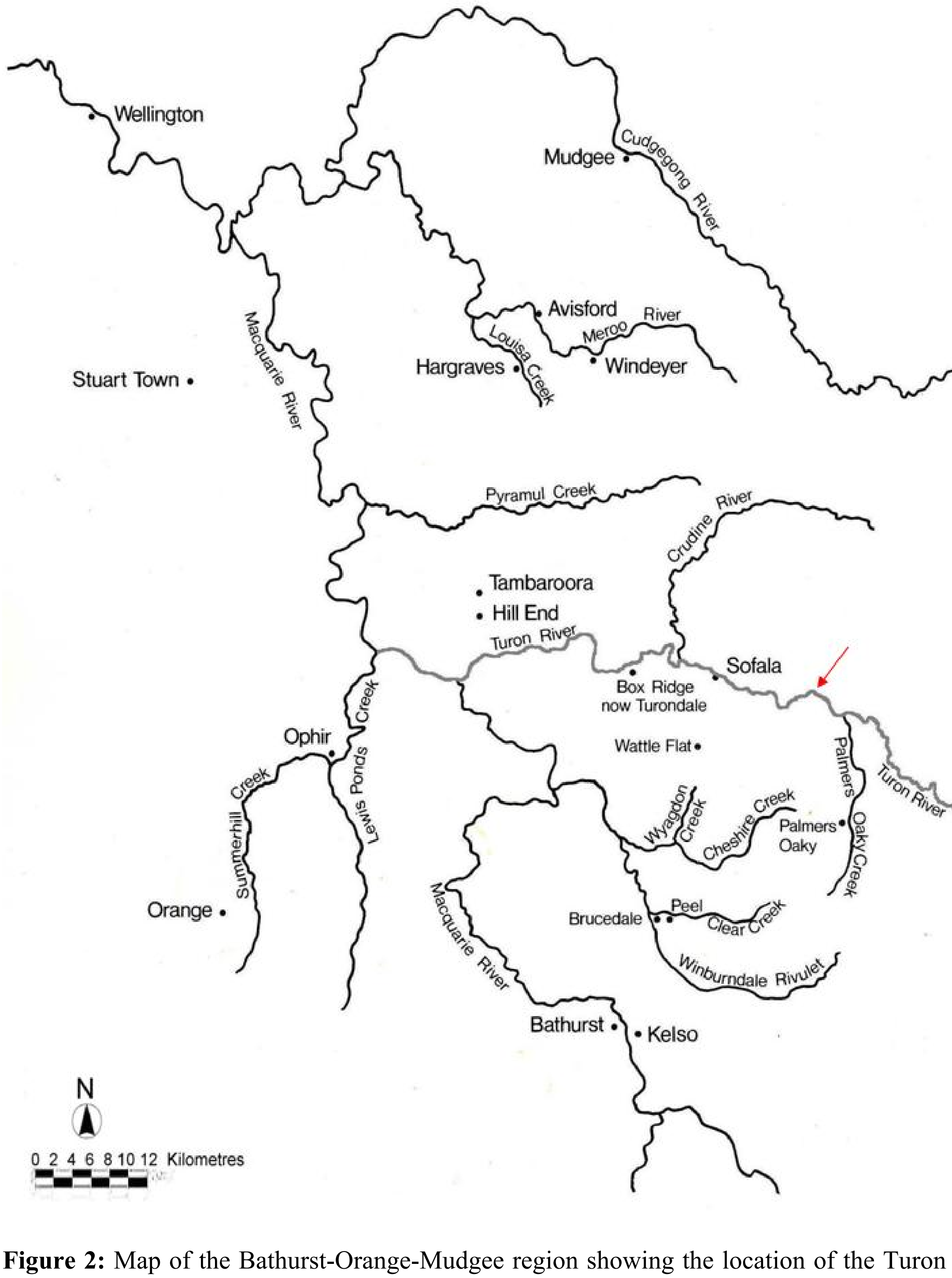


Figure 2: Map of the Bathurst-Orange-Mudgee region showing the location of the Turon River (Source: Higgins 1990).

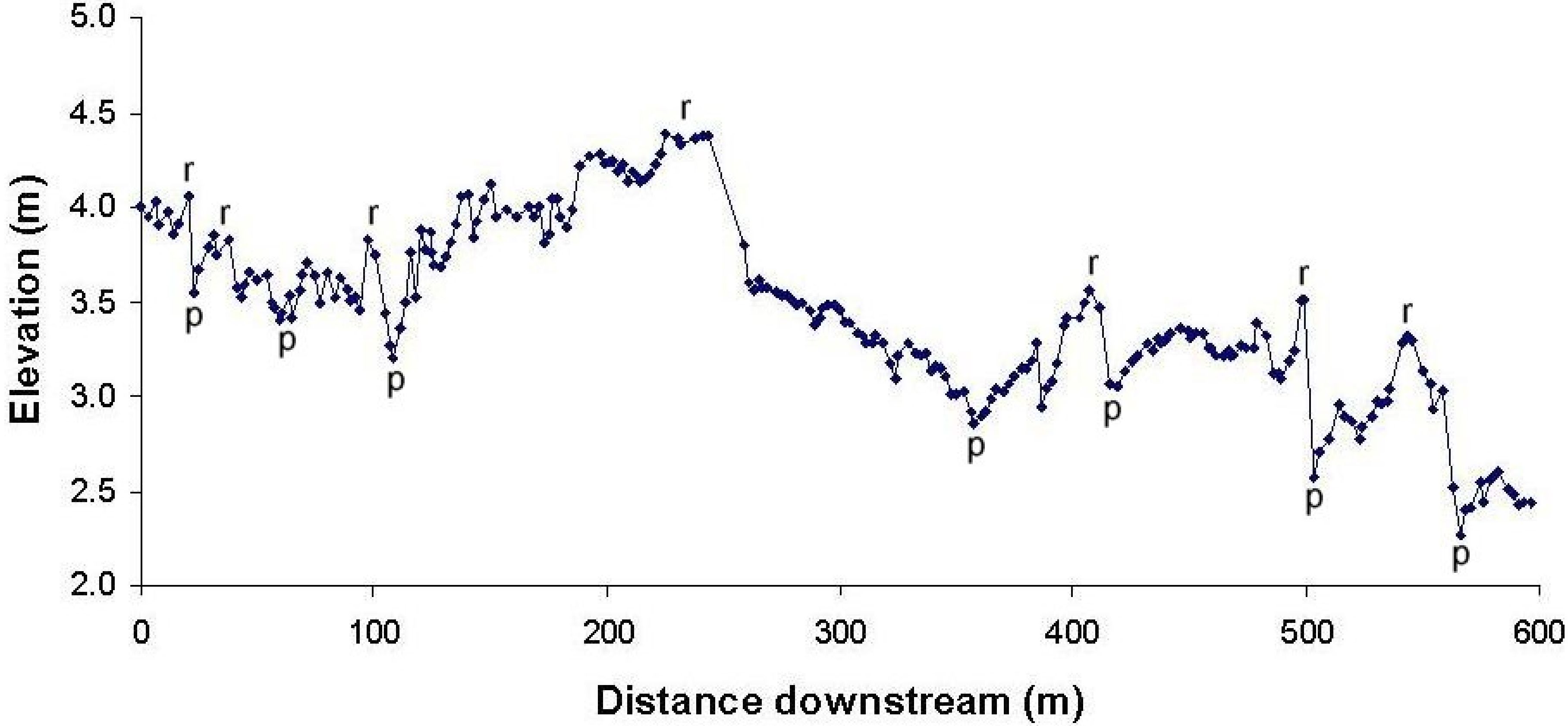
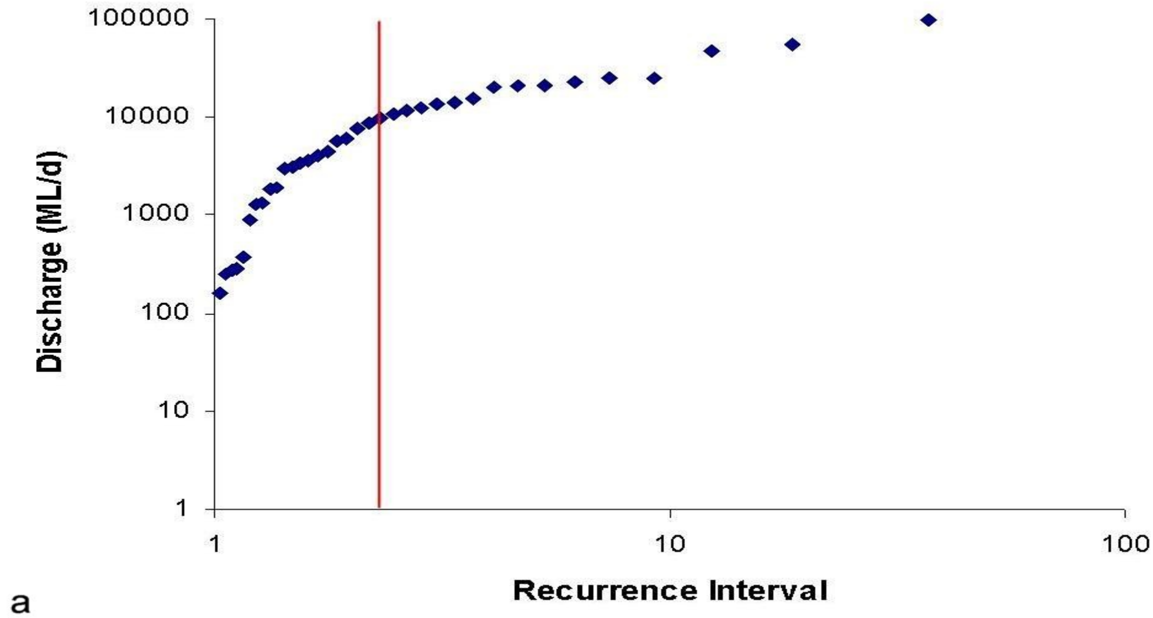


Figure 3: Longitudinal profile of the Turon River depicting the location of pools (p) and riffles (r).



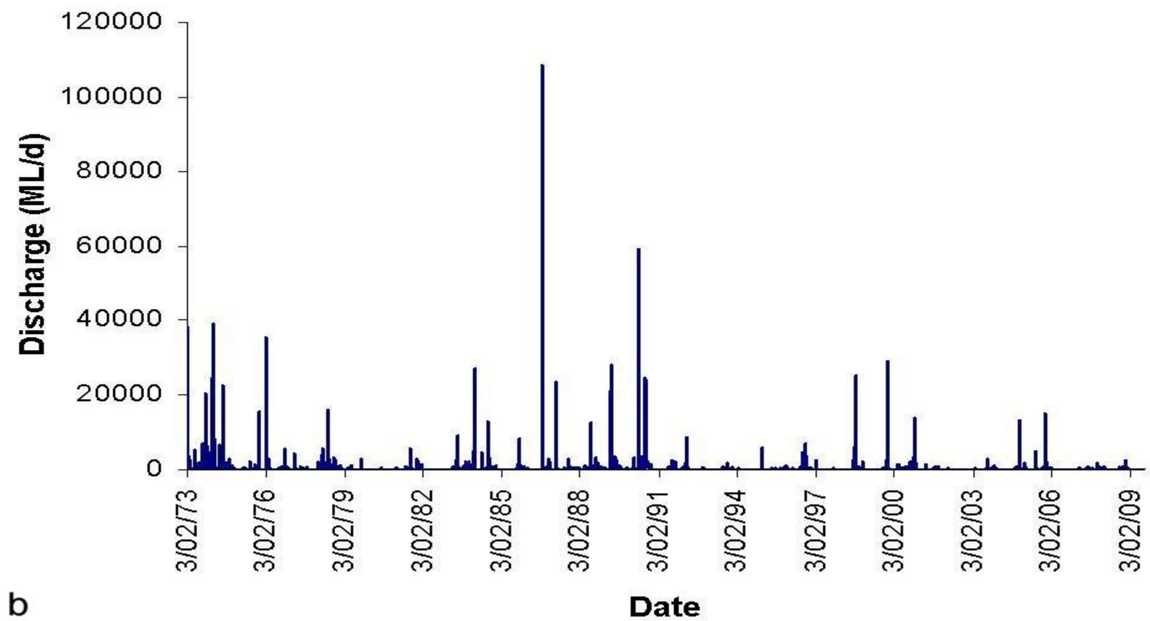


Figure 4: Hydrographs for the Turon River at Sofala depicting a) the recurrence interval for yearly peak discharges (red line denotes the mean annual flood) and b) the daily discharge since the construction of the gauge station.

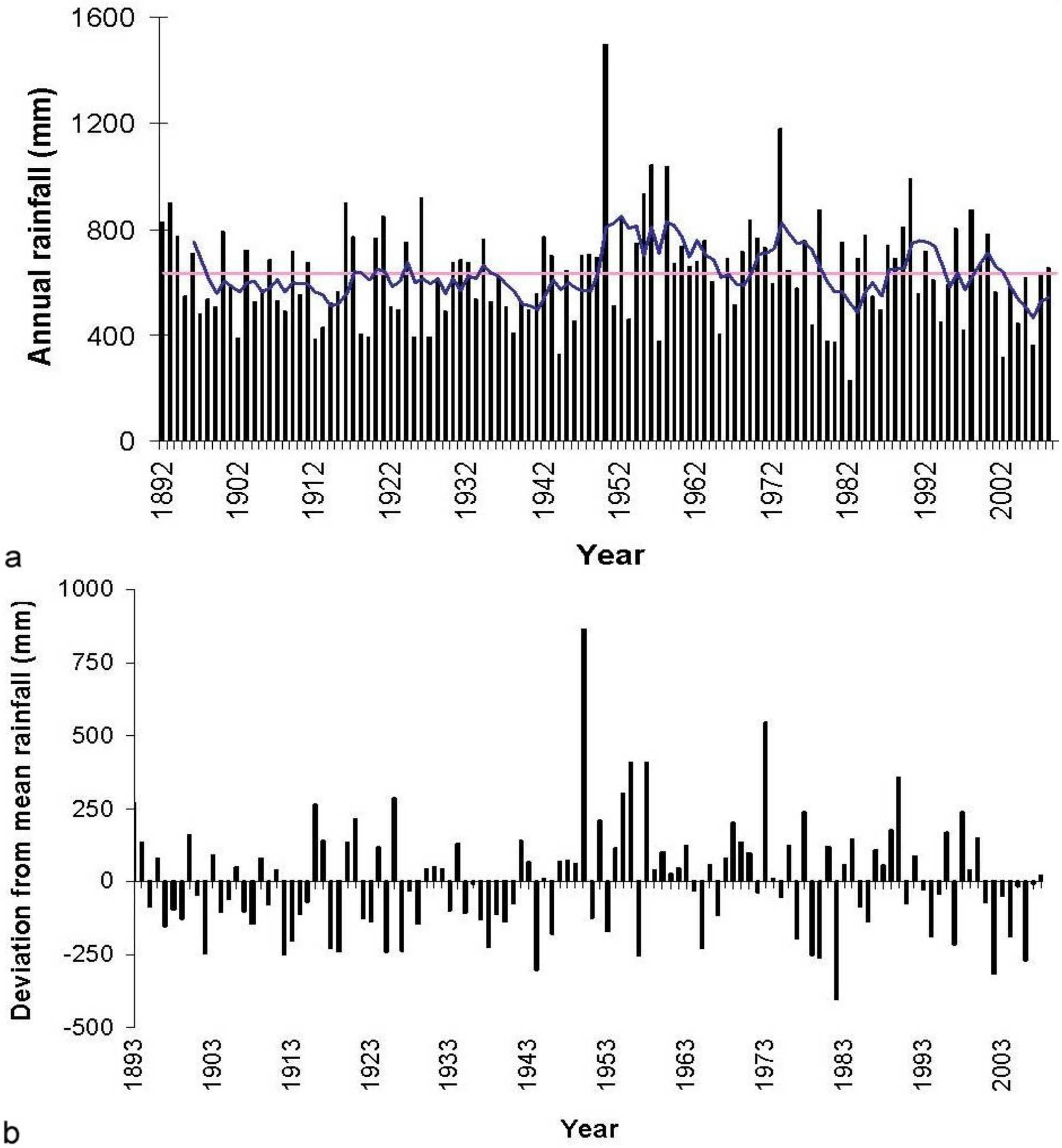


Figure 5: Annual rainfall data for the town of Sofala, situated approximately 6.5km west of the study site. a) Annual rainfall (bars) plotted with the mean annual rainfall (pink line) and five year moving average (blue line). b) Deviation from mean annual rainfall.

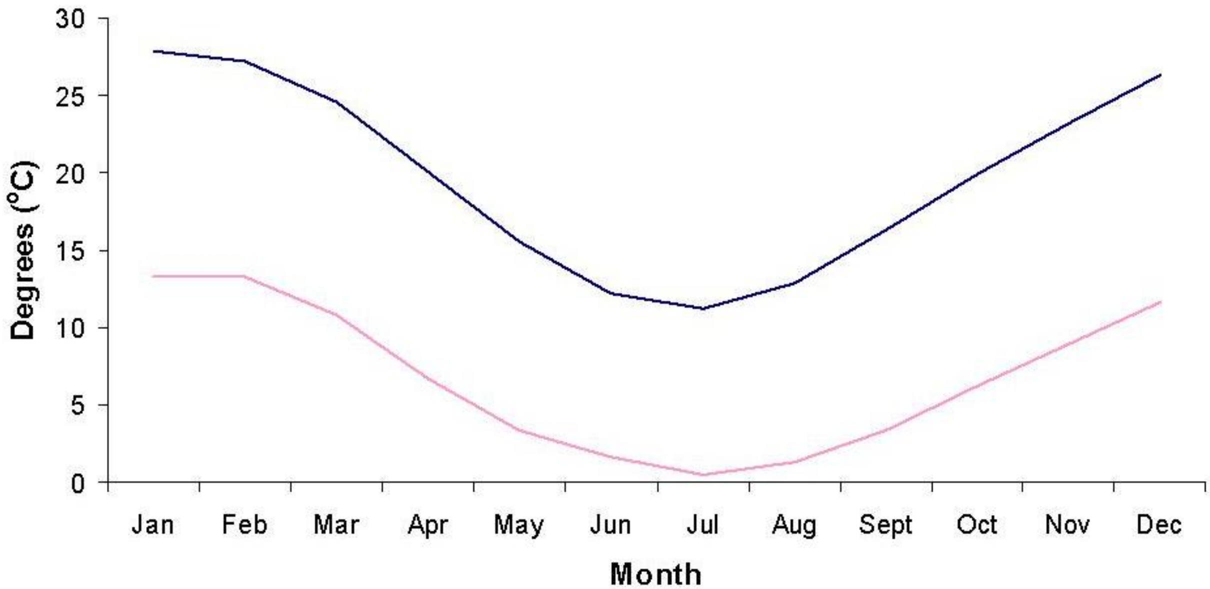


Figure 6: Maximum (blue) and minimum (pink) monthly mean temperature for the Bathurst-Sofala region.

2.2 Historical background and land-use along the Turon River

In 1851, the Turon goldfield was Australia's most populated field with more than 10,000 people working the sediments for gold (Marshall 1969). Ten years later, however, the population had decreased and European miners were in the minority, with 42% of the population (or 1877 people) being of Chinese heritage. A further, more gradual decline in the number of miners followed from 1866 onward (Higgins 1990).

Washing and sluicing was the main technique used to work the river bank deposits, particularly by the Chinese. However, this required a fast, continuous flow of water for cradle operation. Consequently, water races (Figure 10a) were constructed along the Turon River; evidence of which can still be seen along the river valley walls (Figure 10b). In addition, the potential of reef gold (i.e., gold locked in rock-encased quartz veins) had been recognised earlier than the late 1850s, although the development of reef mining was delayed by a preoccupation with the more easily accessible alluvial gold and a lack of expertise. For example, the Turon Ridge Quartz Crushing Company was founded in July 1852, only to be sold out at a loss by January 1853 and for the rest of the 1850s quartz mining was limited to small-scale operations (Higgins 1990). Most gold mining continued to occur to a greater or lesser extent until 1948 when commercial mining ceased.

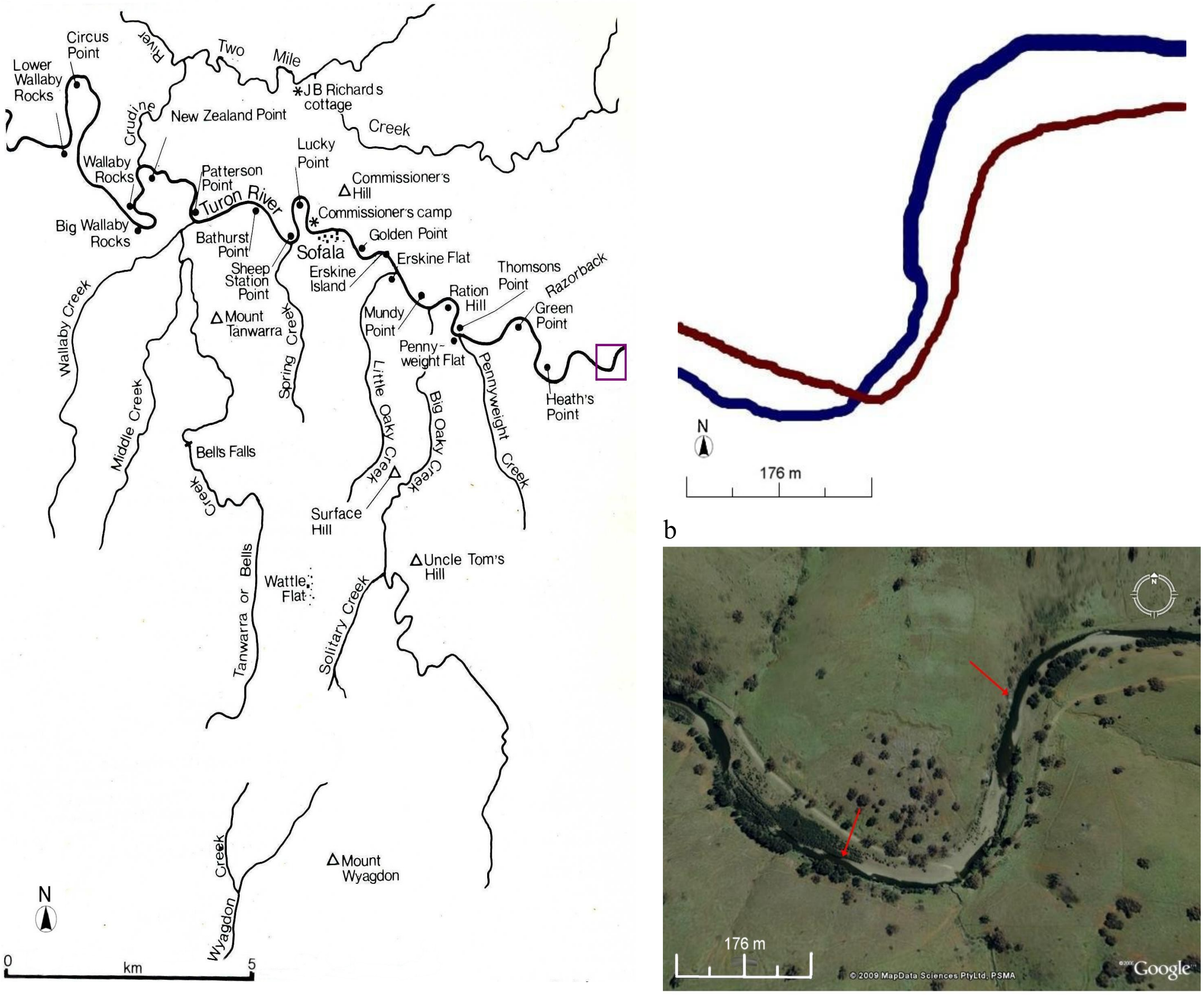


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Figure 7: Regional setting of the study site. a) Location of the study site relative to the town of Sofala (Source: Higgins 1990). b) Planform view of the study reach (blue line) and the adjacent road (brown line) (Primary source: Higgins 1990). c) Aerial image of the study site (reach between the red arrows) (Source: Google Earth).

Agriculture began to play an important role in the continuation of the economy within the Turon goldfields from the 1870s onwards and by the end of the nineteenth century it had become difficult to maintain a decent livelihood from mining alone (Higgins 1990). The hills surrounding the Turon River valley were recognized as good sheep country (Walker 1998) and it was not uncommon to drive past flocks of sheep when travelling through the small towns and some farmers also kept a few cattle on their properties.

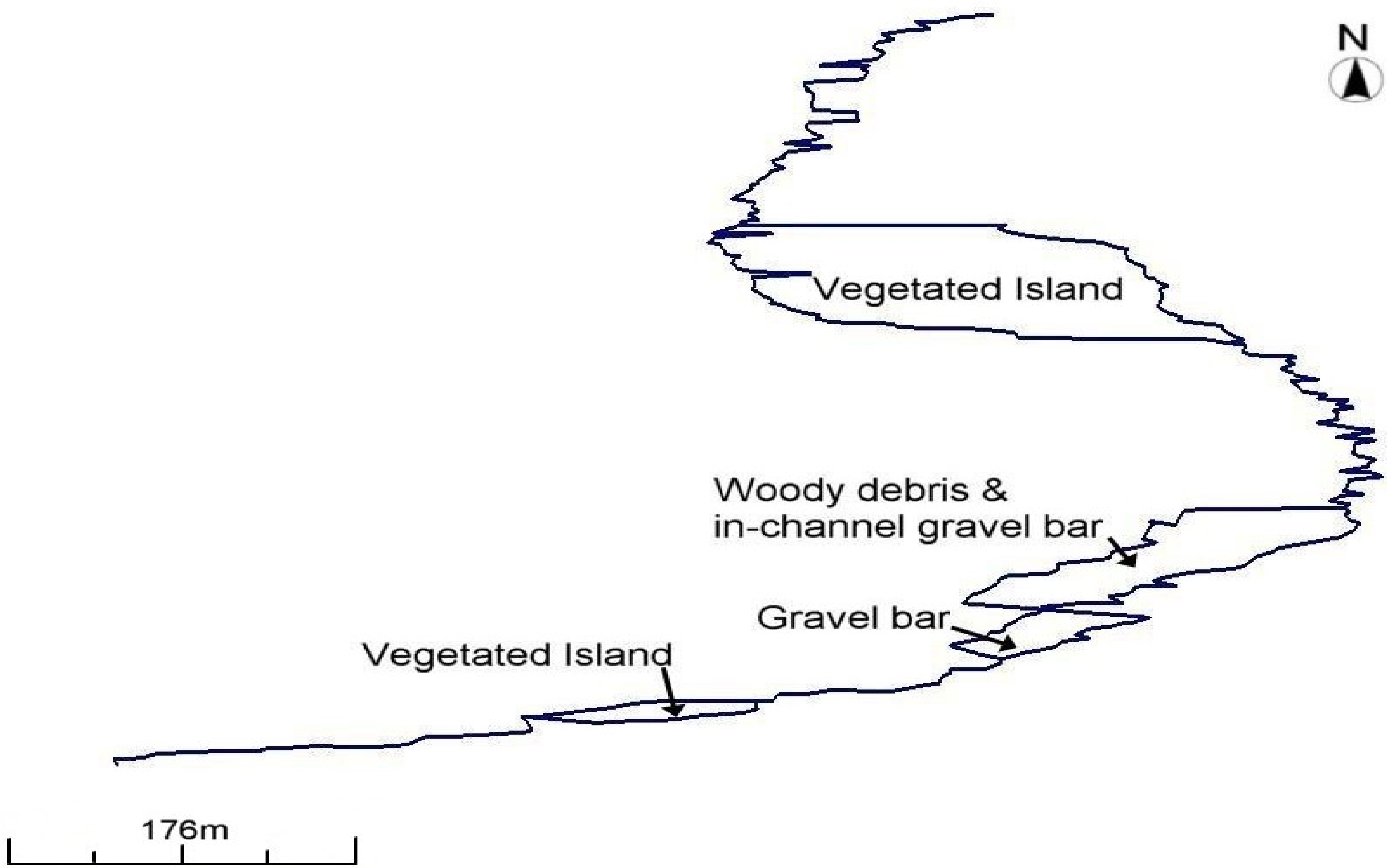
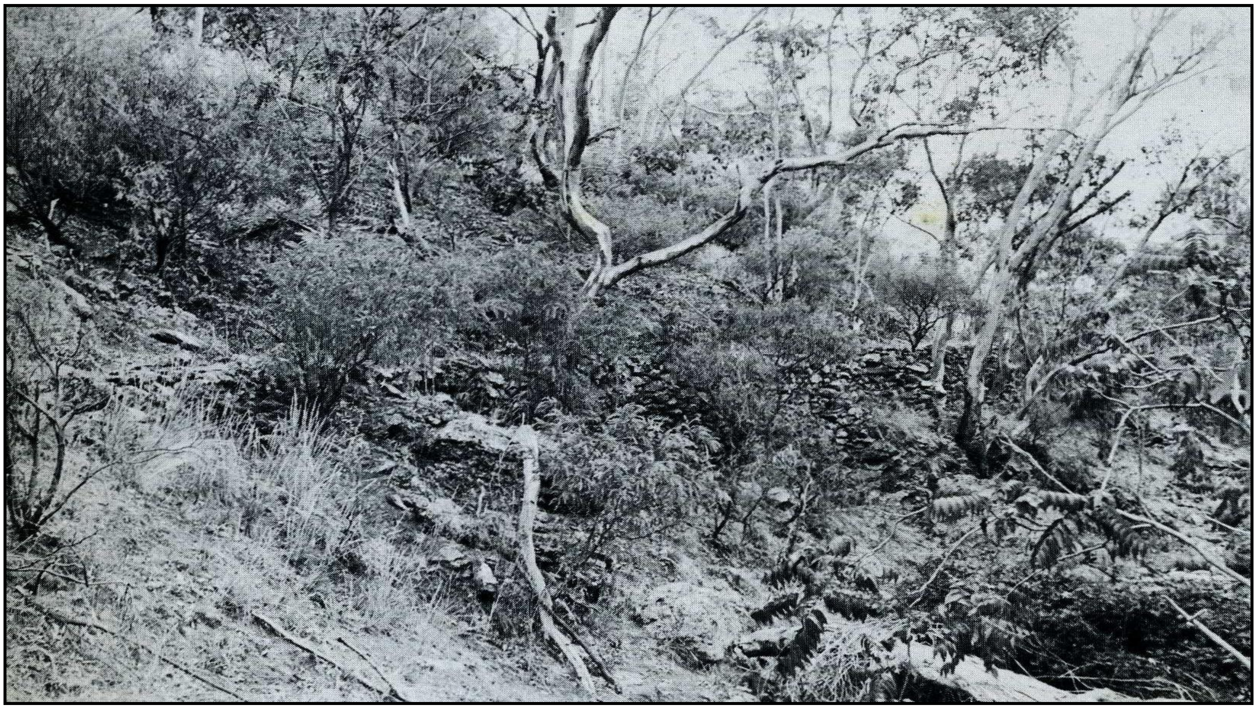


Figure 8: Planform view of the study reach including bifurcations around in-channel islands.

Figure 9: Photograph of the woody debris jam within the study channel.

Figure 10: Photograph of the causeway that crosses the study reach.



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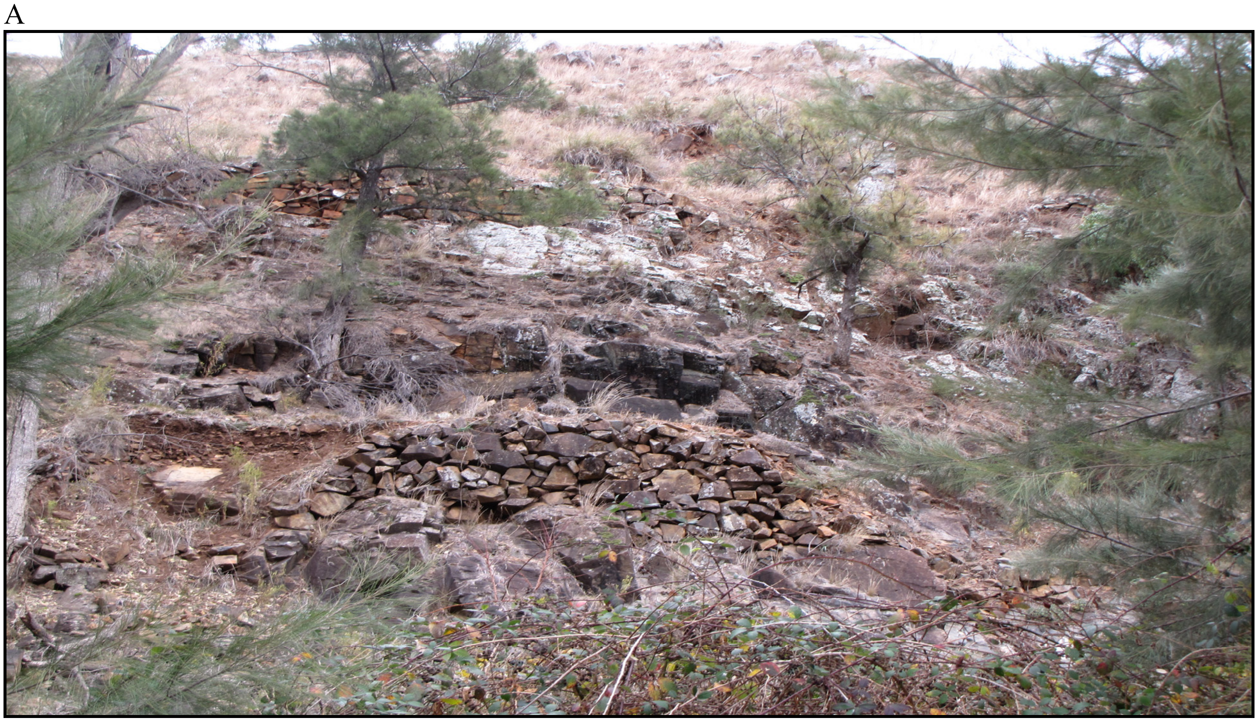

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Figure 11: Photographs of the water races that were built along the slopes of the Turon River valley for gold mining purposes. a) A historic view of a water race on a steep slope that had to be supported with dry stone walls (Source: Higgins 1990). b) The remnants of a water race built on the rocky slopes along the left hand side of the Turon River near the study site.

3 Methods

3.1 Data Collection and Processing

A total of four field trips to the Turon River study site were taken to obtain the data required for this investigation. The first field trip was undertaken over a period of four days (14th-17th April, 2009) to make and record observations of the external factors in the study area. The three subsequent field trips took place over the periods of 12th-14th June, 20th-24th June and 1st-3rd July. During these field trips, a total of 231 cross-sections were recorded using a total station.

Observations on the abundance and type of riparian vegetation, sediment size, valley width, presence of woody debris, distance from the causeway and channel width were recorded and photographs of potentially influencing external factors (e.g., woody debris, riparian vegetation, river valley encroachment and the causeway) were taken. In addition, 231 cross-sections were surveyed, spaced approximately every 2 metres along the river channel (Figure 11). Each cross-section began at the left-hand side of the active channel (when looking downstream) and contained between five and eighteen points depending upon the complexity of the river bed. That is, whenever a notable change in elevation occurred, a point was recorded.

The data collected during the field survey were collated in Microsoft Excel and used to create visual representations of the cross-sections. From these cross-sectional areas, maximum depths, widths, hydraulic radii and irregularities were obtained (where an irregularity is defined as the deviation of the channel cross-section from a channel with low complexity—modelled as a 2nd order polynomial). Average depth and width-to-depth ratios were calculated by dividing cross-sectional area by width and width by depth, respectively.

Cross-sectional asymmetry was determined using Knighton's (1981) formula for A_2 (area and depth displacement relative to the channel centreline) which is given by

$$A_2 = \frac{2x}{W}\frac{(D_{max} - D_{avg})}{D_{avg}}$$

where x is the distance between maximum depth location and the channel centreline, W is the channel width, D_{max} is the maximum depth and D_{avg} is the average depth (Rayburg & Neave 2008). These parameters (i.e., area, width, maximum depth, width-to-depth ratio, average depth, hydraulic radius, irregularity and A_2) were subsequently used to quantify the variability of each classification (refer to section 3.3).

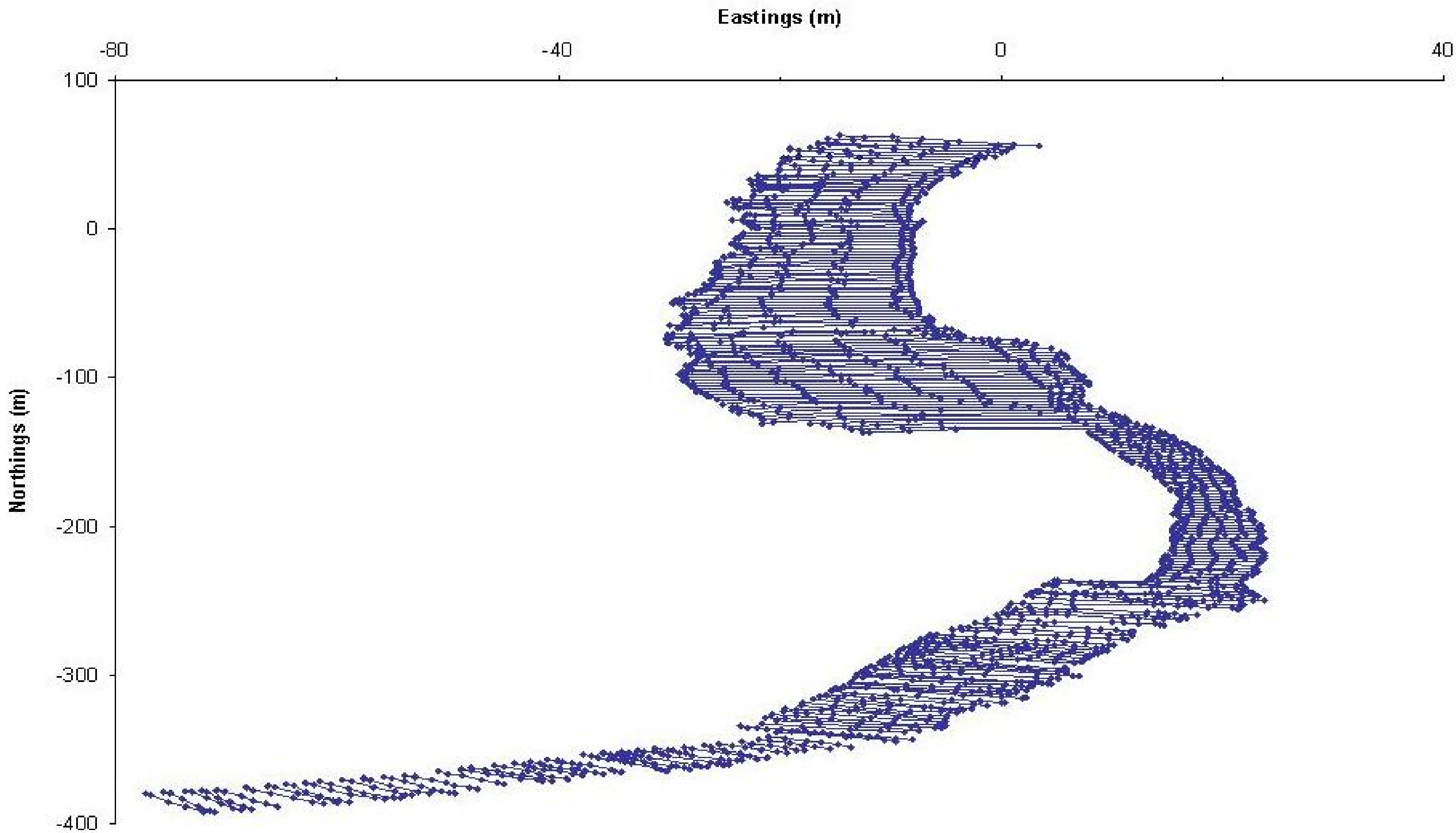

Figure 12: Planform view of the 231 cross-sections that were surveyed along the study reach.

Thalweg measurements of the main channel were extracted from the surveyed cross-sectional data and used to plot the longitudinal profile of the river. Bartley and Rutherford's (2002; 2005) "chain-and-tape" (CT) method and equation for vector dispersion (VD) were then used to determine downstream asymmetry within the resultant long profile. The "chain-and-tape" method calculates the ratio of the downstream topographic bed distance against the straight line distance between points, whilst the vector dispersion method provides a measure of the angular variance between consecutive points. The equations for each method are

$$CT = L_A/L_S$$

$$VD = \frac{(n - [\sum \cos\theta])}{n-1} \text{ or } \frac{(n - [\sum (A/C)])}{n-1}$$

where L_A is the apparent distance downstream, L_S is the linear distance, n is the number of points along the transect (long profile), θ is the angle of each thalweg point from the horizontal, A is the distance along the bed (i.e., distance between points) and C is hypothetical hypotenuse of the right angled triangle containing angle θ and can be found by applying Pythagora's theorem to A and the bed elevation (Figure 12).

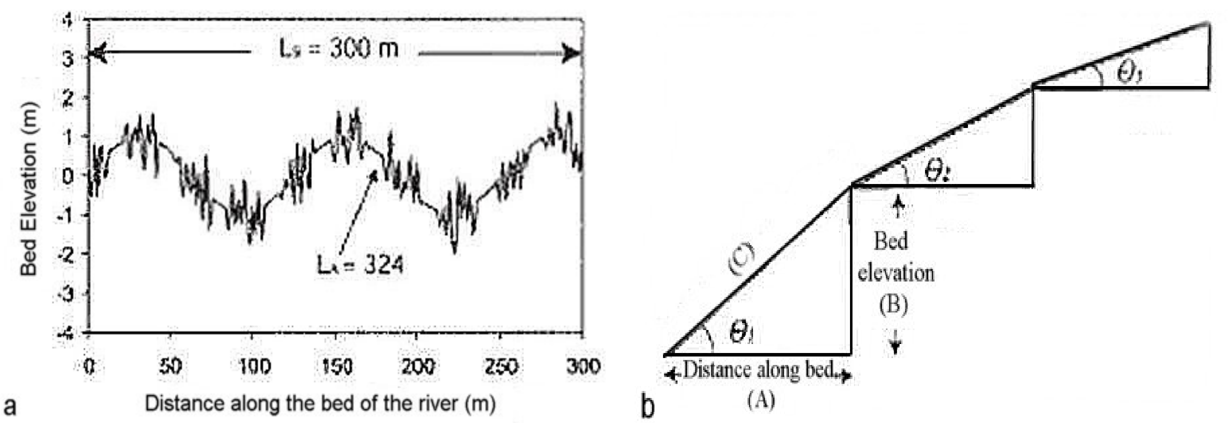

Figure 13: Visual depiction of the calculation of thalweg variables (Source: Bartley & Rutherford 2005). a) Example of the chain-and-tape method, where LA is the apparent distance (distance along the bed) and Ls is the linear distance (straight line distance). b) Representation of vector dispersion technique, where A is the distance along the bed, B is the bed elevation and C is the hypothetical hypotenuse found by using Pythagora's theorem.

To identify the locations of pool and riffle crests and troughs along the longitudinal profile the O'Neill and Abrahams (1984) technique was applied, using a tolerance value of 2-times the standard deviation of the bed elevation series. This technique, however, fails to identify the inflection (or cross-over) points that denote the up- and down-stream limits of each bedform. To remedy this problem the O'Neill and Abrahams (1984) technique was used in conjunction with a revised form of Richard's (1976) regression line method. The Richards (1976) technique can determine the lengths of the individual bedforms and their entrance and exit slopes based on the inflection points (+ or -) of the bed elevation series. That is, when the longitudinal profile crosses the regression line a cross-over point is identified. The result of using these techniques is presented in Figure 2.

A series of parameters, including the mean of all the cross-sectional variables, pool or riffle length, pool depth or riffle height, length-to-mean width, average pool depth or riffle height, and bedform asymmetry, were used to quantify the variability of bedforms within each of the classified groups (refer to section 3.3). Pool-riffle variables, including pool-riffle height, pool-riffle length, asymmetry and spacing, were also calculated. The bedform and pool-riffle (i.e., bar unit) asymmetry were determined using Rayburg and Neave's (2008) formulae for the area and depth displacement relative to the bedform centreline (A_{h1}), pure length asymmetry relative to the pool trough or riffle crest (A_L), length asymmetry of the pool-riffle sequence (A_{L2}) and the asymmetry of riffle height to pool depth (A_H) (Table 1).

Table 1: Definitions and equations if the bedform (i.e., pool or riffle) and bar unit (i.e., pool-riffle sequence) asymmetry indices.

Scale	Type of asymmetry	Asymmetry Index	Formula*	Source
Bedform	Downstream	A_{h1}	$A_{h1} = \frac{2x}{W}\frac{(D_{max} - D_{avg})}{D_{avg}}$	Rayburg and Neave (2008)
	Downstream	A_L	$A_L = \frac{L_{r1} - L_{r2}}{L}$	Rayburg and Neave (2008)
Bar unit	Downstream	A_{L2}	$A_{L2} = \frac{L_p - L_r}{L_t}$	Rayburg and Neave (2008)
	Downstream	A_H	$A_H = \frac{H_p - H_r}{H}$	Rayburg and Neave (2008)

* Variable definitions are listed in Appendix 1

3.2 Analysis of survey data

Descriptive statistics including the minimum, maximum, mean and coefficient of variation (CV) were found for: area, maximum depth, width, average depth, width-to-depth ratio, hydraulic radius, irregularity and A_2 values for the cross-sections; slope, chain-and-tape and vector dispersion values for the long profile; mean cross-sectional variables along with maximum height or depth, average height or depth, length, length-to-width ratio, and asymmetry (A_{h1} and A_L) values for pools and riffles; and height, length, spacing, A_{L2} and A_H values for pool-riffle sequences. The coefficient of variance is a normalised measure of the deviation found within a statistical distribution that is given by the ratio of the standard deviation to the mean. Mann-Whitney U and Levene's tests were then applied to the data to calculate if there were statistically significant differences between each of the aforementioned cross-sectional, long profile, bedform and bar unit variables within each of the classification groups. The Mann-Whitney U test assesses if significant differences are present between two independent samples by determining whether or not the two samples have equal probability distributions. Levene's test, on the other hand, compares the variances of the two samples.

3.3 Classification of variables into groups

All of the cross-sectional, long profile, bedform and bar unit variables were placed into groups based on the external factors in the surrounding area. Sections within the study reach were classified based on the extent of confinement (i.e., confined, partially confined and unconfined), the type of channel confinement (i.e., valley confined or terrace confined), the number of banks covered by riparian vegetation, the type of riparian vegetation present (i.e., minimal vegetation, grass, she-oak and/or blackberries, and a combination of both grass and she-oak and/or blackberries), the presence of woody debris, the proximity to a manmade causeway and whether or not obstructions, such as islands, were present. Variables within the group "woody debris present" were also further subdivided based on the type of woody debris present (i.e., in-channel woody debris and woody debris on the river bank). The potential effect of the causeway was determined by both the distance from the causeway and whether the sections were up- or down-stream of the causeway. The causeway was considered as having a probability of impact on sections within 50 m of it, while areas more than 50 m away from the causeway were not expected to be effected.

4 Results

The results of this study have been presented in order of the scale at which the external factors operate, starting with large-scale factors (i.e., confinement), progressing to intermediate scale (i.e., riparian vegetation) and ending with small-scale influences (i.e., woody debris, in-channel obstructions and impoundment). Within each scale of influence, the results are further subdivided into the influences each external factor has on the different scales of river channel components, starting with cross-sections, through to long-profiles, and finishing with bedforms and bar units. Visual representations of the 231 cross-sections, 14 bedforms (i.e., seven pools and seven riffles) and seven bar unit sequences surveyed in this study are presented in Appendix 2. Descriptive statistics of the variables quantifying geomorphic diversity at each scale and the results of pairwise uni-variate analyses of the variables found within each group (based on the external factors studied) are presented in the subsequent sections.

4.1 Confinement

The majority of the confined section of the Turon River investigated in this study consisted of areas classified as valley impinged. These areas contained cross-sections displaying gentle slopes from the left-hand side of the active channel to the thalweg (or zone of maximum depth) and steeply sloped channel beds along their right-hand sides (Figure 14(a) and (b)). Partially valley confined cross-sections exhibited a slightly different configuration, with fairly short, steep slopes along the left-hand side of the channel, followed by steep gradients rising to backwaters where the channel beds flattened out (Figure 14(c) and (d)). The unconfined river reach began with narrow cross-sections containing very little structural diversity (Figure 14(e)) but gradually became more diverse further downstream (Figure 14(f)). Finally, the terrace confined reach contained cross-sections that closely resembled those found within the valley confined reach (although with somewhat gentler slopes), although the steeper slopes were on the left-hand sides of these channels (Figure 14(g) and (h)).

Descriptive statistics for the cross-sectional variables are presented in Table 2 and the tests for significant differences between variables are provided in Table 3. These results indicate that, on average, the confined reaches are larger, deeper, wider and more asymmetric than the unconfined reaches while the average width-depth ratio and hydraulic radius data suggest that the confined channels are wider relative to their depths than the unconfined channels. When the confined reaches are further subdivided into their constituent parts of valley, terrace and partially valley confined, however, the partially valley confined reaches stand out as having channels that are

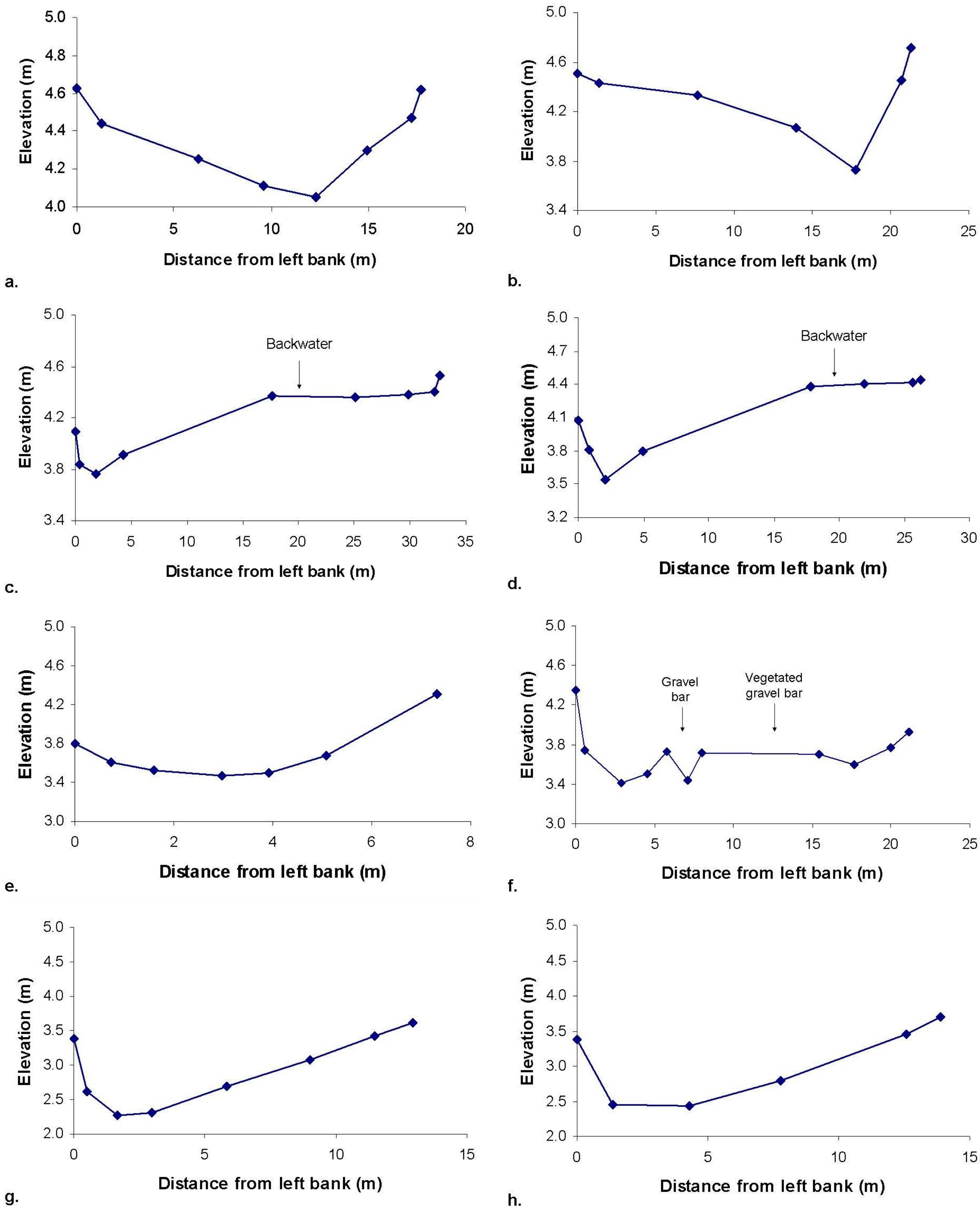

Figure 14: Representative cross-sections from the Turon River: (a) and (b) valley confined; (c) and (d) partially valley confined; (e) and (f) unconfined; (g) and (h) terrace confined.

smaller, deeper and less asymmetric than the other confined reach types. Assessments of cross-sectional parameter variability indicate that the confined reaches are typically less variable than the unconfined reaches (Table 3(b)). Comparing the various confinement types, the partially valley confined reaches are generally more diverse than the valley confined reaches while the relationships between the other confinement types are less clear.

Table 2: Descriptive statistics for cross-sectional variables of confined (a), valley confined (b), terrace confined (c), partially valley confined (d) and unconfined (e) river reaches.

(a)

	Area (m^2)	Max. Depth (m)	Width (m)	W/D	Avg. Depth (m)	Hydraulic Radius (m)	Irregularity	A_2
Mean	4.41	0.58	13.64	57.61	0.30	0.29	1.006	0.568
Min.	0.10	0.08	1.51	17.47	0.04	0.04	1.000	0.014
Max.	8.59	1.29	24.83	208.36	0.64	0.61	1.028	1.763
CV	0.62	0.55	0.43	0.63	0.55	0.55	0.005	0.647

(b)

Mean	4.81	0.61	15.22	63.14	0.30	0.29	1.006	0.644
Min.	0.10	0.08	2.55	25.20	0.04	0.04	1.000	0.027
Max.	8.59	1.29	24.83	208.36	0.57	0.56	1.020	1.763
CV	0.56	0.53	0.37	0.59	0.51	0.51	0.005	0.544

(c)

Mean	3.19	0.51	8.82	40.74	0.30	0.30	1.007	0.335
Min.	0.13	0.10	1.51	17.47	0.05	0.04	1.000	0.014
Max.	7.88	1.11	12.70	152.69	0.64	0.61	1.028	1.613
CV	0.82	0.64	0.39	0.68	0.67	0.67	0.007	0.955

(d)

Mean	1.65	0.31	10.91	213.29	0.14	0.14	1.004	0.131
Min.	0.06	0.01	3.58	31.26	0.01	0.01	1.000	0.006
Max.	4.26	0.65	24.29	1792.28	0.29	0.28	1.022	0.350
CV	0.81	0.66	0.46	1.86	0.62	0.61	0.006	0.815

(e)

Mean	1.82	0.36	8.01	54.35	0.22	0.21	1.007	0.360
Min.	0.04	0.04	1.33	6.52	0.01	0.01	1.000	0.001
Max.	5.57	0.83	19.99	386.26	0.55	0.53	1.040	2.940
CV	0.75	0.50	0.54	1.04	0.58	0.56	0.008	1.258

N.B.: W/D represents width-to-depth ratio; Min. represents minimum; Max. represents maximum; CV represents coefficient of variation.

Table 3: Significance (P) values for the comparison of cross-sectional variables within each confinement category, using (a) Mann-Whitney U and (b) Levene's tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Area	Max. Depth	Width	W/D	Avg. Depth	Hydraulic Radius	Irregularity	A_2
Conf. v Unconf.	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.0007**	**< 0.0001**	**< 0.0001**	0.7591	**< 0.0001**
Val. v Unconf.	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.9363	**< 0.0001**
Ter. v Unconf.	**0.0248**	0.0547	0.0779	0.5115	0.0724	0.0643	0.5307	0.0776
Part. Val. v Unconf.	0.5616	0.2305	**0.0055**	**0.0001**	**0.0108**	**0.0110**	0.0813	**0.0063**
Val. v Part. Val.	**< 0.0001**	**0.0002**	**0.0008**	**0.0192**	**< 0.0001**	**< 0.0001**	0.0657	0.5625
Ter. v Part. Val.	0.0566	**0.0484**	0.4222	**< 0.0001**	**0.0100**	**0.0082**	0.0655	**0.0003**
Val. v Ter.	**0.0015**	0.1029	**< 0.0001**	**< 0.0001**	0.9253	0.9357	0.5254	**< 0.0001**

(b)

	Area	Max. Depth	Width	W/D	Avg. Depth	Hydraulic Radius	Irregularity	A_2
Conf. v Unconf.	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.0154**	**< 0.0001**	**< 0.0001**	**0.0045**	0.8907
Val. v Unconf.	**< 0.0001**	**< 0.0001**	**0.0166**	**0.0440**	**0.0008**	**0.0003**	**0.0016**	0.3170
Ter. v Unconf.	**< 0.0001**	**< 0.0001**	0.3566	**0.0206**	**< 0.0001**	**< 0.0001**	0.5308	0.8825
Part. Val. v Unconf.	0.7307	0.2606	0.8191	**< 0.0001**	0.1000	0.1099	0.2479	**0.0088**
Val. v Part. Val.	**0.0002**	**0.0060**	0.3543	**< 0.0001**	**0.0004**	**0.0004**	0.6241	0.9954
Ter. v Part. Val.	**< 0.0001**	**0.0007**	0.4061	**0.0006**	**< 0.0001**	**< 0.0001**	0.4843	0.4133
Val. v Ter.	0.9440	0.5379	**0.0238**	0.0940	**0.0003**	**0.0005**	0.0666	0.2530

N.B.: Conf. stands for confined; Unconf. Stands for unconfined; Val. Stands for valley confined; Ter. stands for terrace confined and Part. Val. Stands for partially valley confined.

The average slopes of the long-profiles for the confined and unconfined reaches were comparable with mean gradients of -0.0003 and -0.0001, respectively (Table 4). However, the variability of the confined slopes was greater than that of the unconfined slopes (Tables 4 and 5). A consideration of the average size and angle of bed undulations (the chain-and-tape and vector dispersion values, respectively) indicates that the unconfined reaches had greater distances between the heights and depths of their bed undulations but that their bed undulations were not as steep as those in the confined reaches.

Table 4: Descriptive statistics for long-profile variables of confined (a), valley confined (b), terrace confined (c), partially valley confined (d) and unconfined (e) river reaches.

(a)

	Slope	CT	VD
Mean	-0.0003	1.232	0.497
Min.	-0.0266	1.000	0.432
Max.	0.0131	1.310	1.433
CV	-15.1404	0.046	0.231

(b)

Mean	-0.0003	1.211	0.518
Min.	-0.0266	1.000	0.470
Max.	0.0131	1.293	1.433
CV	-13.6131	0.043	0.248

(c)

Mean	-0.0001	1.287	0.440
Min.	-0.0022	1.253	0.432
Max.	0.0006	1.310	0.450
CV	-9.7567	0.012	0.011

(d)

Mean	0.0001	1.242	0.493
Min.	-0.0006	1.219	0.486
Max.	0.0005	1.319	0.496
CV	5.1697	0.025	0.006

(e)

Mean	-0.0001	1.277	0.466
Min.	-0.0028	1.252	0.449
Max.	0.0006	1.317	0.487
CV	-7.0088	0.014	0.027

N.B: CT represents Chain-and-Tape; VD represents Vector Dispersion; Min. represents minimum, Max. represents maximum; CV represents coefficient of variance

Bedforms within confined reaches consisted of cross-sections that were larger, deeper, more asymmetric and more variable in terms of their depths than bedforms in unconfined reaches (Table 6). There were no significant differences, however, between bedforms in confined and unconfined reaches in terms of their downstream characteristics (Table 7(a)).

Table 5: Significance (P) values for the comparison of long-profile variables within each confinement classification, using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Slope	CT	VD
Conf. v Unconf.	0.2489	**< 0.0001**	**< 0.0001**
Val. v Unconf.	0.2533	**< 0.0001**	**< 0.0001**
Ter. v Unconf.	0.5300	**0.0088**	**< 0.0001**
Conf. v Part. Val.	0.8854	0.7450	**0.0004**
Val. v Part. Val.	0.9290	**0.0427**	**0.0052**
Ter. V Part. Val.	0.4894	**0.0001**	**< 0.0001**
Part. Val. v Unconf.	0.1969	**< 0.0001**	**< 0.0001**
Val. V Ter.	0.4794	**< 0.0001**	**< 0.0001**

(b)

	Slope	CT	VD
Conf. v Unconf.	**< 0.0001**	**< 0.0001**	**0.0012**
Val. v Unconf.	**< 0.0001**	**0.0001**	**< 0.0001**
Ter. v Unconf.	0.2091	**0.0466**	**< 0.0001**
Conf. v Part. Val.	0.1589	0.2437	0.1745
Val. v Part. Val.	0.0942	0.4847	0.1190
Ter. V Part. Val.	0.8344	**0.0130**	**0.0327**
Part. Val. v Unconf.	0.5397	**0.0200**	**< 0.0001**
Val. V Ter.	**0.0046**	**0.0054**	**0.0092**

N.B.: CT represents Chain-and-Tape; VD represents Vector Dispersion; Conf. represents confined; Unconf. represents unconfined; Val. represents valley confined; Ter. represents terrace confined and Part. Val. represents partially valley confined.

When considering the individual confinement types, the bedforms in valley confined reaches stood out as being significantly different to the unconfined bedforms by having cross-sections that were substantially larger, deeper, wider and more asymmetric (Tables 6 and 7(a)). Once again, however, the downstream (long-profile) characteristics of the bedforms (such as bedform length or asymmetry) were not significantly different between the valley confined and unconfined reaches. The valley confined reaches also had bedform cross-sections that were significantly larger, deeper and wider than those in terrace confined reaches. Very few statistical differences were observed between reaches in terms of the variability of bedform features (both cross-sectional and downstream) (Table 7(b)).

Table 6: Descriptive statistics for bedform (i.e., pool or riffle) variables of confined (a), valley confined (b), terrace confined (c), and unconfined (d) river reaches.

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Max. Height or Depth (m)	Avg. Height or Depth (m)	Length (m)	L/W	A_{h1}	A_L
(a)														
Mean	5.60	0.73	14.06	46.39	0.38	0.37	1.007	0.488	0.51	0.22	40.35	3.11	0.669	0.544
Min.	1.10	0.25	7.25	23.48	0.14	0.14	1.002	0.273	0.23	0.09	7.81	0.46	0.175	0.160
Max.	7.79	1.09	17.52	109.00	0.51	0.50	1.014	0.947	1.06	0.50	193.64	13.59	1.406	0.893
CV	0.45	0.41	0.26	0.52	0.36	0.36	0.004	0.452	0.58	0.53	1.36	1.25	0.660	0.516
(b)														
Mean	6.70	0.83	16.15	48.32	0.41	0.41	1.007	0.555	0.44	0.21	43.86	2.94	0.555	0.557
Min.	3.23	0.43	14.25	30.97	0.22	0.22	1.002	0.273	0.23	0.09	7.81	0.46	0.175	0.160
Max.	7.79	1.09	17.52	109.00	0.50	0.49	1.014	0.947	1.06	0.50	193.64	13.59	1.171	0.893
CV	0.25	0.29	0.08	0.57	0.24	0.24	0.004	0.423	0.67	0.66	1.52	1.61	0.573	0.545
(c)														
Mean	3.04	0.49	9.19	41.88	0.29	0.28	1.006	0.332	0.69	0.26	32.15	3.49	0.936	0.515
Min.	1.10	0.25	7.25	23.48	0.14	0.14	1.003	0.303	0.39	0.20	24.04	3.32	0.194	0.219
Max.	5.79	0.85	10.96	52.90	0.51	0.50	1.010	0.371	0.93	0.33	37.68	3.71	1.406	0.772
CV	0.81	0.65	0.20	0.38	0.68	0.67	0.003	0.106	0.40	0.26	0.22	0.06	0.694	0.541
(d)														
Mean	2.03	0.41	8.47	46.74	0.24	0.24	1.009	0.266	0.38	0.19	48.19	5.47	0.505	0.498
Min.	0.82	0.27	5.64	25.74	0.16	0.16	1.004	0.188	0.19	0.11	11.02	1.57	0.123	0.144
Max.	2.61	0.52	13.79	82.17	0.33	0.32	1.012	0.355	0.53	0.28	88.94	11.97	0.824	0.949
CV	0.41	0.30	0.43	0.57	0.34	0.33	0.004	0.267	0.37	0.45	0.85	0.85	0.622	0.688

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Min. represents minimum; CV represents coefficient of variation.

Table 7: Significance (P) values for the comparison of bedform (i.e., pool or riffle) variables within each confinement classification, using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Max. Height or Depth	Avg. Height or Depth	Length	L/W	A_{h1}	A_L
Conf. v Unconf.	**0.0339**	0.0897	**0.0237**	0.8875	0.0897	0.0897	0.3961	**0.0339**	0.771	1.0000	0.7773	0.2579	0.5716	0.7773
Val. v Unconf.	**0.0082**	**0.0233**	**0.0082**	0.7055	**0.0233**	**0.0233**	0.5708	**0.0376**	0.8498	0.7055	0.7055	0.1306	0.8501	0.8501
Ter. V Unconf.	0.7237	1.0000	0.4795	0.7237	1.0000	1.0000	0.2888	0.1573	0.2888	0.4795	1.0000	1.0000	0.2888	0.7237
Val. v Ter.	**0.0304**	**0.0527**	**0.0167**	0.9093	0.4250	0.4250	0.9093	0.1385	0.1373	0.2100	0.2100	0.0874	0.3051	0.7324

(b)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Max. Height or Depth	Avg. Height or Depth	Length	L/W	A_{h1}	A_L
Conf. v Unconf.	0.0509	**0.0275**	0.8159	0.6075	0.1597	0.1436	0.8280	0.0560	0.0825	0.8643	0.8480	0.5680	0.3380	0.9678
Val. v Unconf.	0.2921	0.2378	0.0564	0.8372	0.8794	0.8185	0.9334	0.0652	0.2966	0.7592	0.7614	0.8853	0.8211	0.8114
Ter. v Unconf.	0.0738	0.0777	0.3206	0.3271	0.1006	0.0960	0.6187	0.2799	0.2376	0.2481	**0.0002**	0.0955	0.1303	0.7056
Val. v Ter.	0.3956	0.5829	0.5632	0.6210	0.1262	0.1309	0.7097	0.0585	0.9609	0.5389	0.2280	0.1918	0.1049	0.3417

N.B.: Max. represents maximum; W/D represent width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Conf. represents confined; Unconf. represents unconfined; Val. represents valley confined; Ter. represents terrace confined and Part. Val. represents partially valley confined.

Descriptive statistics for the bar unit variables are provided in Table 8. There was only one unconfined bar unit sequence surveyed during this study which prevented comparative analyses between it and the features observed within the confined reaches. At a significance level of 0.05, both Mann-Whitney U and Levene's tests produced no significant differences for any of the variables when comparing bar unit sequences in the only confined reach types that had them (i.e., valley and terrace confined) (Table 9).

4.2 Riparian Vegetation

Cross-sections that only had one bank covered in riparian vegetation were generally parabolic in shape with little to no undulations on the channel bed and gently sloping banks on both sides (Figure 15(a) and (b)). Cross-sections where both banks were covered in riparian vegetation were triangular in shape and had relatively steep slopes (Figure 15(c) and (d)). Sections with minimal vegetation contained cross-sections that were either flat (e.g., Figure 15(e)) or consisted of two triangular shaped channels separated by an obstruction, such as an island or gravel bar (Figure 15(f)). Grass-lined cross-sections (Figure 15(g) and (h)) looked similar to those with she-oak and/or blackberries covering their banks (Figure 15(i) and (j)) with the thalweg skewed to one side. Finally, cross-sections containing both grass and she-oak and/or blackberry covered banks were relatively parabolic in shape but still had a thalweg that was skewed to one side (Figure 15(k) and (l)).

The influence of vegetation on channel form was examined in two ways. Initially, cross-sections with riparian vegetation on either one or two banks were compared (Table 10). The cross-sections were then further analysed according to the vegetation classes of minimal vegetation, grass cover, she-oak and/or blackberry cover, and grass with she-oak and/or blackberries (Table 11). The comparison of cross-sections with riparian vegetation on either one or two banks indicates that there is very little difference in terms of their form (Tables 10 and 12(a)). Indeed, the only parameter that was significantly different between these two vegetation types (i.e., one bank or two) was the asymmetry measure A_2, which was significantly higher for reaches with both banks covered in vegetation. In terms of the type of riparian vegetation present, cross-sections with minimal vegetation covers proved to be consistently different to the vegetated cross-sections for most of the size and form parameters (Tables 11 and 12). In particular, cross-sections with minimal riparian vegetation covers were smaller, shallower and narrower than those covered with grass, she-oak and/or blackberry, and grass with she-oak and/or blackberry. In addition, the cross-sections with minimal bank vegetation tended to be more variable than those with riparian covers (Table 12(b)).

Table 8: Descriptive statistics for bar unit (i.e., pool-riffle sequence) variables within confined (a), valley confined (b), terrace confined (c) and unconfined (d) river reaches.

(a)

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Height (m)	Length (m)	Spacing (L/W)	A_{L2}	A_H
Mean	5.20	0.68	13.88	50.538	0.36	0.35	1.007	0.439	1.01	95.01	7.627	0.359	0.238
Min.	2.50	0.35	9.78	32.609	0.19	0.19	1.003	0.288	0.51	29.19	1.692	0.221	0.000
Max.	7.59	1.00	17.25	81.807	0.48	0.47	1.010	0.677	1.58	282.58	23.495	0.465	0.391
CV	0.43	0.38	0.21	0.430	0.32	0.32	0.002	0.345	0.42	1.02	1.081	0.268	0.598

(b)

Mean	6.13	0.77	15.25	49.146	0.40	0.39	1.007	0.505	0.89	99.00	7.624	0.388	0.179
Min.	3.02	0.46	12.03	32.609	0.26	0.26	1.003	0.330	0.51	29.19	1.692	0.271	0.000
Max.	7.59	1.00	17.25	81.807	0.48	0.47	1.010	0.677	1.58	282.58	23.495	0.465	0.335
CV	0.35	0.33	0.15	0.464	0.26	0.26	0.003	0.281	0.55	1.24	1.389	0.227	0.770

(c)

Mean	3.35	0.50	11.16	53.322	0.29	0.28	1.006	0.305	1.24	87.05	7.634	0.301	0.356
Min.	2.50	0.35	9.78	33.657	0.19	0.19	1.004	0.288	1.13	61.72	6.314	0.221	0.321
Max.	4.19	0.64	12.55	72.987	0.38	0.37	1.008	0.323	1.34	112.37	8.953	0.382	0.391
CV	0.36	0.41	0.18	0.522	0.46	0.46	0.002	0.080	0.12	0.41	0.378	0.378	0.138

(d)

Values	1.41	0.39	6.36	42.88	0.22	0.22	1.010	0.308	0.60	26.17	4.115	0.158	0.365

N.B.: Max. represents maximum; W/D represent width-to-depth ratio; Avg. represents average; L/W represent length-to-width ratio; Min. represents minimum; CV represents coefficient of variation; Values represents the results of sections with only one structure found in a particular classification.

Table 9: Significance (P) values for the comparison of bar unit (i.e., pool-riffle sequence) variables within each confinement classification, using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Height	Length	Spacing (L/W)	A_{L2}	A_H
Val. V Ter.	0.1649	0.1649	0.1649	1.0000	0.3545	0.3545	0.6434	0.0641	0.3545	0.3545	0.3545	0.3545	0.1649

(b)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Height	Length	Spacing	A_{L2}	A_H
Val. V Ter.	0.4633	0.4003	0.8282	0.7465	0.7219	0.7540	0.8388	0.3847	0.2900	0.2232	0.1720	0.6942	0.4696

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Val. Represents valley confined and Ter. represents terrace confined.

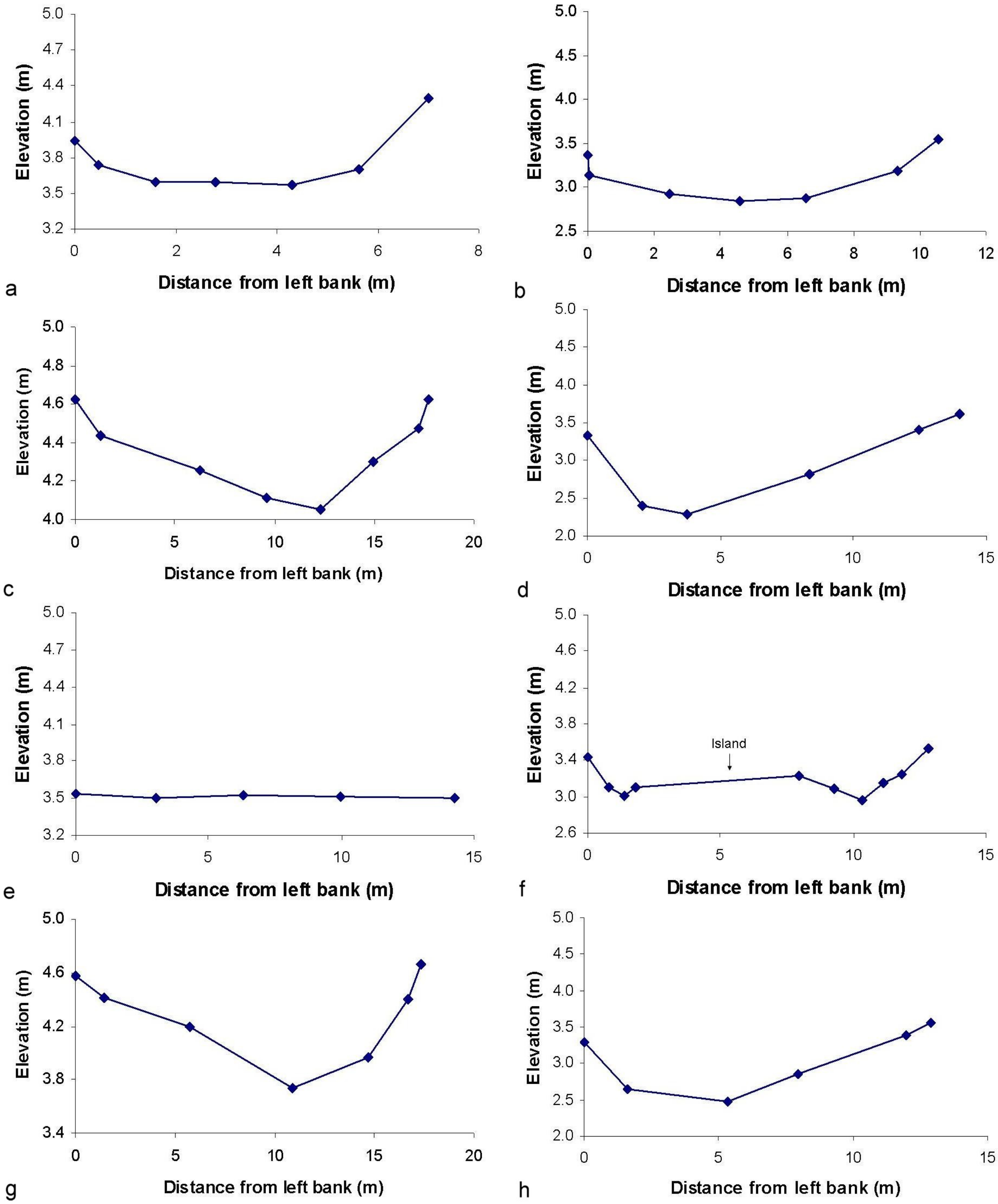

Figure 15: Representative cross-sections from the Turon River: (a) and (b) riparian vegetation on one bank only; (c) and (d) riparian vegetation covering both banks; (e) and (f) minimal vegetation cover; (g) and (h) grass cover; (i) and (j) she-oak and/or blackberries; (k) and (l) both grass and she-oak and/or blackberries.

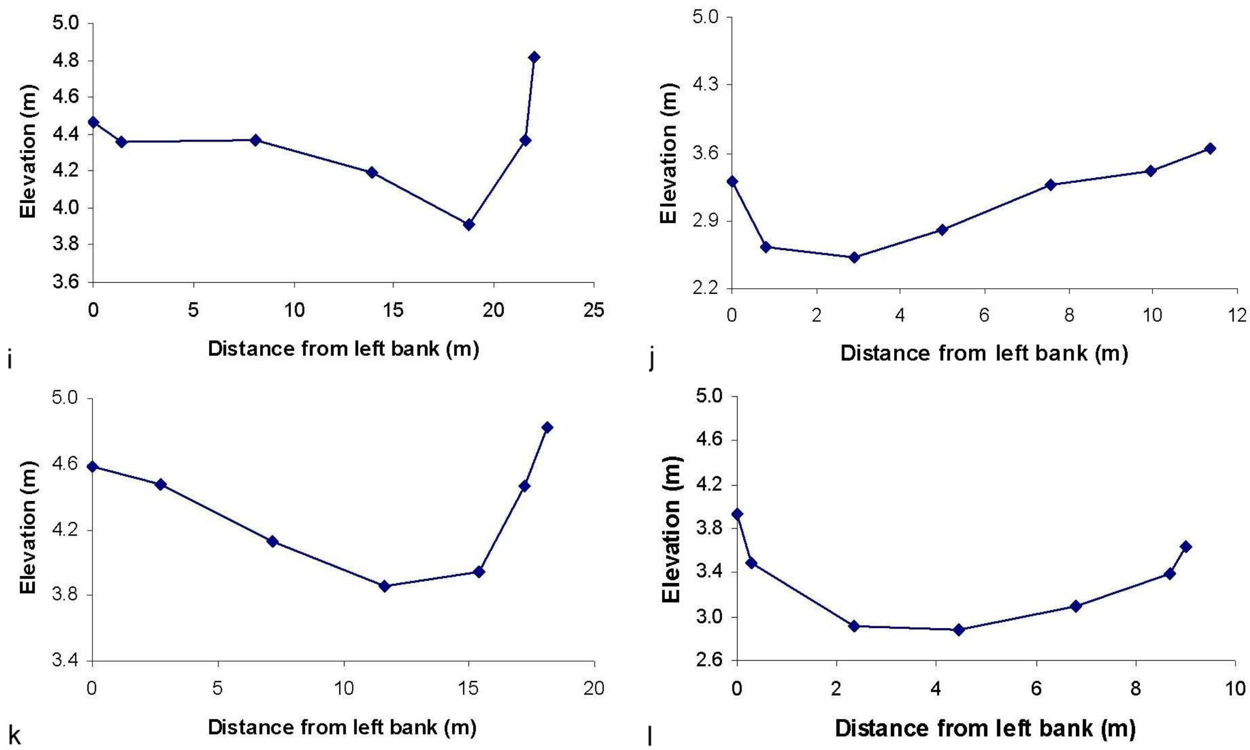

Figure 16 (cont.): Representative cross-sections from the Turon River: (a) and (b) riparian vegetation on one bank only; (c) and (d) riparian vegetation covering both banks; (e) and (f) minimal vegetation cover; (g) and (h) grass cover; (i) and (j) she-oak and/or blackberries; (k) and (l) both grass and she-oak and/or blackberries.

Table 10: Descriptive statistics for the variables of cross-sections that have riparian vegetation covering one bank (a) or both banks (b).

(a)

	Area (m^2)	Max. Depth (m)	Width (m)	W/D	Avg. Depth (m)	Hydraulic Radius (m)	Irregularity	A_2
Mean	2.89	0.45	10.30	52.226	0.25	0.25	1.006	0.350
Min.	0.07	0.04	1.91	14.592	0.01	0.01	1.000	0.006
Max.	8.37	1.13	21.69	368.663	0.64	0.61	1.031	1.573
CV	0.82	0.59	0.53	0.858	0.56	0.55	0.006	0.983

(b)

Mean	3.21	0.48	11.42	75.546	0.25	0.25	1.007	0.517
Min.	0.04	0.01	1.33	6.524	0.01	0.01	1.000	0.001
Max.	8.59	1.29	24.83	1792.282	0.62	0.60	1.040	2.940
CV	0.81	0.62	0.53	1.901	0.63	0.63	0.007	0.853

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; Min. represents minimum; CV represents coefficient of variation.

Comparisons between riparian vegetation cover types reveal that cross-sections with grass covered banks tend to be significantly larger, deeper, wider and more asymmetric than cross-sections with she-oak and/or blackberries on their banks (Tables 11 and 12). Cross-sections covered with grass and she-oak and/or blackberry tended to fall between the other two riparian vegetation cover types in terms of their areas, depths, widths and asymmetries. In addition, cross-sections with grass covered banks tended to be less variable than those with she-oak and/or blackberry covers (Table 12 (b)).

Table 11: Descriptive statistics for the variables of cross-sections that have minimal vegetation (a), grass (b), she-oak and/or blackberries (c) or both grass and she-oak and/or blackberries (d).

(a)

	Area (m^2)	Max. Depth (m)	Width (m)	W/D	Avg. Depth (m)	Hydraulic Radius (m)	Irregularity	A_2
Mean	0.64	0.19	5.73	88.356	0.09	0.09	1.004	0.548
Min.	0.04	0.05	1.33	15.755	0.02	0.02	1.000	0.61
Max.	3.59	0.48	12.51	386.255	0.29	0.28	1.010	2.203
CV	1.44	0.62	0.73	1.071	0.75	0.74	0.003	1.115

(b)

Mean	3.96	0.58	12.00	48.767	0.29	0.28	1.007	0.577
Min.	0.05	0.06	1.71	19.069	0.03	0.03	1.000	0.006
Max.	8.47	1.13	21.42	131.333	0.57	0.56	1.040	1.838
CV	0.73	054	0.48	0.507	0.53	0.53	0.007	0.681

(c)

Mean	2.15	0.38	9.05	56.200	0.22	0.22	1.006	0.313
Min.	0.07	0.04	1.91	13.395	0.01	0.01	1.000	0.007
Max.	7.57	1.11	21.69	368.663	0.64	0.61	1.028	2.940
CV	0.83	0.56	0.52	0.874	0.61	0.60	0.007	1.198

(d)

Mean	3.74	0.51	12.95	85.581	0.28	0.28	1.007	0.475
Min.	0.06	0.01	3.01	6.524	0.01	0.01	1.000	0.001
Max.	8.59	1.29	24.83	1792.282	0.62	0.60	1.035	1.763
CV	0.66	0.56	0.46	2.148	0.55	0.54	0.006	0.823

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; Min. represents minimum; CV represents coefficient of variation.

Reaches with vegetation on either one or two banks had similar slopes but significantly different chain-and-tape and vector dispersion values (Tables 13 and 14(a)). Thus, reaches with vegetation on one bank had greater distances between the heights and depths of their bed undulations but their bed undulations were not as steep as those in the reaches with vegetation on both banks. The reaches with two vegetated banks also displayed higher variabilities in their chain-and-tape and vector dispersion values but had less variable slopes (Table 14(b)).

There was no clear pattern in the slopes of channels with different riparian vegetation types (Tables 13 and 14(a)). Likewise, it was difficult to identify a clear pattern between vegetation type and chain-and-tape and vector dispersion values, although grass covered reaches returned lower chain-and-tape and higher vector dispersion values than reaches with she-oak and/or blackberry covers (Tables 13 and 14(a)). Finally, patterns in variability between reaches with various vegetation types were also difficult to define, although the grass covered reaches had more variable chain-and-tape values and less variable vector dispersion values (Table 14(b)).

Table 12: Significance (P) values for the comparison of cross-sectional variables within each riparian vegetation category, using (a) Mann-Whitney and (b) Levene's tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Area	Max. Depth	Width	W/D	Avg. Depth	Hydraulic Radius	Irregularity	A_2
1 v 2 sides	0.5026	0.5004	0.1197	0.0225	0.5069	0.4706	0.2073	**< 0.0001**
Min. v grass	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.1845	**< 0.0001**	**< 0.0001**	**0.0399**	0.1939
Min. v grass and SO/BB	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.5325	**< 0.0001**	**< 0.0001**	0.1240	0.9209
Min. v SO/BB	**< 0.0001**	**< 0.0001**	**0.0016**	0.1655	**< 0.0001**	**< 0.0001**	0.2022	0.1341
Grass v grass and SO/BB	0.8070	0.1622	0.2488	0.3759	0.6530	0.6280	0.7194	**0.0478**
Grass v SO/BB	**0.0001**	**< 0.0001**	**0.0014**	0.6707	**0.0042**	**0.0044**	0.2286	**< 0.0001**
Grass and SO/BB v SO/BB	**< 0.0001**	**0.0006**	**< 0.0001**	0.2229	**0.0049**	**0.0050**	0.5909	**0.0004**

(b)

	Area	Max. Depth	Width	W/D	Avg. Depth	Hydraulic Radius	Irregularity	A_2
1 v 2 sides	0.1916	0.1096	0.2628	0.0550	**0.0090**	**0.0090**	0.0833	0.0711
Min. v grass	**< 0.0001**	**< 0.0001**	**0.0127**	**< 0.0001**	**0.0002**	**0.0002**	0.1320	0.0898
Min. v grass and SO/BB	**< 0.0001**	**0.0005**	**0.0167**	0.8896	**< 0.0001**	**< 0.0001**	**0.0118**	0.0615
Min. v SO/BB	**0.0042**	**0.0386**	0.4965	**0.0031**	**0.0123**	**0.0121**	**0.0400**	**0.0128**
Grass v grass and SO/BB	**0.0040**	0.1569	0.8086	**0.0067**	0.6350	0.7696	0.3149	0.8505
Grass v SO/BB	**< 0.0001**	**< 0.0001**	**0.0019**	**0.0011**	0.0528	**0.0339**	0.5416	**0.0443**
Grass and SO/BB v SO/BB	**< 0.0001**	**0.0009**	**0.0008**	**0.0284**	**0.0079**	**0.0071**	0.6932	**0.0435**

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; Min. represents minimal vegetation; SO/BB represents she-oak and/or blackberries.

Table 13: Descriptive statistics for long-profile variables of areas with: one bank covered in riparian vegetation (a); both banks covered in riparian vegetation (b); minimal vegetation (c); grass (d); she-oak and/or blackberries (e); and both grass and she-oak and/or blackberries (f).

(a)

	Slope	CT	VD
Mean	0.0000	1.269	0.466
Min.	-0.0028	1.193	0.434
Max.	0.0034	1.317	0.494
CV	21.9103	0.026	0.041

(b)

Mean	-0.0003	1.238	0.498
Min.	-0.0266	1.000	0.432
Max.	0.0131	1.319	1.433
CV	-12.1242	0.044	0.222

(c)

Mean	-0.0002	1.277	0.445
Min.	-0.0022	1.256	0.442
Max.	0.0004	1.286	0.451
CV	-5.3818	0.011	0.008

(d)

Mean	0.000	1.249	0.480
Min.	-0.0037	1.146	0.434
Max.	0.0044	1.319	0.516
CV	34.5825	0.033	0.031

(e)

Mean	-0.0001	1.274	0.460
Min.	-0.0028	1.181	0.435
Max.	0.0006	1.314	0.488
CV	-8.5697	0.020	0.037

(f)

Mean	-0.0004	1.232	0.509
Min.	-0.0266	1.000	0.432
Max.	0.0131	1.310	1.433
CV	-11.8793	0.048	0.256

N.B: CT represents Chain-and-Tape; VD represents Vector Dispersion; Min. represents minimum, Max. represents maximum; CV represents coefficient of variance

Table 14: Significance (P) values for comparisons of long-profile variables within each riparian vegetation category, using (a) Mann-Whitney and (b) Levene's tests. Bold entries signify a significant difference.

(a)

	Slope	CT	VD
1 v 2 sides	0.8913	**< 0.0001**	**< 0.0001**
Min. v grass	0.9738	0.0630	**0.0001**
Min. v grass and SO/BB	07726	**0.0052**	**< 0.0001**
Min. v SO/BB	0.3236	0.8807	**0.0103**
Grass v grass and SO/BB	0.9611	0.2641	0.9159
Grass v SO/BB	0.6487	**< 0.0001**	**< 0.0001**
Grass and SO/BB v SO/BB	0.5662	**< 0.0001**	**< 0.0001**

(b)

	Slope	CT	VD
1 v 2 sides	**0.0021**	**0.0182**	**0.0126**
Min. v grass	0.2861	**0.0296**	0.0724
Min. v grass and SO/BB	0.4257	0.1097	0.2135
Min. v SO/BB	**0.0285**	0.2435	**< 0.0001**
Grass v grass and SO/BB	0.1597	0.2902	**0.0025**
Grass v SO/BB	**< 0.0001**	**0.0002**	**0.0009**
Grass and SO/BB v SO/BB	**0.0007**	**0.0002**	**0.0013**

N.B.: CT represents Chain-and-Tape; VD represents Vector Dispersion; in. represents minimal vegetation; SO/BB represents she-oak and/or blackberries.

Bedform cross-sections showed few statistically significant differences between reaches with respect to either the presence of vegetation on different banks or the vegetation type (Tables 15-17). Thus, while reaches with vegetation on one bank had cross-sections through their bedforms that were significantly narrower than those with vegetation on both banks and less asymmetric than those with vegetation on both one and two banks (Tables 15 and 17(a)), no other statistically significant relationships were identified when bank coverage was considered. Similarly, few differences were identified between the variabilities of bank coverages in reaches with bedforms, although reaches with two banks covered had more variable bedform length-width ratios and downstream asymmetries than those with one bank covered (Tables 15 and 17(b)). There was also no clear pattern between vegetation type and channel form in reaches containing bedforms (Tables 15-17). The only statistically different cross-sectional forms in bedform sequences were identified between those with grass and she-oak and/or blackberry covers and those with only she-oak and/or blackberry covers (Tables 16 and 17(a)) for mean area and width (the reaches with grass were both larger and wider than those without grass). The grass covered reaches also showed some tendency to be more variable than the she-oak and/or blackberry covered reaches, specifically with respect to the cross-sectional asymmetry parameter (A2) and the average height or depth of the bedform feature (Tables 16 and 17(b)). Bedform reaches with grass banks and she-oak and/or blackberry were also more variable with respect to their length-width ratios and downstream asymmetries (for AL) than the reaches with she-oak and/or blackberry and no grass. No bedforms were located in reaches with minimal vegetation on the banks.

Comparisons of channel cross-sections in bar unit (i.e., pool-riffle) sequences reveal no distinct differences between channel forms under different riparian vegetation covers or types (Tables 18 and 19(a)). Indeed, the only significant difference identified in bar unit sequence cross-sections was between the asymmetries of grass covered reaches with reaches having she-oak and/or blackberry covers (with the reaches containing grass being more asymmetric than those with shoe-oak or blackberry alone). Likewise, only the spacing of bar units exhibited significant differences in terms of their variabilities between grass covered reaches and those with grass and she-oak and/or blackberry covers (Tables 18 and 19(b)). As only one bar unit sequence was present in reaches with both one and two banks covered by vegetation and reaches with only grass covers it was not possible to statistically compare these reaches with the others. The cross-sections in the grass covered bar unit sequence, however, reveal that this channel is larger, deeper and wider than the reaches with she-oak and/or blackberry and those with grass and she-oak and/or blackberry (Table 18).

Table 15: Descriptive statistics for bedform (i.e., pool or riffle) variables within reaches with riparian vegetation on: one bank (a); both banks (b); and both one and two banks (c).

(a)

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Max. Height or Depth (m)	Avg. Height or Depth (m)	Length (m)	L/W	A_{h1}	A_L
Mean	2.94	0.50	8.65	41.75	0.30	0.29	1.008	0.287	0.62	0.23	19.19	3.28	0.999	0.624
Min.	0.82	0.27	5.64	23.48	0.16	0.16	1.006	0.237	0.19	0.11	15.15	2.69	0.385	0.545
Max.	5.79	0.85	10.96	52.50	0.51	0.50	1.010	0.321	0.93	0.33	37.68	3.71	1.406	0.772
CV	0.87	0.62	0.32	0.38	0.63	0.62	0.002	0.154	0.62	0.49	0.42	0.16	0.542	0.206

(b)

Mean	5.57	0.71	14.84	51.72	0.37	0.36	1.007	0.478	0.45	0.22	55.16	4.51	0.526	0.530
Min.	2.58	0.64	7.43	25.74	0.18	0.18	1.002	0.188	0.23	0.09	7.81	0.46	0.123	0.144
Max.	7.79	1.09	17.52	109.00	0.50	0.49	1.014	0.947	1.06	0.50	193.64	13.59	1.171	0.949
CV	0.42	0.40	0.22	0.56	0.32	0.32	0.004	0.554	0.60	0.59	1.16	1.19	0.643	0.651

(c)

Mean	3.58	0.57	9.94	37.29	0.30	0.30	1.008	0.419	0.39	0.18	22.47	2.32	0.502	0.440
Min.	1.10	0.25	7.03	26.56	0.14	0.14	1.003	0.355	0.37	0.12	11.02	1.57	0.194	0.219
Max.	7.52	0.95	15.55	52.90	0.48	0.48	1.012	0.531	0.41	0.22	32.34	3.32	0.824	0.748
CV	0.96	0.62	0.49	0.37	0.57	0.58	0.005	0.232	0.05	0.29	0.48	0.39	0.628	0.624

N.B.: W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Min. represents minimum; Max. represents maximum; CV represents coefficient of variance.

Table 16: Descriptive statistics for bedform (i.e., pool or riffle) variables within reaches with: grass covered banks (a); she-oak and/or blackberry covered banks (b); and both grass and she-oak and/or blackberry covered banks (c).

(a)

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Max. Height or Depth (m)	Avg. Height or Depth (m)	Length (m)	L/W	A_{h1}	A_L
Mean	4.96	0.70	12.39	40.12	0.36	0.35	1.008	0.503	0.58	0.21	24.56	2.32	0.962	0.552
Min.	2.22	0.37	9.36	30.97	0.22	0.22	1.006	0.303	0.23	0.09	14.39	0.93	0.518	0.331
Max.	7.70	1.03	15.43	49.27	0.50	0.49	1.010	0.704	0.93	0.33	34.73	3.71	1.406	0.772
CV	0.78	0.66	0.35	0.32	0.55	0.55	0.003	0.563	0.85	0.80	0.59	0.85	0.652	0.565

(b)

Mean	2.46	0.47	7.72	38.86	0.27	0.27	1.008	0.321	0.43	0.17	21.97	2.75	0.653	0.418
Min.	0.82	0.25	5.64	23.77	0.14	0.14	1.003	0.237	0.19	0.11	11.02	1.57	0.194	0.219
Max.	5.79	0.85	10.96	52.90	0.51	0.50	1.012	0.371	0.75	0.24	37.68	3.44	1.207	0.555
CV	0.93	0.60	0.29	0.41	0.62	0.62	0.004	0.186	0.54	0.36	0.54	0.31	0.696	0.387

(c)

Mean	5.55	0.70	14.86	51.90	0.36	0.36	1.007	0.457	0.47	0.24	57.40	4.66	0.522	0.582
Min.	2.58	0.34	7.43	25.74	0.18	0.18	1.002	0.188	0.26	0.11	7.81	0.46	0.123	0.144
Max.	7.79	1.09	17.52	109.00	0.48	0.48	1.014	0.947	1.06	0.50	193.64	13.59	1.171	0.949
CV	0.42	0.39	0.22	0.56	0.31	0.31	0.004	0.549	0.56	0.50	1.09	1.14	0.648	0.588

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Min. represents minimum; CV represents coefficient of variance.

Table 17: Significance (P) values for the comparison of bedform (i.e., pool or riffle) variables within each riparian vegetation category, using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Max. Height or Depth	Avg. Height or Depth	Length	L/W	A_{h1}	A_L
1 side v 2 sides	0.0662	0.1530	**0.0412**	0.8383	0.5403	0.5403	0.5403	0.3074	0.6824	0.6831	0.8383	0.5403	0.1530	0.8383
1 side v both 1 and 2 sides	0.8273	0.8273	0.8273	0.8273	0.8273	0.8273	0.8273	**0.0495**	0.5127	0.5127	0.2752	0.1266	0.2752	0.2752
2 sides v both 1 and 2 sides	0.2207	0.5403	0.1025	0.5403	0.5403	0.5403	0.8383	0.8383	0.8379	0.8383	0.6831	0.6831	0.8383	0.8383
Grass v SO/BB	0.1649	0.3545	0.1649	1.0000	0.6434	0.6434	1.0000	0.6434	0.6434	1.0000	1.0000	1.0000	0.3545	0.6434
Grass v grass and SO/BB	0.7940	1.0000	0.2963	0.6015	0.7940	0.7940	0.4334	0.6015	0.7934	0.7940	0.7940	0.7940	0.1917	1.0000
Grass and SO/BB v SO/BB	**0.0272**	0.1264	**0.0108**	0.6104	0.3082	0.3082	0.6104	0.4969	1.0000	0.3082	0.3958	0.7341	0.4969	0.3958

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; SO/BB represents she-oak or blackberries.

Table 17 (cont) Significance (P) values for the comparison of bedform (i.e., pool or riffle) variables within each riparian vegetation category, using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(b)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Max. Height or Depth	Avg. Height or Depth	Length	L/W	A_{h1}	A_L
1 side v 2 sides	0.7788	0.8068	0.8579	0.3719	0.2639	0.2769	0.1268	**0.0297**	0.4318	0.8173	0.1102	**0.0284**	0.2834	**0.0036**
1 side v both 1 and 2 sides	0.4863	0.9026	0.2100	0.7103	0.7582	0.7885	0.3963	0.1283	**0.0374**	0.3626	0.6849	0.3509	0.2756	0.1982
2 sides v both 1 and 2 sides	0.4070	0.9870	0.3334	0.2951	0.5845	0.5559	0.7980	0.0769	0.1281	0.3801	0.0978	**0.0382**	0.7920	0.1276
Grass v SO/BB	0.3152	0.3266	0.2191	**0.0079**	0.8360	0.8249	0.5662	**0.0037**	0.1511	**0.0028**	0.7837	0.0912	0.5707	0.0989
Grass v grass and SO/BB	0.2931	0.2536	0.6607	0.3426	0.2729	0.2827	0.5559	0.9485	0.2295	0.5305	0.2187	0.1663	0.2395	0.3704
Grass and SO/BB v SO/BB	0.5258	0.6760	0.6042	0.3809	0.4461	0.4871	0.9504	0.0665	0.8348	0.5666	0.0755	**0.0203**	0.3813	**0.0210**

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; SO/BB represents she-oak or blackberries.

Table 18: Descriptive statistics for bar unit (i.e., pool-riffle sequence) variables within reaches with: riparian vegetation on one bank (a); both banks (b); both one and two banks (c); grass covered banks (d); she-oak and/or blackberry covered banks (e); and both grass and she-oak and/or blackberry covered banks (f).

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Height (m)	Length (m)	Spacing (L/W)	A_{L2}	A_H
(a)													
Mean	2.80	0.52	8.07	38.27	0.30	0.29	1.009	0.315	0.87	43.95	5.22	0.189	0.343
Min.	1.41	0.39	6.36	33.66	0.22	0.22	1.008	0.308	0.60	26.17	4.12	0.158	0.321
Max.	4.19	0.64	9.78	42.88	0.38	0.37	1.010	0.323	1.13	61.72	6.31	0.221	0.365
CV	0.70	0.35	0.30	0.17	0.37	0.38	0.002	0.034	0.44	0.57	0.30	0.235	0.090
(b)													
Mean	6.13	0.77	15.25	19.15	0.40	0.39	1.007	0.505	0.89	99.00	7.62	0.388	0.179
Min.	3.02	0.46	12.03	32.61	0.26	0.26	1.003	0.330	0.51	29.19	1.69	0.271	0.000
Max.	7.59	1.00	17.25	81.81	0.48	0.47	1.010	0.677	1.58	282.58	23.50	0.465	0.335
CV	0.35	0.33	0.15	0.46	0.26	0.26	0.003	0.281	0.55	1.24	1.39	0.227	0.770
(c)													
Values	2.50	0.35	12.55	72.99	0.19	0.19	1.004	0.288	1.34	112.37	8.95	0.382	0.391
(d)													
Values	7.51	0.95	15.62	32.61	0.48	0.47	1.008	0.502	0.57	39.50	2.53	0.271	0.184
(e)													
Mean	2.70	0.46	9.56	49.84	0.27	0.26	1.007	0.306	1.02	66.75	6.46	0.254	0.359
Min.	1.41	0.35	6.36	33.66	0.19	0.19	1.004	0.288	0.60	26.17	4.12	0.158	0.321
Max.	4.19	0.64	12.55	72.99	0.38	0.37	1.010	0.323	1.34	112.37	8.95	0.382	0.391
CV	0.52	0.34	0.32	0.41	0.38	0.38	0.003	0.057	0.37	0.65	0.38	0.456	0.098
(f)													
Mean	5.67	0.71	15.12	54.659	0.37	0.36	1.006	0.506	1.00	118.83	9.32	0.427	0.177
Min.	3.02	0.46	12.03	34.351	0.26	0.26	1.003	0.330	0.51	29.19	1.69	0.371	0.000
Max.	7.59	1.00	17.25	81.807	0.47	0.47	1.010	0.677	1.58	282.58	23.50	0.465	0.335
CV	0.42	0.39	0.18	0.447	0.29	0.29	0.003	0.344	0.54	1.20	1.32	0.117	0.953

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Min. represents minimum; CV represents coefficient of variance; Values represents the results of sections with only one structure found in a particular classification.

Table 19: Significance (P) values for the comparison of bar unit (i.e., pool-riffle sequence) variables within each riparian vegetation category, using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Height	Length	Spacing (L/W)	A_{L2}	A_H
1 v 2 sides	0.1649	0.1649	0.0641	0.64	0.3545	0.3545	0.3545	0.0641	0.6434	0.6434	0.36	0.0641	0.1649
Grass and SO/BB	0.1266	0.1266	0.1266	0.51	0.2752	0.2752	0.5127	**0.0495**	0.8273	0.8273	0.51	0.1266	0.1266

(b)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Height	Length	Spacing (L/W)	A_{L2}	A_H
1 v 2 sides	0.8587	0.2941	0.9228	0.29	0.9683	0.9915	0.4767	0.3299	0.7010	0.1840	0.16	0.3098	0.3789
Grass and SO/BB	0.3243	0.4301	0.9530	0.74	0.8969	0.9242	0.9342	0.1359	0.5937	0.0610	**0.04**	0.1883	0.1433

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; SO/BB represents she-oak and blackberries.

4.3 Woody Debris

Cross-sections that did not contain woody debris were narrow and roughly parabolic in shape with little to no undulations in the channel bed (Figure 16(a) and (b)). Cross-sections that did have woody debris (either on the banks or within the channel) were wide and triangular in shape (Figures 16(c)-(f)). Cross-sections with woody debris on their banks contained channel bifurcations (Figure 16(c) and (d)), as did cross-sections containing in-channel woody debris (Figure 16(e) and (f)). However, the number of bifurcations was greater for cross-sections containing in-channel woody debris than those within cross-sections with woody debris on their banks.

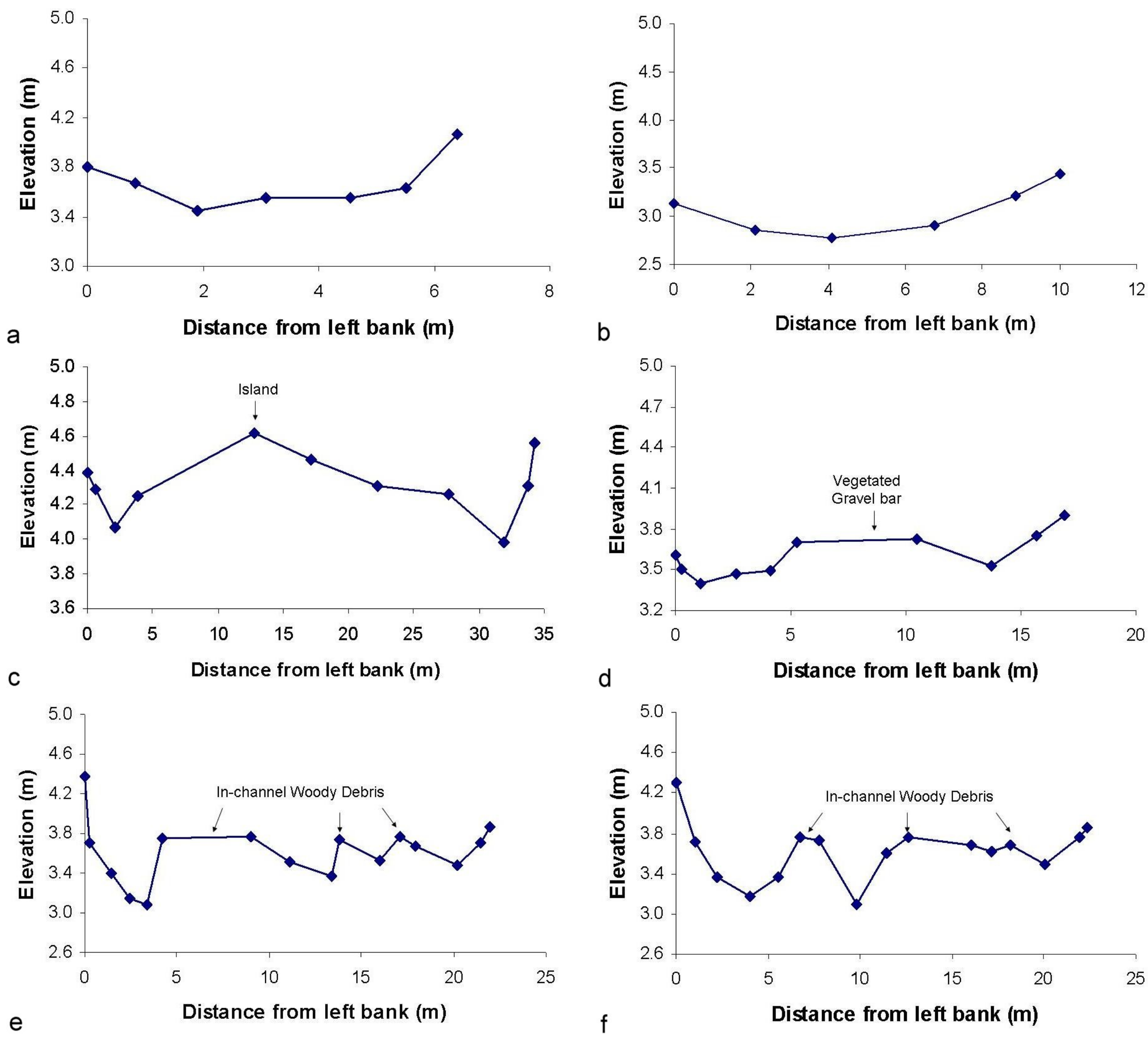

Figure 176: Representative cross-sections from the Turon River with: (a) and (b) containing no woody debris; (c) and (d) containing woody debris on the banks; and (e) and (f) containing in-channel woody debris.

Cross-sections in reaches containing no woody debris were significantly larger and wider than reaches with woody debris in general (i.e., both in-channel and on the banks combined) and reaches with only in-channel woody debris (Tables 20 and 21(a)). In addition, reaches with woody debris on the banks had larger and wider cross-sections than reaches with in-channel woody debris.

The variability of cross-sectional forms varied with the presence and type of woody debris, although there was no systematic pattern to those variations (Tables 20 and 21(b)). For example, channels containing woody debris had more variable cross-sectional areas and irregularities but less variable depths and hydraulic radii than channels with no woody debris. Channels with woody debris on their banks, however, had more variable cross-sectional widths but less variable depths and irregularities.

Table 20: Descriptive statistics for the variables of cross-sections that contain: woody debris (a); woody debris on the banks (b); in-channel woody debris (c); and no woody debris (d).

(a)

	Area (m^2)	Max. Depth (m)	Width (m)	W/D	Avg. Depth (m)	Hydraulic Radius (m)	Irregularity	A_2
Mean	1.91	0.39	8.88	48.91	0.20	0.20	1.009	0.483
Min.	0.08	0.08	2.18	6.52	0.04	0.04	1.000	0.021
Max.	5.33	0.83	23.23	120.71	0.49	0.42	1.035	2.94
CV	0.88	0.49	0.74	0.60	0.54	0.51	0.010	1.175

(b)

Mean	2.61	0.36	12.29	61.00	0.20	0.20	1.006	0.414
Min.	0.57	0.19	4.72	13.40	0.11	0.11	1.000	0.074
Max.	5.16	0.57	23.23	20.71	0.36	0.34	1.020	1.100
CV	0.69	0.34	0.63	0.55	0.33	0.32	0.006	0.713

(c)

Mean	1.31	0.42	5.95	38.54	0.20	0.19	1.011	0.542
Min.	0.08	0.08	2.18	6.52	0.04	0.04	1.000	0.021
Max.	5.33	0.83	13.99	77.36	0.49	0.42	1.035	2.940
CV	1.04	0.57	0.59	0.55	0.69	0.65	0.012	1.351

(d)

Mean	3.20	0.48	11.18	68.06	0.26	0.25	1.006	0.449
Min.	0.04	0.01	1.33	14.59	0.01	0.01	1.000	0.001
Max.	8.59	1.29	24.83	1792.28	0.64	0.61	1.040	2.203
CV	0.80	0.62	0.51	1.78	0.60	0.60	0.006	0.885

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represent average; Min. represents minimum; CV represents coefficient of variance.

The long-profile slopes of reaches containing debris were not statistically different to those without debris (Tables 22 and 23(a)). Indeed, there were no significant differences between the long-profile variables of reaches with and without woody debris for all parameters except the chain-and-tape values for reaches with woody debris on the banks compared to those with in-channel woody debris (bank debris reaches had higher chain-and-tape values and, therefore, were more irregular in the downstream direction). Likewise, woody debris channels appear to exhibit comparable variabilities (Tables 22 and 23(b)). The only exceptions to this are for comparisons between reaches with different debris locations with the variabilities of both chain-and-tape and vector dispersion values being higher for reaches with woody debris on the banks than for those with in-channel woody debris.

Table 21: Significance (P) values for the comparison of cross-sectional variables within each woody debris category, using Mann-Whitney (a) and Levene's (b) analyses. Bold entries signify significant differences at a significance level of 0.05.

(a)

	Area	Max. Depth	Width	W/D	Avg. Depth	Hydraulic Radius	Irregularity	A_2
WD v no WD	**0.0225**	0.2447	**0.0106**	0.5488	0.0912	0.0785	0.4613	0.8850
Bank v no WD	0.6963	0.2867	0.8701	0.4434	0.3284	0.3405	0.8529	0.8715
In-chan. v no WD	**0.0049**	0.5259	**0.0002**	0.1234	0.1480	0.1170	0.2319	0.9586
Bank v in-chan.	**0.0308**	0.7968	**0.0156**	0.0570	0.2801	0.2793	0.2457	0.9590

(b)

	Area	Max. Depth	Width	W/D	Avg. Depth	Hydraulic Radius	Irregularity	A_2
WD v no WD	**0.0022**	**0.0073**	0.7161	0.3006	**0.0034**	**0.0020**	**< 0.0001**	0.8375
Bank v no WD	0.0905	**0.0030**	**0.0464**	0.5872	**0.0011**	**0.0012**	0.4938	0.1620
In-chan. v no WD	**0.0009**	0.3860	**0.0020**	0.3519	0.2656	0.1631	**< 0.0001**	0.1572
Bank v in-chan.	0.1365	**0.0078**	**0.0013**	0.0782	**0.0496**	0.0636	**0.0040**	0.2715

N.B.: W/D represents width-to-depth ratio; Avg. represents average; WD represents woody debris; Bank represents bank woody debris; In-chan. represents in-channel.

Bedform structures in channels containing woody debris showed no patterns in terms of channel cross-sectional form and the presence or location of debris (Tables 24 and 25(a)). Indeed, the only significant difference between channels with and without woody debris was for one of the downstream asymmetry variables (AL), which was higher for the reaches devoid of woody debris (Table 24). Considerations of differences in diversity between channels with and without woody debris, however, indicate that, in most cases, channels devoid of woody debris are more diverse with respect to their cross-sectional parameters (e.g., area, depth and hydraulic radius) but less diverse with respect to their down-stream parameters (e.g., average bedform height or depth and bedform length) (Tables 24 and 25(b)).

There were no evident differences between cross-sections through bar unit reaches with or without woody debris (Tables 26 and 27(a)). As with the bedform reaches, however, the diversities of bar unit lengths and spacings (both of which are downstream parameters) were higher in channels containing woody debris than for those devoid of debris (Tables 26 and 27(b)).

Table 22: Descriptive statistics for the long-profiles of sections that contain: woody debris (a); woody debris on the banks (b); in-channel woody debris (c); and no woody debris (d).

(a)

	Slope	CT	VD
Min.	-0.0006	1.209	0.457
Max.	0.0012	1.269	0.489
Mean	0.0002	1.247	0.471
CV	2.6174	0.019	0.028

(b)

Min.	-0.0006	1.209	0.457
Max.	0.0012	1.260	0.489
Mean	0.0002	1.234	0.477
CV	2.6048	0.018	0.031

(c)

Min.	0.0000	1.264	0.462
Max.	0.0001	1.269	0.463
Mean	0.0001	1.267	0.463
CV	0.8369	0.002	0.001

(d)

Min.	-0.0266	1.000	0.432
Max.	0.0131	1.319	1.433
Mean	-0.0002	1.252	0.484
CV	-17.1604	0.039	0.179

N.B.: CT represents Chain-and-Tape; VD represents Vector Dispersion; Min. represents minimum; Max. represents maximum; CV represents coefficient of variance.

Table 23: Significance (P) values for comparisons of long-profile variables within each woody debris category, using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Slope	CT	VD
WD v no WD	0.1947	0.3308	0.9268
Bank v no WD	0.2437	0.0799	0.4092
In-chan. v WD	0.5200	0.5507	0.2450
Bank v In-chan.	0.5224	**0.0105**	0.3938

(b)

	Slope	CT	VD
WD v no WD	0.3477	0.1949	0.5006
Bank v no WD	0.5296	0.2494	0.6112
In-chan. v WD	0.4619	0.0615	0.4713
Bank v In-chan.	0.1741	**0.0154**	**0.0020**

N.B.: CT represents Chain-and-Tape; VD represents Vector Dispersion; WD represents woody debris; Bank represents bank woody debris; In-chan. represents in-channel woody debris.

Table 24: Descriptive statistics of bedforms (i.e., pools or riffles) found in sections containing: woody debris (a); woody debris on the banks (b); in-channel woody debris (c); and no woody debris (d).

(a)

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Max. Height or Depth (m)	Avg. Height or Depth (m)	Length (m)	L/W	A_{h1}	A_L
Mean	2.64	0.49	9.57	53.77	0.28	0.28	1.009	0.404	0.66	0.30	97.87	9.04	0.374	0.219
Min.	2.11	0.43	7.03	25.74	0.22	0.22	1.004	0.188	0.41	0.12	11.02	1.57	0.123	0.144
Max.	3.23	0.52	14.25	109.00	0.33	0.32	1.012	0.667	1.06	0.50	193.64	13.59	0.824	0.354
CV	0.21	0.10	0.42	0.89	0.20	0.19	0.004	0.603	0.52	0.63	0.94	0.72	1.046	0.532

(b)

Mean	2.67	0.48	10.64	67.78	0.26	0.25	1.008	0.511	0.73	0.31	102.33	7.58	0.499	0.257
Min.	2.11	0.43	7.03	26.56	0.22	0.22	1.004	0.355	0.41	0.12	11.02	1.57	0.145	0.160
Max.	3.23	0.52	14.25	109.00	0.29	0.28	1.012	0.667	1.06	0.50	193.64	13.59	0.824	0.354
CV	0.29	0.13	0.48	0.86	0.18	0.16	0.006	0.431	0.63	0.86	1.26	1.12	0.920	0.533

(c)

Values	2.58	0.50	7.43	25.74	0.33	0.32	1.011	0.188	0.53	0.28	88.94	11.97	0.123	0.144

(d)

Mean	5.11	0.68	13.26	44.50	0.35	0.35	1.007	0.430	0.42	0.19	27.51	2.34	0.690	0.616
Min.	0.82	0.25	5.64	23.48	0.14	0.14	1.002	0.237	0.19	0.09	7.81	0.46	0.194	0.219
Max.	7.79	1.09	17.52	82.17	0.51	0.50	1.014	0.947	0.93	0.33	77.64	5.63	1.406	0.949
CV	0.55	0.48	0.32	0.36	0.42	0.42	0.003	0.507	0.55	0.37	0.70	0.68	0.577	0.420

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Min. represents minimum; CV represents coefficient of variance; Values represents the results of sections with only one structure found in a particular classification.

Table 25: Significance (P) values for comparison of bedform (i.e., pool or riffle) variables for each woody debris category, using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Max. Height or Depth	Avg. Height or Depth	Length	L/W	A_{h1}	A_L
WD v no WD	0.2429	0.4835	0.1857	0.5858	0.4835	0.4835	0.3115	0.8153	0.1017	0.2429	0.3115	0.1391	0.1857	**0.0356**
Bank v no WD	0.3237	0.5537	0.3237	0.8435	0.5537	0.5537	0.6930	0.4298	0.1138	0.5537	0.8435	0.4298	0.5537	0.1143

(b)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Max. Height or Depth	Avg. Height or Depth	Length	L/W	A_{h1}	A_L
WD v no WD	**0.0076**	**0.0021**	0.6994	**0.0049**	**0.0205**	**0.0186**	0.6490	0.8748	0.3577	**0.0460**	**0.0054**	**0.0005**	0.8977	0.1123
Bank v no WD	**0.0349**	**0.0109**	0.9973	**0.0019**	**0.0377**	**0.0341**	0.3802	0.9545	0.1824	**0.0007**	**< 0.0001**	**< 0.0001**	0.9659	0.2123

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; WD represents woody debris; Bank represents bank woody debris.

Table 26: Descriptive statistics for bar unit (i.e., pool-riffle) sequences found in sections containing: woody debris (a); bank woody debris (b); in-channel woody debris (c); and no woody debris (d).

(a)

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Height (m)	Length (m)	Spacing (L/W)	A_{L2}	A_H
Mean	2.22	0.42	9.19	62.34	0.24	0.24	1.008	0.409	1.09	154.38	13.81	0.264	0.350
Min.	1.41	0.39	6.36	42.88	0.22	0.22	1.006	0.308	0.60	26.17	4.12	0.158	0.335
Max.	3.02	0.46	12.03	81.81	0.26	0.26	1.010	0.511	1.58	282.58	23.50	0.371	0.365
CV	0.51	0.12	0.44	0.44	0.11	0.12	0.002	0.631	0.64	1.17	0.99	0.569	0.059

(b)

Values	3.02	0.46	12.03	81.81	0.26	0.26	1.006	0.511	1.58	282.58	23.50	0.371	0.335

(c)

Values	1.41	0.39	6.36	42.88	0.22	0.22	0.010	0.308	0.60	26.17	4.12	0.158	0.365

(d)

Mean	5.64	0.72	14.26	44.29	0.38	0.37	1.007	0.424	0.89	57.50	4.45	0.357	0.218
Min.	2.50	0.35	9.78	32.61	0.19	0.19	1.003	0.288	0.51	29.19	1.69	0.221	0.000
Max.	7.59	1.00	17.25	72.99	0.48	0.47	1.010	0.677	1.34	112.37	8.95	0.465	0.391
CV	0.39	0.36	0.21	0.39	0.31	0.30	0.003	0.388	0.40	0.57	0.69	0.301	0.686

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Min. represents minimum; CV represents coefficient of variance; Values represents the results of sections with only one structure found in a particular classification.

Table 27: Significance (P) values for comparison between bar unit (i.e., pool-riffle) sequence variables in each woody debris category, using Mann-Whitney (a) and Levene's (b) tests. Bold entries indicate a significant difference at a significance level of 0.05.

(a)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Height	Length	Spacing (L/W)	A_{L2}	A_H
WD v no WD	0.1213	0.2453	0.1213	0.2453	0.2453	0.2453	0.4386	1.0000	0.4386	1.0000	0.2453	0.2453	0.2453

(b)

WD v no WD	0.1741	0.1521	0.7228	0.3929	0.3438	0.3604	0.5417	0.5815	0.1527	**0.0008**	**0.0004**	0.5930	0.1937

N.B.: Max. represents maximum, W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio: WD represents presence of woody debris.

4.4 Presence of Obstructions

Cross-sections with no obstructions (i.e., no gravel bars or islands) varied in shape from triangular (Figure 17(a)) to parabolic (Figure 17(b)), depending upon their position in the study reach. In comparison, areas where the study reach contained obstructions had cross-sections displaying multiple channels that often consisted of deep main channels and shallow secondary channels with obstructions that either rose above the water level (Figure 17(c)) or would be inundated with water at high flows (Figure 17(d)).

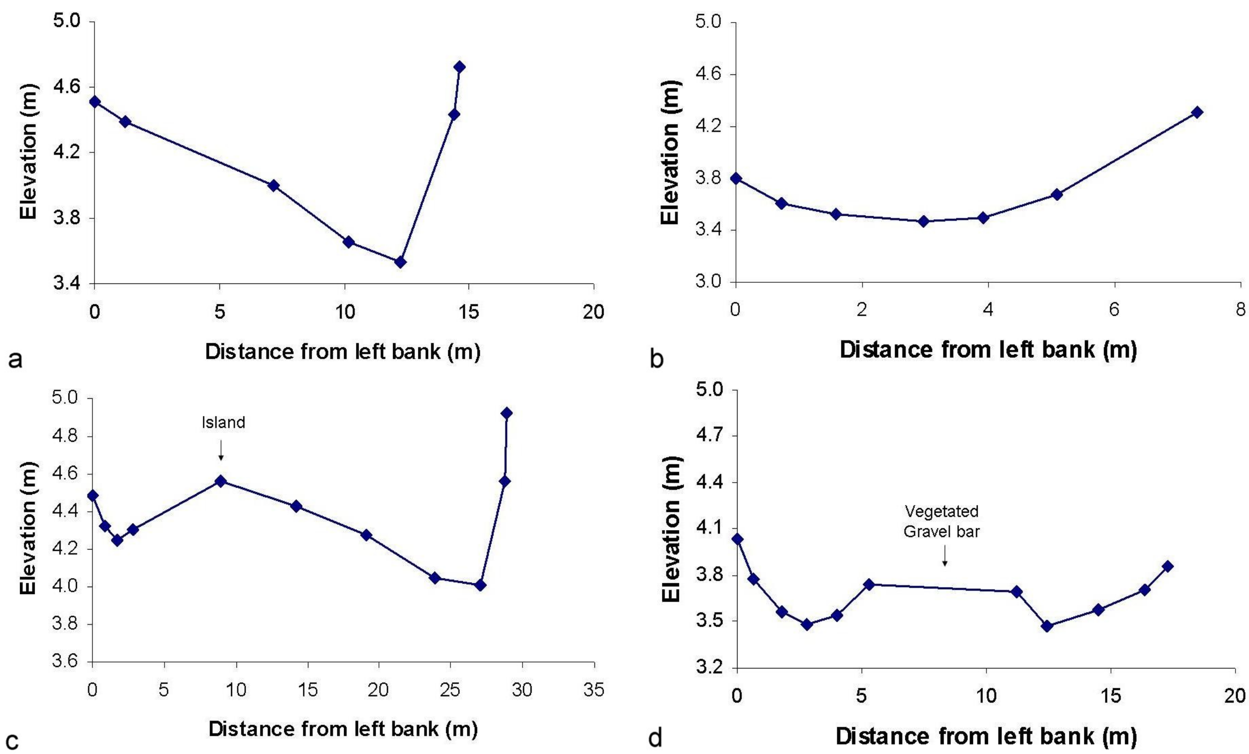

Figure 187: Representative cross-sections of areas within the Turon River devoid of obstructions ((a) and (b)) and areas that contained obstructions, with the main channel on the right (c) and left (d).

There were significant differences between reaches with and without obstructions for all of the cross-sectional parameters except asymmetry (A_2) (Tables 28 and 29(a)). Thus, channels without obstructions were significantly larger, deeper, wider and more irregular than channels containing some form of obstruction. In terms of their variability, however, channels containing obstructions were more variable than those without obstructions for all parameters except irregularity (Tables 28 and 29(b)).

Table 28: Descriptive statistics for variables of cross-sections devoid of obstructions (a) and those that contain obstructions (b).

(a)

	Area (m^2)	Max. Depth (m)	Width (m)	W/D	Avg. Depth (m)	Hydraulic Radius (m)	Irregularity	A_2
Mean	4.39	0.62	12.09	40.67	0.35	0.34	1.007	0.397
Min.	0.19	0.10	2.42	16.28	0.06	0.06	1.000	0.001
Max.	8.59	1.29	22.05	131.33	0.64	0.61	1.028	1.201
CV	0.58	0.45	0.41	0.63	0.40	0.40	0.006	0.841

(b)

Mean	1.77	0.31	9.86	92.51	0.16	0.15	1.005	0.508
Min.	0.04	0.01	1.33	6.52	0.01	0.01	1.000	0.013
Max.	7.57	0.83	24.83	1792.28	0.49	0.42	1.040	2.940
CV	0.94	0.59	0.65	1.71	0.59	0.58	0.007	0.937

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; Min. represents minimum; CV represents coefficient of variance.

Table 29: Significance (P) values for comparisons between cross-sectional variables in each obstruction category, using Mann-Whitney (a) and Levene's (b) tests. Bold entries indicate a significant difference at a significance level of 0.05.

(a)

	Area	Max. Depth	Width	W/D	Avg. Depth	Hydraulic Radius	Irregularity	A_2
Obs. v no Obs.	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.0670

(b)

Obs. v no Obs.	**< 0.0001**	**< 0.0001**	**0.0312**	**0.0002**	**< 0.0001**	**< 0.0001**	0.4155	**0.0148**

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; Obs. represents presence of obstructions.

Reaches with obstructions had steeper slopes but less irregular beds (i.e., lower chain-and-tape values) than reaches without obstructions (Tables 30 and 31(a)). In addition, reaches with obstructions had greater variability in their slopes but less variability in their chain-and-tape values (Tables 30 and 31(b)).

Table 30: Descriptive statistics for long-profile variables of sections devoid of obstructions (a) and areas that contain obstructions (b).

(a)

	Slope	CT	VD
Mean	-0.0003	1.253	0.490
Min.	-0.0266	1.000	0.432
Max.	0.0131	1.317	1.433
CV	-14.1954	0.045	0.208

(b)

Mean	0.0000	1.248	0.470
Min.	-0.0022	1.181	0.442
Max.	0.0014	1.319	0.496
CV	21.6307	0.020	0.038

N.B.: CT represents Chain-and-Tape; VD represents Vector Dispersion; in. represents minimum; Max. represents maximum; CV represents coefficient of variance.

Table 31: Significance (P) values for comparisons of long-profile variables in each obstruction category, using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significant level of 0.05.

(a)

	Slope	CT	VD
Obs. v no Obs.	**0.0225**	**0.0055**	0.4906

(b)

Obs. v no Obs.	**0.0059**	**0.0003**	0.0583

N.B.: CT represents Chain-and-Tape; VD represents Vector Dispersion; Obs. represents presence of obstructions.

Bedforms in reaches devoid of obstructions were larger, deeper and wider than those in reaches containing obstructions (Tables 32 and 33(a)). Thus, most cross-sectional parameters were higher in the reaches devoid of obstructions. The downstream parameter of bedform spacing (i.e., the length-width ratio), was larger in the reaches containing obstructions than in the unobstructed reaches. There were few differences in variability observed between bedform channels with and without obstructions (Tables 32 and 33(b)). The exceptions to this were for the cross-sectional width-depth ratios and the downstream length and spacing (length-width ratio) parameters, all of which displayed greater variability in the obstructed reaches.

Cross-sections for bar unit sequences in reaches with no obstructions were significantly larger, deeper and wider than those in reaches containing obstructions (Tables 34 and 35(a)). The downstream parameters of spacing (length-width ratio) and asymmetry (for the parameter of AH), however, were significantly larger in the obstructed reaches. Only two parameters for bar unit sequence reaches displayed significant differences in terms of their variabilities between channels with and without obstructions (Tables 34 and 35(b)). These were for the cross-sectional parameter of width-depth ratio, which was higher in the reaches with obstructions, and the downstream asymmetry parameter of AH, which was higher in the reaches without obstructions.

4.5 Anthropogenic Impoundment

Cross-sections located further than 50 m from the causeway were often deep and parabolic in shape (Figure 18(a) and (b)). In comparison, sections within 50 m of the causeway contained shallow, triangular shaped cross-sections (Figure 18(c) and (d)). The most distant cross-sections upstream of the causeway were deep, parabolic to triangular in shape and contained a few bed undulations (Figure 18(e)). However, the cross-sections upstream of the causeway became shallower and contained less bed undulations as they got closer to the causeway (Figure 18(f)). Conversely, cross-sections directly downstream of the causeway were structurally diverse with numerous bed undulations and no distinct shape (Figure 18(g)). These undulations diminished further downstream, resulting in cross-sections that were parabolic in shape with maximum depths situated to the left of the channel centreline (Figure 18(h)).

Descriptive statistics for cross-sectional variables related to their position to the causeway are presented in Table 36 and comparisons between variables are provided in Table 37. These results indicate that, on average, sections situated more than 50 m from the causeway are larger, deeper, more irregular and more asymmetric than sections within 50 m of the causeway. When the location of sections up- or down-stream relative to the causeway is taken into account, channels downstream stand out as having smaller average width-depth ratios than the upstream channels.

The Levene’s analyses (Table 37(b)) indicate that reaches more than 50 m above the causeway have more variable depths, hydraulic radii, irregularities and asymmetries while reaches within 50 m of the causeway have more variable areas. In addition, the downstream reaches exhibit greater variability in their depths, hydraulic radii and asymmetries but less variability in their widths than the upstream reaches.

Table 32: Descriptive statistics for bedform (i.e., pool or riffle) variables within reaches devoid of obstructions (a) and reaches that contain obstructions (b).

(a)

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Max. Height or Depth (m)	Avg. Height or Depth (m)	Length (m)	L/W	A_{h1}	A_L
Mean	7.06	0.89	15.68	36.10	0.45	0.45	1.008	0.506	0.39	0.17	21.58	1.49	0.703	0.613
Min.	5.79	0.56	10.96	23.48	0.34	0.34	1.002	0.273	0.23	0.09	7.81	0.46	0.365	0.237
Max.	7.79	1.09	17.52	51.69	0.51	0.50	1.014	0.947	0.75	0.24	37.68	3.44	1.207	0.893
CV	0.12	0.19	0.14	0.25	0.13	0.12	0.004	0.482	0.49	0.33	0.51	0.68	0.498	0.406

(b)

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Max. Height or Depth (m)	Avg. Height or Depth (m)	Length (m)	L/W	A_{h1}	A_L
Mean	2.10	0.38	9.25	56.88	0.22	0.22	1.007	0.343	0.56	0.26	63.60	6.07	0.542	0.449
Min.	0.82	0.25	5.64	25.74	0.14	0.14	1.003	0.188	0.19	0.11	11.02	1.57	0.123	0.144
Max.	3.23	0.52	14.25	109.00	0.33	0.32	1.012	0.667	1.06	0.50	193.64	13.59	1.406	0.949
CV	0.41	0.28	0.37	0.52	0.32	0.31	0.004	0.455	0.57	0.53	1.02	0.79	0.860	0.706

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Min. represents minimum; CV represents coefficient of variance.

Table 33: Significance (P) values for comparisons between bedform (i.e., pool or riffle) variables within each obstruction category, using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Max. Height or Depth	Avg. Height or Depth	Length	L/W	A_{h1}	A_L
Obs. v no Obs.	**0.0017**	**0.0017**	**0.0040**	0.1417	**0.0017**	**0.0017**	0.6547	0.1417	0.2243	0.1417	0.1797	**0.0127**	0.3379	0.2774

(b)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Max. Height or Depth	Avg. Height or Depth	Length	L/W	A_{h1}	A_L
Obs. v no Obs.	0.8640	0.5695	0.1720	**0.0499**	0.6302	0.6683	0.9830	0.2096	0.1911	0.1218	**0.0190**	**0.0058**	0.4604	0.4140

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Obs. represents presence of obstructions.

Table 34: Descriptive statistics for bar unit (i.e., pool-riffle) sequence variables within reaches devoid of obstructions (a) and reaches containing obstructions (b).

(a)

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Height (m)	Length (m)	Spacing (L/W)	A_{L2}	A_H
Mean	7.16	0.87	16.32	38.26	0.44	0.44	1.007	0.503	0.66	37.80	2.33	0.394	0.126
Min.	6.39	0.67	15.62	32.61	0.37	0.37	1.003	0.330	0.51	29.19	1.69	0.271	0.000
Max.	7.59	1.00	17.25	47.82	0.48	0.47	1.010	0.677	0.91	44.72	2.78	0.465	0.195
CV	0.09	0.21	0.05	0.22	0.14	0.14	0.003	0.346	0.33	0.21	0.24	0.271	0.867

(b)

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Height (m)	Length (m)	Spacing (L/W)	A_{L2}	A_H
Mean	2.78	0.46	10.18	57.53	0.26	0.26	1.007	0.357	1.16	120.71	10.72	0.283	0.353
Min.	1.41	0.35	6.36	33.66	0.19	0.19	1.004	0.288	0.60	26.17	4.12	0.158	0.321
Max.	4.19	0.64	12.55	81.81	0.38	0.37	1.010	0.511	1.58	282.58	23.50	0.382	0.391
CV	0.41	0.28	0.28	0.40	0.31	0.31	0.002	0.289	0.36	0.94	0.82	0.392	0.088

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Min. represents minimum; CV represents coefficient of variance.

Table 35: Significance (P) values for comparisons of bar unit (i.e., pool-riffle) sequence variables in each obstruction category, using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Height	Length	Spacing (L/W)	A_{L2}	A_H
Obs. v no Obs.	**0.0339**	**0.0339**	**0.0339**	0.2888	0.0771	0.0771	1.0000	0.1573	0.0771	0.2888	**0.0339**	0.1573	**0.0339**

(b)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Height	Length	Spacing (L/W)	A_{L2}	A_H
Obs. v no Obs.	0.4787	0.4326	0.1411	**0.0114**	0.7362	0.7099	0.5229	0.5246	0.4110	0.1062	0.0849	0.6481	**0.0269**

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Obs. represents presence of obstructions.

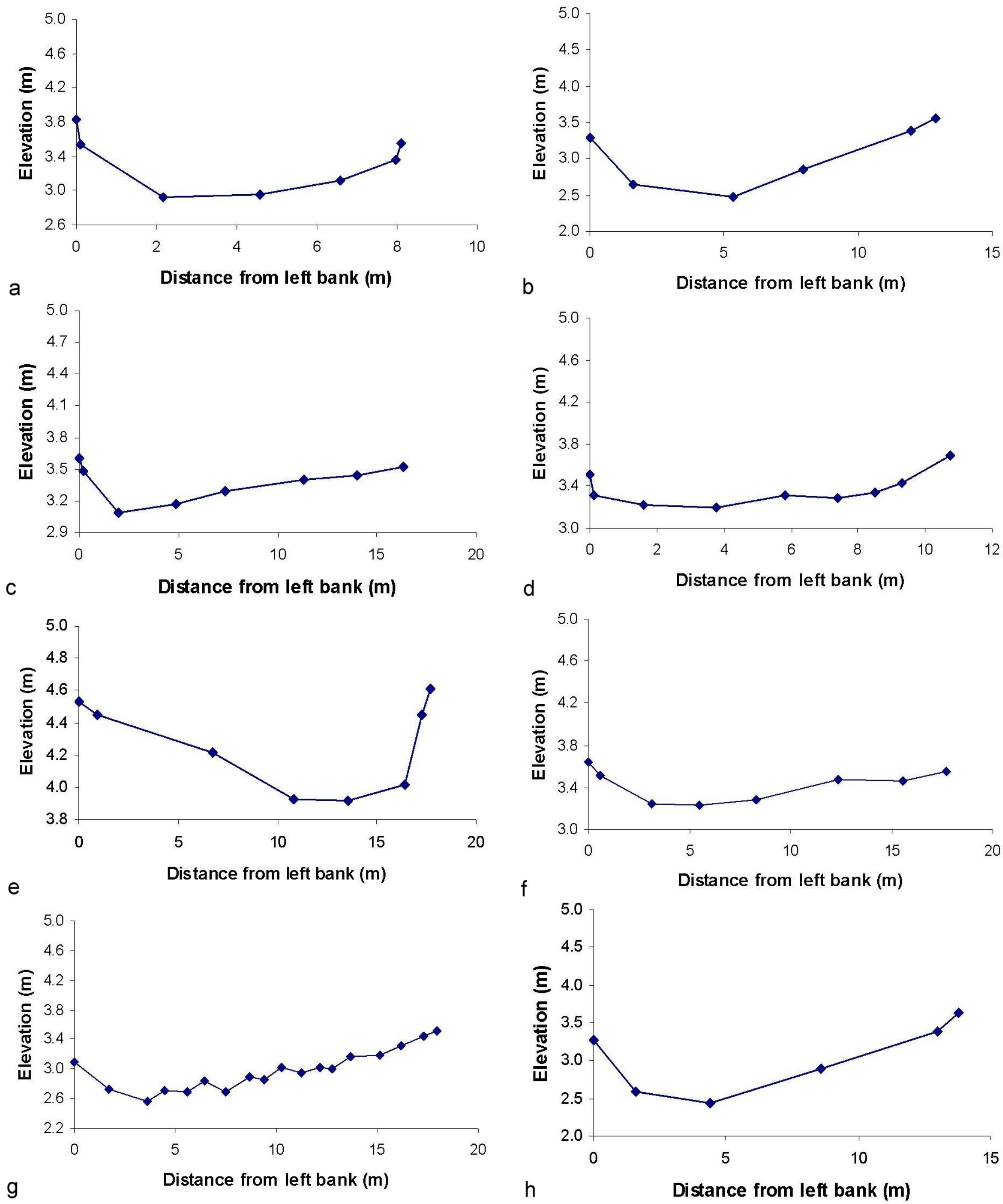

Figure 198: Representative cross-sections from the Turon River with: (a) and (b) located more than 50 m from causeway; (c) and (d) located within 50 m from causeway; (e) and (f) located upstream from the causeway; and (g) and (h) located downstream of the causeway.

Table 36: Descriptive statistics for variables of cross-sections located less than 50 m (a), further than 50 m (b), upstream (c) and downstream (d) from the causeway.

(a)

	Area (m^2)	Max. Depth (m)	Width (m)	W/D	Avg. Depth (m)	Hydraulic Radius (m)	Irregularity	A_2
Mean	1.92	0.29	10.40	77.95	0.16	0.16	1.004	0.317
Min.	0.04	0.04	1.33	14.59	0.01	0.01	1.000	0.013
Max.	7.57	0.56	19.99	368.66	0.39	0.38	1.017	1.613
CV	0.81	0.50	0.52	0.72	0.54	0.54	0.004	1.038

(b)

Mean	3.33	0.50	11.10	64.04	0.27	0.27	1.007	0.480
Min.	0.05	0.01	1.71	6.52	0.01	0.01	1.000	0.001
Max.	8.59	1.29	24.83	1792.28	0.64	0.61	1.040	2.940
CV	0.79	0.58	0.53	1.95	0.57	0.57	0.007	0.884

(c)

Mean	3.07	0.46	11.27	70.05	0.25	0.24	1.006	0.468
Min.	0.04	0.01	1.33	6.52	0.01	0.01	1.000	0.001
Max.	8.89	1.29	24.83	1792.28	0.57	0.56	1.040	2.940
CV	0.82	0.61	0.53	1.76	0.58	0.58	0.006	0.905

(d)

Mean	3.20	0.52	8.94	40.96	0.30	0.30	1.007	0.338
Min.	0.13	0.10	1.51	17.47	0.05	0.04	1.000	0.014
Max.	7.88	1.11	13.3	152.69	0.64	0.61	1.028	1.613
CV	0.81	0.63	0.38	0.67	0.67	0.66	0.007	0.936

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Min. represents minimum; CV represents coefficient of variance.

Table 37: Significance (P) values for comparisons of cross-section variables for each anthropogenic impoundment category, using Mann-Whitney's (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Area	Max. Depth	Width	W/D	Avg. Depth	Hydraulic Radius	Irregularity	A_2
0 – 50m v 50m+	**0.0008**	**< 0.0001**	0.5511	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.0182**	**0.0040**
Up. v down.	0.9481	0.5552	0.0723	**0.0043**	0.1747	0.1641	0.3472	0.0768

(b)

0 – 50m v 50m+	**< 0.0001**	**< 0.0001**	0.2692	0.5420	**< 0.0001**	**< 0.0001**	**0.0028**	**0.0335**
Up. v down.	0.4706	**0.0300**	**< 0.0001**	0.1359	**< 0.0001**	**< 0.0001**	0.8576	**0.0342**

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represent average; 0 – 50m represents expected effect; 50m+ represents no expected effect; up. represents upstream; down. represents downstream.

The long-profile data for reaches in the vicinity of the causeway indicate that there is no statistical difference between the slopes of the reaches within 50 m of the causeway and those greater than 50 m away from the causeway or between those upstream and downstream of the causeway (Tables 38 and 39 (a)). The vector displacement values are higher for reaches greater than 50 m from the causeway, indicating that these reaches have steeper undulations than reaches within 50 m of the causeway. For reaches upstream of the causeway the chain-and-tape values were significantly lower but the vector displacement values were significantly higher, indicating that these reaches have larger vertical variations but smaller angular variations than the downstream reaches.

The channel slopes within 50 m of the causeway exhibit a higher level of variability than those more than 50 m from the causeway while both the chain-and-tape and vector dispersion values are lower for cross-sections near the causeway (indicating that these sections have both lower vertical and angular variations than reaches more than 50 m from the causeway) (Tables 38 and 39(b)). Only the chain-and-tape values displayed a difference in variability with respect to channel position relative to the causeway, with upstream reaches being more variable in terms of their vertical variations than downstream reaches.

Cross-sections through bedform reaches within 50 m of the causeway are shallower and have lower hydraulic radii than cross-sections in reaches more than 50 m away from the causeway (Tables 40 and 41(a)). These were the only significant differences identified within the causeway bedform dataset. Thus, although there were slight differences in the bedform cross-sectional parameters there were no differences in the downstream parameters (such as feature height or depth, length or spacing) depending upon distance to the causeway and no differences in any parameters with respect to their positions upstream or downstream of the causeway. The cross-sections through bedform reaches within 50 m of the causeway are less variable in terms of their areas, depths and hydraulic radii than those more than 50 m from the causeway (Tables 40 and 41(b)). In addition, the upstream reaches have higher average asymmetries than reaches downstream of the causeway.

Descriptive statistics and value of bar unit (i.e., pool-riffle sequence) variables are presented in Table 42. These results show that even though there is only one entire pool-riffle sequence within 50 m the causeway, bar units more than 50 m from the causeway contain larger, deeper and more irregular and asymmetric cross-sections than bedforms within 50 m of the causeway.

Table 38: Descriptive statistics for long-profile variables for sections located less than 50 m (a), more than 50 m (b), upstream (c) and downstream (d) from the causeway.

(a)

	Slope	CT	VD
Mean	0.0000	1.267	0.449
Min.	-0.0022	1.252	0.441
Max.	0.0006	1.288	0.454
CV	-38.3857	0.009	0.009
(b)			
Mean	-00002	1.248	0.492
Min.	-0.0266	1.000	0.432
Max.	0.0131	1.319	1.433
CV	-16.6805	0.042	0.188
(c)			
Mean	-0.0002	1.246	0.491
Min.	-0.0266	1.000	0.451
Max.	0.0131	1.319	1.433
CV	-17.5756	0.040	0.183
(d)			
Mean	0.0000	1.286	0.441
Min.	-0.0022	1.253	0.432
Max.	0.0006	1.310	0.450
CV	-9.9894	0.013	0.011

N.B.: CT represents Chain-and-Tape; VD represents Vector Dispersion; in. represents minimum, Max. represents maximum; CV represents coefficient of variance.

Table 39: Significance (P) values for comparisons between long-profile variables for each anthropogenic impoundment category, using Mann-Whitney (a)and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Slope	CT	VD
0 – 50 m v 50 m+	0.9880	0.0683	**< 0.0001**
Up. v down.	0.9452	**< 0.0001**	**< 0.0001**

(b)

0 – 50 m v 50 m+	**0.0197**	**< 0.0001**	**0.0389**
Up. v down.	0.0742	**0.0003**	0.0811

N.B.: CT represents Chain-and-Tape; VD represents Vector Dispersion; 0 – 50 m represents expected effect; 50 m+ represents no expected effect; up. represents upstream; down. represents downstream.

For the purposes of this study the causeway was considered a riffle and, therefore, its upstream extent was represented as part of a sixth riffle-pool sequence. Therefore, five bar units were classified as located upstream of the causeway, one bar unit was classified as located downstream of the causeway and one bar unit was classified as both up- and down-stream of the causeway. Unfortunately, the small sample sizes of bar unit types (both in terms of distance from and position relative to the causeway) made it impossible to run comparative statistics between them. However, the data suggest that the bar units located within 50 m of the causeway are smaller and less asymmetric than those located further away while bar units upstream of the causeway contain larger, deeper (in terms of maximum depth), wider and more asymmetric cross-sections than the bar units located downstream of them.

Table 40: Descriptive statistics for bedform (i.e., pool or riffle) variables for sections located less than 50 m (a), more than 50 m (b), upstream (c) and downstream (d) from the causeway.

(a)

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Max. Height or Depth (m)	Avg. Height or Depth (m)	Length (m)	L/W	A_{h1}	A_L
Mean	1.98	0.32	10.13	61.45	0.18	0.18	1.004	0.319	0.57	0.26	45.47	4.22	0.763	0.647
Min.	1.10	0.25	7.25	49.27	0.14	0.14	1.003	0.282	0.39	0.20	24.04	3.32	0.194	0.219
Max.	2.61	0.37	13.79	82.17	0.22	0.22	1.006	0.371	0.93	0.33	77.64	5.63	1.406	0.949
CV	0.40	0.21	0.33	0.29	0.23	0.23	0.001	0.145	0.54	0.25	0.62	0.29	0.799	0.589

(b)

Mean	5.29	0.72	13.10	42.41	0.38	0.37	1.008	0.454	0.45	0.20	41.80	3.66	0.584	0.499
Min.	0.82	0.27	5.64	23.48	0.161	0.16	1.002	0.188	0.19	0.09	7.81	0.46	0.123	0.144
Max.	7.79	1.09	17.52	109.00	0.51	0.50	1.014	0.947	1.06	0.50	193.64	13.59	1.207	0.893
CV	0.49	0.38	0.34	0.57	0.31	0.31	0.004	0.516	0.58	0.58	1.32	1.26	0.620	0.540

(c)

Mean	5.00	0.68	13.36	47.75	0.35	0.35	1.008	0.450	0.42	0.20	45.44	3.86	0.537	0.535
Min.	0.82	0.27	5.64	25.74	0.16	0.16	1.002	0.188	0.19	0.09	7.81	0.46	0.123	0.144
Max.	7.79	1.09	17.52	109.00	0.50	0.49	1.014	0.947	1.06	0.50	193.64	13.59	1.171	0.949
CV	0.54	0.43	0.33	0.54	0.35	0.35	0.004	0.526	0.58	0.58	1.24	1.20	0.562	0.564

(d)

Mean	3.04	0.49	9.19	41.88	0.29	0.28	1.006	0.332	0.69	0.26	32.15	3.49	0.936	0.515
Min.	1.10	0.25	7.25	23.48	0.14	0.14	1.003	0.303	0.39	0.20	24.04	3.32	0.194	0.219
Max.	5.79	0.85	10.96	52.90	0.51	0.50	1.010	0.371	0.93	0.33	37.68	3.71	1.406	0.772
CV	0.81	0.65	0.20	0.38	0.68	0.67	0.003	0.106	0.40	0.25	0.22	0.06	0.694	0.541

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Min. represents minimum; CV represents coefficient of variance.

Table 41: Significance (P) values for comparisons of bedform (pool or riffle) variables within each anthropogenic impoundment using Mann-Whitney (a) and Levene's (b) tests. Bold entries signify a significant difference at a significance level of 0.05.

(a)

	Mean Area	Mean Max. Depth	Mean Width	Mean W/D	Mean Avg. Depth	Mean Hydraulic Radius	Mean Irregularity	Mean A_2	Max. Height or Depth	Avg. Height or Depth	Length	L/W	A_{h1}	A_L
0 – 50m v 50m+	0.1021	**0.0240**	0.2429	0.0734	**0.0240**	**0.0240**	0.1021	0.4835	0.3913	0.1857	0.3115	0.1391	0.5858	0.3918
Up. v down.	0.1857	0.1857	0.1857	0.9379	0.5858	0.5858	0.5858	0.6971	0.1387	0.2429	0.3918	0.2429	0.2429	0.9379

(b)

0 – 50m v 50m+	**0.0251**	**0.0098**	0.2589	0.8678	**0.0490**	**0.0490**	0.1137	0.0639	0.6901	0.5174	0.5514	0.2113	0.3497	0.5168
Up. v down.	0.2492	0.7862	0.1205	0.5157	0.2977	0.2977	0.6173	**0.0495**	0.7001	0.5182	0.1309	0.0585	0.0557	0.4311

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; 0 – 50m represents expected effect; 50m+ no expected effect; Up. represents upstream; Down. represents downstream.

Table 42: Descriptive statistics for bar unit (i.e., pool-riffle) sequences for sections located less than 50 m (a), more than 50 m (b), upstream (c), downstream (d) and both up- and down-stream (e) from the causeway.

(a)

	Mean Area (m^2)	Mean Max. Depth (m)	Mean Width (m)	Mean W/D	Mean Avg. Depth (m)	Mean Hydraulic Radius (m)	Mean Irregularity	Mean A_2	Height (m)	Length (m)	Spacing (L/W)	A_{L2}	A_H
Values	2.50	0.35	12.55	72.99	0.19	0.19	1.004	0.288	1.34	112.37	8.95	0.382	0.391

(b)

Mean	5.02	0.68	12.85	45.52	0.36	0.36	1.007	0.442	0.88	80.65	6.82	0.322	0.233
Min.	1.41	0.39	6.36	32.61	0.22	0.22	1.003	0.308	0.51	26.17	1.69	0.158	0.000
Max.	7.59	1.00	17.25	81.81	0.48	0.47	0.010	0.677	1.58	282.58	23.50	0.465	0.365
CV	0.51	0.37	0.33	0.41	0.29	0.30	0.002	0.334	0.47	1.24	1.22	0.388	0.587

(c)

Mean	5.19	0.69	13.47	47.89	0.36	0.36	1.007	0.466	0.83	84.43	7.89	0.342	0.216
Min.	1.41	0.39	6.36	32.61	0.22	0.22	1.003	0.308	0.51	26.17	1.69	0.158	0.000
Max.	7.59	1.00	17.25	81.81	0.48	0.47	1.010	0.677	1.58	282.58	23.50	0.465	0.365
CV	0.54	0.40	0.33	0.42	0.33	0.33	0.003	0.325	0.53	1.32	1.17	0.375	0.673

(d)

Values	4.19	0.64	9.78	33.66	0.38	0.37	1.008	0.323	1.13	61.72	6.31	0.221	0.321

(e)

Values	2.50	0.35	12.55	72.99	0.19	0.19	1.004	0.288	1.34	112.37	8.95	0.382	0.391

N.B.: Max. represents maximum; W/D represents width-to-depth ratio; Avg. represents average; L/W represents length-to-width ratio; Min. represents minimum; CV represents coefficient of variance; Values represents the results of sections with only one structure found in a particular classification.

5 Discussion

The geomorphic diversity of fluvial systems is an important parameter that provides information on a system's health and biological activity (Semeniuk 1997; Burnett et al. 1998; Bartley & Rutherford 2005) and its resilience to change. In spite of its value, few studies have specifically investigated the mechanisms or processes that control or influence geomorphic diversity. Hence, our understanding of this fundamental trait of any geomorphic system is incomplete. Moreover, those studies that have attempted to link channel morphologic character to external controlling factors (such as valley confinement, riparian vegetation, obstructions including woody debris and islands, and human made impoundments) without a consideration of geomorphic diversity have tended to focus on only one or two factors (and a single geomorphic scale) at one time. Thus, the complex interaction of external controls and the multi-scale geomorphic responses that arise from them are only poorly understood. This study seeks to identify the main influences on fluvial geomorphic diversity across multiple scales and through the simultaneous consideration of a wide range of external controlling factors in the hopes of bridging this knowledge gap.

The relationships between various cross-sectional, long-profile, bedform and bar unit variables (classified according to the external factors in the surrounding area) that quantify the geomorphic diversity of reaches at a variety of spatial scales were examined for the Turon River, NSW. Cross-sectional geomorphic diversity was quantified using cross-sectional area, maximum depth, width, width-depth ratio, average depth, hydraulic radius, irregularity and the asymmetry index A_2 (used by Rayburg & Neave 2008). Long-profile geomorphic diversity was assessed using slope, chain-and-tape and the downstream angular variance (i.e., vector dispersion) (Bartley & Rutherford 2005). Finally, the geomorphic diversity of bedforms and bar unit sequences was assessed using the means of the cross-sectional variables in conjunction with maximum riffle height or pool depth, average riffle height or pool depth, length, length-width ratio and the asymmetry indices A_{h1} and A_L for bedforms and height, length, spacing (length-width ratio) and the asymmetry indices A_{L2} and A_H for bar unit sequences. These variables provided a sense of geomorphic diversity at each scale and when used in conjunction allowed for an understanding of which external factors influenced the size, shape and diversity of the channel at each spatial scale.

The influence of external controls on channel diversity was assessed through a consideration of the following factors: confinement, presence and type of riparian vegetation, presence of woody debris, obstructions and anthropogenic impoundment. The objective was to determine how these external factors influenced channel form at each of the four spatial scales considered within this study (cross-section, long-profile, bedform and bar unit).

5.1 Confinement

Channel confinement has a significant impact on both the size and variability of channel cross-sections. For example, confined channel sections were shown to be significantly larger than unconfined sections in terms of their cross-sectional areas, maximum and average depths, widths, hydraulic radii, w/d ratios and cross-sectional asymmetries. However, the effect of channel confinement on the diversity of channel cross-sectional properties was reversed, with confined channels exhibiting much lower variabilities than unconfined sections for their cross-sectional areas, maximum and average depths, widths, hydraulic radii, w/d ratios and cross-sectional irregularities. Further, the type of confinement was shown to influence channel cross-sectional morphology and diversity with valley, terrace and partially confined cross-sections being larger but less diverse than the unconfined reaches.

The impact of confinement on channel cross-sectional morphology, therefore, seems to be an increase in overall channel dimensions but a decrease in morphologic diversity. In addition, these findings indicate that both the type and level of confinement are key influences on cross-sectional morphology and diversity. These results are consistent with those of Zimmermann et al. (2006) who found that flow depths are considerably larger in confined channels than in unconfined channels but contradict those of Milne (1983) who suggests that confined cross-sections are likely to be less asymmetrical than unconfined cross-sections.

A more detailed look at confinement type indicates that the nature and magnitude of the effect of confinement on channel morphology is dependent on the type of confinement considered. For example, when compared to terrace confined reaches valley confinement (which is associated with geologic control) leads to larger channel dimensions (such as cross-sectional area and channel width) and lower channel diversity. This is somewhat counterintuitive as it suggests that erosion occurs more readily in the harder geologically controlled reaches than in those bounded by softer alluvial deposits. The nature of the confinement, however, may be the cause of this apparent contradiction. In geologically confined channels (with only one sided bounded as was the case here) the entire erosive capacity of the stream is directed at only one bank and the channel bed as the alternate bank is resistant to erosion. Hence, the bed and non-valley impinged bank will experience comparatively high rates of erosion. Meanwhile, in terrace confined sections, both banks and the bed are susceptible to erosion. In these reaches, then, erosion rates would be reduced as they are more evenly distributed across the entire channel boundary.

Confinement also appears to have a significant impact on the morphology and diversity of a stream’s long-profile. At the largest scale, unconfined long-profiles have higher vertical but lower angular variations than those in confined reaches, and therefore the long-profiles of unconfined and confined reaches are morphologically different. In addition, the long-profiles of the confined sections were found to be more variable than those of unconfined reaches. Within confinement types, systematic variations were observed in the magnitudes of the chain-and-tape and vector dispersion values with the chain-and-tape values of terrace confined long-profiles being greater than valley confined long-profiles which are, in turn, greater than partially confined long-profiles and the reverse being true for the vector dispersion values (i.e., partially confined > valley confined > terrace confined). Therefore, terrace confined long-profiles have more vertical and less angular variation than valley confined long-profiles which, in turn, have more vertical and less angular variation than partially confined long-profiles.

Bartley and Rutherford (2002) present an alternative way to look at long-profile variability by stating that a long-profile can be considered highly variable, and therefore geomorphically diverse, if it has both high vertical variation (i.e., large chain-and-tape values) and high angular variation (i.e., large vector dispersion values). In this study, however, the chain-and-tape and dispersion values worked in opposition with the vertical variation being lower and the angular variation being higher for confined long-profiles than for unconfined long-profiles. This suggests that these two reaches are both structurally diverse in their long profiles, albeit in different ways.

Although channel confinement has a significant impact on both the channel-cross-section and long-profile of the Turon River, the same cannot be said of its influence on the morphology of pools and riffles. Although there were some impacts evident, for example, bedforms in confined sections were wider, had larger cross-sectional areas and were more asymmetrical than those in unconfined reaches, only maximum depth showed a difference in terms of variability (with confined sections being more diverse than unconfined sections for this variable). Similarly, few significant results were returned when the different confinement types were considered.

As confinement does not appear to readily influence bedform structures, except perhaps through frequent rockfalls which would likely increase the number of bedforms, these findings contradict those of Rayburg and Neave (2008) who found that the dimensions of pools and riffles are, to a certain degree, influenced by factors operating at large scales (e.g., confinement). Additionally, the results of this study indicate no significant change in the downstream spacing (i.e., the length-width ratio) of pools, which suggests that the rocky outcrops observed in the confined reaches of the Turon River (and not elsewhere) are not a control on the spacing of bedform structures.

As there was only one unconfined bar unit, analyses could not be performed to test for significant differences between confined and unconfined pool-riffle sequences. However, no significant differences between valley confined sequences and terrace confined sequences were identified in the data suggesting that the type of confinement has no influence on bar unit morphology or diversity. Thus, the overall effect of confinement on the channel of the Turon River is an increase in the cross-sectional and downstream (i.e., long-profile) dimensions of the channel and a decrease in geomorphic diversity.

5.2 Riparian Vegetation

Riparian vegetation appears to have some impact on the size and variability of channel cross-sections, although the nature of this depends on the extent of the cover (i.e., whether one or two banks were vegetated) and the type of vegetation present. For example, sections containing riparian vegetation on both banks were found to have significantly larger width-depth ratios and cross-sectional asymmetries than sections with riparian vegetation on only one bank. In addition, reaches with both banks covered in vegetation had higher variabilities in their average depths and hydraulic radii than reaches with only one vegetated bank. These impacts, however, are limited to only a few cross-sectional variables and, thus, the differences between cross-sections with one or two banks covered by riparian vegetation are minimal.

When considering the impact of riparian vegetation type on cross-sectional geomorphic diversity several patterns were identified. Firstly, channels with limited riparian vegetation cover were significantly smaller (having lower areas, maximum and average depths, widths and hydraulic radii) and less irregular than channels with vegetated banks (including grass and/or she-oak and/or blackberry covers). In contrast, however, reaches with minimal vegetation covers had larger variabilities in their areas, widths, maximum and average depths, width-depth ratios, and hydraulic radii than well vegetated channels. Secondly, grass-lined sections were significantly larger, more asymmetric and had more variable areas, maximum depths, width-depth ratios, widths, hydraulic radii and asymmetries than sections covered in she-oak and/or blackberries. These findings show that the type of riparian vegetation is a much more important control on channel form and complexity than simply the presence or absence of vegetation alone. In addition, the nature of the relationships between riparian cover, cover type and channel form suggest that shrub or tree riparian covers (e.g., those covered in she-oak and/or blackberries) promote channel contraction and the formation of simple channels, due to their bank stabilising properties and their ability to moderate the influx of water, sediment and nutrients. Meanwhile, grass lined channels are easily erodible leading to the formation of large diverse channels. These findings have important implications for stream restoration efforts which often focus on re-establishing trees in riparian zones. Although this would clearly have a stabilising affect on the channel (leading to a reduction in channel dimensions) and leads to increased organic matter inputs and temperature regulation in the channel, the results of this study also suggest that such changes may reduce the morphologic diversity in the channel. Such changes could reduce the structural habitat complexity in rivers leading to a loss of biological productivity and diversity. More work needs to be done to firmly establish the relative positive and negative effects of riparian vegetation on morphologic and biologic diversity to provide meaningful advice to river management agencies about the benefits (or consequences) of restoring riparian vegetation.

Other studies have investigated the impact of riparian vegetation on channel morphology. For example, Gurnell (1997) and Charron et al. (2008) found that riparian vegetation provides bank stability and, thus, restrains a river's lateral movement (Knighton 2000) which would be expected to result in smaller overall channel dimensions as was observed in this study. However, Andrews (1982) and Ward et al. (2002) argue that the restraining nature of riparian vegetation may cause a river to begin to undercut its banks as a result of bank retreat caused by channel migration. Although undercutting, easily identifiable through the exposure of tree roots and the presence of bent tree trucks (Gregory & Davis 1992), did occur in some areas of the Turon River these were generally sections with only one bank covered in riparian vegetation. Hence, the riparian vegetation in the Turon River does not seem to promote undercutting with its corresponding increase in channel dimensions.

Both the extent and type of riparian vegetation cover also have significant impacts on the morphology and variability of the Turon River's long-profile. At the larger scale, reaches with vegetation covers on both banks have lower chain-and-tape values and higher vector dispersions than those of sections with only one bank covered in vegetation. In other words, the long-profiles of sections with vegetation cover on both banks have lower vertical variation but higher angular variation in their beds than long-profiles with only one bank covered in riparian vegetation. Within riparian vegetation types, minimally vegetated long-profiles exhibit significantly smaller vector dispersions than sections of long-profile containing grass and/or she-oak and/or blackberry covered banks. However, comparisons between grass covered and she-oak and/or blackberry covered sections of long-profile show that the former have smaller chain-and-tape values and larger vector dispersions than the latter. Hence, and similar to the results for long-profiles in different confinement types, there is a distinct variation in the magnitude of the vector dispersion of the long profile and riparian vegetation with grass-lined sections being greater than she-oak and/or blackberry-lined sections which in turn are greater than minimally vegetated sections. With respect to the chain-and-tape values, however, the minimally vegetated long-profiles are similar to she-oak and/or blackberry-lined long-profiles but are greater than grass-lined long-profiles. The variability of long-profile characteristics observed here are likely the result of the influence of riparian vegetation on the influx of water and sediment in the channel. For example, grass tends to afford banks a relatively complete vegetation cover that decreases the amount of runoff into the channel due to ponding and increased infiltration rates, therefore, decreasing in-channel erosion and, thus the vertical variation (i.e., chain-and-tape) of the long-profile. The patchy growth of she-oak and/or blackberries, however, allows excess runoff from the banks to reach the channel which may increase channel erosion, therefore increasing the vertical variation of the long-profile.

Similar to the findings for confinement, the variables depicting vertical variation (i.e., chain-and-tape) and angular variation (i.e., vector dispersion) were shown to operate in opposite directions for the level and type of riparian vegetation present in this study. In other words, vertical variation was lower and angular variation was higher in heavily vegetated reaches (i.e., reaches with vegetation cover on both banks) than in lightly vegetated reaches (i.e., reaches with vegetation on one bank). However, sections of river with minimal vegetation cover have equal vertical variation but lower angular variation to those with she-oak and/or blackberry cover, which have higher vertical variation and lower angular variation to grass covered reaches. As Bartley and Rutherford (2002) indicated that these two parameters should both be large in geomorphically diverse channels, the results of this study suggest that both vegetated and unvegetated reaches can exhibit structural diversity.

Even though riparian vegetation has a significant impact on the long-profile and, to a lesser extent, the cross-sectional form of the Turon River, the same cannot be said of its influence on the morphology of pools and riffles. Although there were some impacts evident, for example, bedforms with both banks maintaining riparian vegetation had variabilities greater than those in sections with only one vegetated bank in terms of their width-depth and length-width ratios and cross-sectional and bedform asymmetries, only their widths showed a difference in terms of size (with sections containing vegetation cover on both banks being wider than sections with only one bank covered in vegetation). Similarly, few significant results were found when the different types of riparian vegetation were considered. Hence, most pool-riffle variables were not influenced by either the presence or type of riparian vegetation within a reach.

As riparian vegetation does not appear to readily influence bedform structures, these findings support those of Ferguson (1981) who found that induced channel changes in bedform structures may simply be accelerated versions of natural adjustments that could occur provided the same changes occur in sediment supply or hydrologic regime (which the level and type of riparian vegetation affect). They also support the work of Bowman (1977) who found that changes in stream long-profiles (particularly channel slope which is believed to cause changes in bed configuration) are often not accompanied by changes in bedform morphology.

Riparian vegetation was also shown to have no significant impact on bar unit (i.e., pool-riffle sequence) morphology. However, as there was only one bar unit that had grass covered banks, analyses could not be performed to test for significant differences between these and bar units containing she-oak and/or blackberry covered banks. Although there were very minor impacts evident, for example, bar units that had she-oak or blackberries growing on their banks had larger cross-sectional asymmetries than those with both grass and she-oak and/or blackberry covered banks, only bar unit spacing (i.e., length-width ratio) showed a difference in terms of variability (with bar units containing she-oak and/or blackberries being more diverse than those containing both grass and she-oak and/or blackberries). These findings suggest that the type of riparian vegetation has more of an influence on bar unit morphology or diversity than the level of riparian vegetation cover, although in both cases this influence is minor.

5.3 Woody Debris

Woody debris has more of an effect on the variability of channel cross-sections than it does on their size. For example, sections containing woody debris were shown to be significantly smaller than sections devoid of woody debris only in terms of their cross-sectional areas and widths. However, the affect of woody debris on the diversity of channel cross-sectional properties was reversed and more significant, with channels containing woody debris exhibiting much higher variabilities than channels without woody debris for their cross-sectional area, maximum and average depth and hydraulic radius but lower variabilities for their cross-sectional irregularity. Further, the type of woody debris (i.e., in-channel or bank) was shown to have an important influence on channel cross-sectional morphology and diversity with sections containing in-channel woody debris exhibiting similar patterns in size to those described above when compared to sections without woody debris, but slightly different patterns in diversity.

A more detailed look at the data indicates that the nature and magnitude of the effect of woody debris on channel morphology depends on the type of woody debris considered. For example, in-channel woody debris results in a reduction in overall channel dimensions (such as area and width, which are smaller in these reaches) and an increase in channel diversity when compared to sections with woody debris on the banks. These findings suggests erosion and lateral migration occurs more readily in sections containing woody debris on the banks than in those containing a large in-channel woody debris jam, thus contradicting the work of Keller et al. (1995) and Abbe and Montgomery (2003) who found the partial damming of a channel by a woody debris jam can lead to sufficient water build-up, creating overbank flow and channel widening. However, these results support those of Mao et al. (2008) who found that approximately 36% of flow-deflection jams caused channel narrowing.

Unlike channel cross-sections, the presence of woody debris has no impact on the morphology and diversity of stream long-profiles. However, the type of woody debris did exhibit some control on channel morphology and diversity. That is, sections with in-channel woody debris had significantly larger vertical variations than those with woody debris on the banks and their diversities in both vertical and angular variation were lower. Thus, these findings indicate that the long-profiles of sections with woody debris on the banks are more geomorphically diverse than long-profiles containing in-channel woody debris. The mechanisms responsible for this phenomenon are unknown and, thus, require further investigation.

Similar to channel cross-sections, woody debris has a significant impact on the diversity of bedforms but does not have an impact on their morphology. For example, bedforms containing woody debris were shown to have smaller variabilities in their cross-sectional area, maximum and average depth and hydraulic radius (all of which are cross-sectional variables) than those containing no woody debris. Additionally, bedforms containing woody debris were shown to have higher variabilities than bedforms containing no woody debris in terms of their width-depth ratios, average heights or depths, lengths and length-to-depth ratios (all of which are downstream parameters with the exception of the w-d ratio). Similar results were found when comparing sections with woody debris on their banks to sections without woody debris. Hence, woody debris was found to both increase and decrease geomorphic diversity, depending on the variable (or direction; i.e., cross- or downstream) of interest. These results are quite unique, in that, for most factors, the influence of the factor in question at any particular scale has been either a fairly uniform increase or decrease in geomorphic diversity. These findings, therefore, imply that the affect of woody debris on morphologic diversity (at least for bedforms) is more complex than that for other factors. This contradicts the work of Abbe and Montgomery (1996) who found that, on average, bedforms related to woody debris display larger variations in their depths than free-formed pools due to the effect of scour. However, as there was only one bedform containing in-channel woody debris, analyses could not be performed to test its affects on bedform morphology and diversity.

No significant impacts of woody debris on the morphology of bar units were identified in this study. Although there were some minor impacts evident, for example, bar units containing woody debris were shown to be more highly variable in length and spacing than bar units containing no woody debris, no other variables were shown to have significant differences in terms of size or variability. Since there was only one bar unit containing woody debris on the bank and one containing in-channel debris, further analyses on the effect different types of woody debris has on bar unit morphology and diversity could not be performed. None-the-less, the findings of this study support those of Gregory et al. (1994) who found that pool-riffle sequences (i.e., bar units) are more diverse in woody debris channels than in those lacking woody debris. This is because woody debris is, in itself, a part of the structural diversity of channels and is therefore expected to increase the geomorphic diversity of river channels.

5.4 Obstructions

In-channel obstructions, such as islands and in-channel bars, have significant impacts on both the size and variability of channel cross-sections. For example, obstructed channels were shown to be significantly smaller than unobstructed channels in terms of their cross-sectional areas, maximum and average depths, widths, hydraulic radii and cross-sectional irregularities, but significantly larger than unobstructed channels in terms of their width-depth ratios. However, the effect of obstructions on the diversity of channel cross-sectional properties was reversed, with obstructed cross-sections exhibiting much higher variabilities than unobstructed cross-sections for their areas, maximum and average depths, widths, width-depth ratios, hydraulic radii and asymmetries. Thus, the impact of in-channel obstructions on channel cross-sectional morphology seems to be a decrease in channel dimensions but an increase in morphologic diversity. These findings suggest that in-channel obstructions are a key influence on cross-sectional morphology and diversity and support those of Richards (1980) and Roy and Roy (1988) who found that channel width adjustments occur downstream of channel confluences (i.e., at the junction of the main and secondary channel after an obstruction). This is because obstructions impede flow which decreases bank erosion and promotes deposition, thus reducing channel width and depth. However, when two channels converge after an obstruction, the additional input of water enables flow velocities to increase once more, thus increasing channel erosion. Moreover, the divergence of a single thread channel into two sub-channels must be accompanied by a reduction in channel bed dimensions as the flow becomes divided between the two smaller branches.

Similar to channel cross-sections, obstructions have a significant impact on the morphology and diversity of stream long-profiles. Both channel slope and vertical variation were affected by in-channel obstructions in the Turon River, with obstructed channels having higher slopes and chain-and-tape values but less variability than unobstructed channels. These findings may be the result of backwater effects that lead to a reduction in channel capacity below a convergence and the storage of flow above the convergence, as described by Roy and Roy (1988) and Best (1988). The increased storage of water above the convergence after an obstruction may cause the channel in these sections to increase its slope in an attempt to remove the excess water.

Obstructions also have a significant impact on the morphology of pools and riffles. Bedforms within obstructed channels were significantly smaller than bedforms in unobstructed channels in terms of cross-sectional area, maximum and average depth, width and hydraulic radius but had significantly larger length-width ratios. The effect of obstructions on the diversity of bedform properties was reversed, however, with bedforms in obstructed channels exhibiting higher variabilities than unobstructed bedforms for their lengths, and width-depth and length-width ratios. These findings suggest that in-channel obstructions are key influences on bedform morphology and diversity. This is to be expected as obstructions such as islands and bars are part of the overall diversity of geomorphic types and influence water flow and sediment yield, thus influencing the internal variability of channels. Furthermore, obstructions divide the channel into larger and smaller branches (which are smaller than the single channel from which they originate), each of which typically contains its own bed structures. Hence, the bedforms within these reaches would be automatically smaller than those outside the obstructed reaches and more diverse because they would be quite different to each other and to those found in single thread reaches.

In addition, obstructions have an impact on the morphology of bar units (i.e., pool-riffle sequences). Obstructed bar units in the Turon River were found to be significantly smaller than unobstructed bar units in terms of their cross-sectional areas, maximum depths and widths but had larger spacings and asymmetries than unobstructed bar units. The affect of obstructions on the diversity of pool-riffle sequences, however, was only minor with obstructed sequences having larger variabilities only in their width-depth ratios and asymmetries. These findings are probably the result of obstructions impeding flows and altering sediment transport mechanisms, which alter channel dimensions and variability in addition to the scaling issues described above.

5.5 Anthropogenic Impoundment

The presence of an anthropogenic impoundment (e.g., a causeway) has a significant effect on the structure and diversity of channel cross-sections in the Turon River. For example, cross-sections within 50 m of the causeway were shown to be significantly smaller than cross-sections located more than 50 m away from the causeway in terms of cross-sectional area, maximum and average depth, hydraulic radius, cross-sectional irregularity and asymmetry. This result is likely caused by the build-up sediments behind the causeway. The effect of impoundment on the variability of cross-section characteristics was less obvious with the variability of cross-sectional area and asymmetry being significantly higher but the variability of maximum and average depth, hydraulic radius and irregularity being significantly lower for sections within 50 m of the causeway. The position of the causeway (i.e., up- or down-stream), however, was shown to only have a significant influence on the variability of channel cross-section characteristics. Hence, it does not matter, in terms of its effect on channel dimensions, whether a particular location is upstream or downstream of a causeway, only that there is a causeway present.

The effect of an anthropogenic impoundment on the form and diversity of the Turon River, therefore, is a decrease in both channel dimensions and cross-sectional diversity. These findings support those of Parsons and Gilvear (2002) and Bartley and Rutherford (2005) who found that anthropogenic activities (e.g., the construction of impoundments) can lead to a simplification of a river's physical structure and, thus, a reduction in its geomorphic diversity. The findings also concur with those of Assani and Petit (2004) who found that due to the far-reaching influence of an impoundment, channel incision and channel widening immediately below the impoundment is no more important than that occurring further downstream. In fact, in the present study the sections downstream of the causeway were shown to be narrower than the upstream sections, which is similar to the findings of Rovira et al. (2005) who reported that some river channels are narrower than their original channels downstream of an impoundment.

Unlike channel cross-sections, anthropogenic impoundment has little impact on the morphology of long-profiles. Only sections of long-profile located within 50 m of the causeway have significantly lower vector dispersions than sections of long-profile located more than 50 m from the causeway. However, anthropogenic impoundment does have a significant impact on the diversity of long-profiles. For example, sections of long-profile located within 50 m of the causeway were shown to have significantly lower variabilities in their slopes, chain-and-tape values and vector dispersions than long-profiles located more than 50 m from the causeway. In addition, the up- or down-stream location of the causeway has a significant impact on the morphology of long-profiles. For example, sections of long-profile located upstream of the causeway were shown to have lower chain-and-tape values and higher vector dispersions than long-profiles located downstream of the causeway and the variability of their chain-and-tape values was higher than those of long-profiles downstream of the causeway.

The overall influence of an anthropogenic impoundment on the Turon River, therefore, is a decrease in angular variation and in the variability of slope, vertical variation and angular variation. Once again, these findings concur with those of Parson and Gilvear (2002) and Bartley and Rutherford (2005) who found that the simplification of a channel's physical structure can occur as a result of anthropogenic activities. Additionally, since it is well documented that anthropogenic impoundments alter sediment supplies to downstream reaches (e.g., Gaeuman et al. 2005; Thoms et al. 2007), it comes as no surprise that the long-profiles of sections within 50 m of an impoundment will be most affected.

Anthropogenic impoundment also has a slight impact on the morphologic structure and diversity of bedforms. However, it seems that impoundments have more of an effect on the cross-sections that make up the bedforms than the downstream structure of the bedforms, since only the cross-sectional maximum and average depths and hydraulic radii of bedforms located within 50 m of the causeway were shown to be significantly smaller than those of bedforms located more than 50 m from the causeway. Additionally, the variability of cross-sectional areas, maximum and average depths and hydraulic radii within bedforms located less than 50 m from the causeway were significantly lower than the variability of the same parameters within bedforms located more than 50 m from the causeway. Furthermore, bedforms located upstream of the causeway were shown not to be significantly different than bedforms located downstream of the causeway.

These findings contradict those of Parson and Gilvear (2002) and Freeman et al. (2007) who found that the inevitable changes in flow patterns and sediment fluxes to downstream reaches created by impoundments is likely to remove distinctive habitats (i.e., bedform structures). However, the impacts of sediment retention behind an impoundment have been known to be less obvious in coarse-grained reaches with well-vegetated banks (e.g., the Turon River) (Ferguson 1981).

As there was only one bar unit within 50 m of the causeway, the impact of anthropogenic impoundment on bar units could not be considered. Likewise, the influence of the up- or down-stream location of anthropogenic impoundment on bar units could not be investigated as there was only one pool-riffle sequence located downstream of the causeway. However, values obtained for these pool-riffle sequences suggest that bar units within 50 m of anthropogenic impoundments are narrower, higher, longer and more asymmetric than bar units located more than 50 m from impoundments. Additionally, values for bar units located downstream of the impoundment are narrower, higher and shorter than bar units located upstream of the impoundment. These findings contradict those of Parsons and Gilvear (2002) who found that the decreased sediment load created by the trapping of sediment behind impoundments may remove gravel-based features (e.g. riffles). These findings also contradict those of Freeman et al. (2007) who found that a decrease in distinctive habitats (e.g., pool-riffle sequences) may occur downstream of an anthropogenic impoundment. In fact, these findings indicate a potential increase in pool-riffle sequences downstream of an impoundment.

5.6 The factors most responsible for channel size, shape and diversity at each spatial scale

When the results of this study are combined to give an overall view of what external factors are the most influential on the geomorphic structure of the Turon River (Figure 19), they indicate that obstructions have the greatest influence on channel size, with confinement and impoundments being the second and third most influential. All three of these external factors affected the morphology of cross-sections, long-profiles and, to a lesser extent, bedform structures (i.e., pools and riffles). This is likely a result of the effects these factors have on channel flow, sediment supply and channel movement. For example, obstructions and impoundments impede flows which can increase rates of deposition. In the case of impoundments on the Turon River, channel narrowing occurred within 50 m of the causeway, therefore suggesting that the impoundment led to a narrowing of the channel. Additionally, confinement restricts channel movement and, due to this restriction, may promote the narrowing of channels. As a result, flow depths within confined reaches are proportionally greater than flow depths in unconfined channels, thus inundating bed features that would be partially emergent in a wider channel (Zimmermann et al. 2006).

In terms of geomorphic diversity, the variability of the channel of the Turon River is mainly influenced by woody debris and obstructions (Figure 19) which, themselves, represent part of the overall structural diversity of river channels. Woody debris was shown to affect the variability of approximately half of the cross-sectional and bedform parameters used in this study, while obstructions affected the variability of cross-sectional and long-profile parameters. These external factors (i.e., woody debris and obstructions) both influence water flow, sediment transport and stream energy. For example, they both affect the dissipation of stream energy (Gurnell 1997) and can redirect a large portion of river flow around their in-channel structures, resulting in bank erosion, channel widening and local bed scour (Abbe & Montgomery 2003). Additionally, the convergence of water around these structures results in substantial changes in the downstream hydraulic geometry (Best 1988), including changes in channel width (Richards 1980; Roy & Roy 1988).

Of the four scales investigated in this study, (i.e., cross-section, long-profile, bedform or bar unit) cross-sections were found to be most sensitive to external factors. Indeed all of the factors, with the possible exception of woody debris, were found to have a significant effect on the size, shape and diversity of channel cross-sections. Confinement and riparian vegetation act as constraints to channel movement, therefore creating narrower and less diverse cross-sections than unconfined and non-vegetated channels. Confinement and riparian vegetation can also influence the amount of run-off entering a river channel.

	Cross-section	Long profile	Bedform	P-R Sequence	Total
Confinement	7/8 Magnitude 7/8 Variability	2/3 Magnitude 2/3 Variability	3/14 Magnitude 1/14 Variability	0/13 Magnitude 0/13 Variability	12/38 Magnitude 10/38 Variability
P/A riparian vegetation	4/8 Magnitude 4/8 Variability	2/3 Magnitude 3/3 Variability	1/14 Magnitude 1/14 Variability	0/13 Magnitude 0/13 Variability	7/38 Magnitude 8/38 Variability
Type riparian vegetation	6/8 Magnitude 6/8Variability	2/3 Magnitude 2/3 Variability	0/14 Magnitude 2/14 Variability	1/13 Magnitude 1/13 Variability	9/38 Magnitude 11/38 Variability
Woody debris	2/8 Magnitude 4/8 Variability	0/3 Magnitude 0/3 Variability	0/14 Magnitude 8/14 Variability	0/13 Magnitude 2/13 Variability	2/38 Magnitude 14/38 Variability
Obstructions	7/8 Magnitude 7/8 Variability	2/3 Magnitude 2/3 Variability	6/14 Magnitude 3/14 Variability	5/13 Magnitude 2/13 Variability	20/38 Magnitude 14/38 Variability
Impoundments	7/8 Magnitude 6/8 Variability	1/3 Magnitude 3/3 Variability	3/14 Magnitude 4/14 Variability	0/13 Magnitude 0/13 Variability	11/38 Magnitude 13/38 Variability
Total	33/48 Magnitude 34/48 Variability	9/18 Magnitude 12/18 Variability	13/84 Magnitude 19/84 Variability	6/78 Magnitude 5/78 Variability	61/228 Magnitude 70/228 Variability

Figure 19: Number of significant variables returned between each factor and scale. For example, confinement is a significant control on the magnitude and variability of cross-sectional form and variability for seven out of eight cross-sectional variables. N.B.: P-R sequences represents pool-riffles sequences; P/A represents presence or absence.

For example, valley confined reaches are prone to excess run-off from their adjacent steep, rock walls and, thus, cross-sections within valley confined reaches would be expected to be deeper than those in unconfined sections. Alternatively, obstructions and impoundments impede river flows causing sediment deposition to occur, thus, resulting in shallower channels. This results from backwater effects created by the convergence of the main and secondary channel around an obstruction and the storage of flow behind an impoundment which reduces flow velocity (Best 1988).

In comparison, bar units (i.e., pool-riffle sequences) were shown to be the scale least affected by external factors, with their magnitudes being influenced only by obstructions and their variability being influenced by obstructions and woody debris. Both of these factors (i.e., obstructions and woody debris) are known to impede river flow, which can result in backwater effects and the build-up of water behind these obstructions may cause local scour and the formation of pools. These findings contradict those of Keller and Tally (1979) and Abbe and Montgomery (1996) who found clear relationships between bedforms and woody debris. Specifically, they found that in-channel accumulations of woody debris influence the characteristics, spacing and development of pool-riffle sequences, both in woodland channels (Keller & Tally 1979) and in large rivers (Abbe & Montgomery 1996). The Turon River, however, is neither a woodland nor a large river which may explain why the non-significant influence of obstructions and woody debris on bar units in this study.

For all factors except obstructions and confinement, the influence of external factors on channel morphology was more profound on channel diversity than on channel dimensions. This suggests that the factors chosen for this investigation (i.e., confinement, riparian vegetation, woody debris, obstructions and anthropogenic impoundment) affect the structural diversity of the Turon River more than they affect the morphology itself. This is likely the result of the combination of the effects each factor has on channel size and structure. That is, each factor has been shown to have its own influence on the different scales examined within this study and as these factors interact within the same reach, the effects they have on each scale combine to result in a geomorphically diverse fluvial system.

Additionally, for all factors except impoundment, the influence of external factors on the magnitude and diversity of channel dimensions and morphology are reversed. In other words, channels influenced by external factors tend to be either large with little physical diversity or small but structurally diverse. This study has shown that the larger channels, resulting from the influence of certain factors (i.e., confinement and riparian vegetation), tend to be deeper and, as such, are expected to have higher flow velocities. These high velocities would be expected to result in high levels of in-channel erosion which may reduce the diversity of features on the channel bed. Similarly, the small but more diverse channels result from the influence of different factors (i.e., woody debris and obstructions). These factors tend to act to impede the flow of water within the river, which causes the deposition of sediment, potentially creating depositional bed structures (e.g., bars, riffles, benches). However, local bed scour produced by the storage of water (i.e., backwater effect) behind these structures can also result localised scour, thereby creating an undulating bed profile and possibly scouring pools. This combination of scour and deposition can be a prime factor in generating high levels of morphologic diversity.

The data presented in this study, therefore, illustrate that even within a relatively short reach, morphologies of different fluvial components can vary considerably both within and between different geomorphic regions. These results support those of Rayburg and Neave (2008) insofar as no two cross-sections, sections of long-profile, bedforms or bar unit sequences were identical (although they often looked similar). Additionally, the data presented in this study suggest that large scale external factors (i.e., confinement and riparian vegetation) have influences on all small scale (i.e., cross-sections) and some intermediate scale river structures (i.e., long-profile), while small scale external factors (i.e., woody debris, obstructions and anthropogenic impoundment) have an impact on both large scale river structures (i.e., bedforms and bar units) and small scale structures (Figure 17).

5.7 Applicability and limitations to study

This study improves our understanding of geomorphic diversity in several ways. Firstly, it improves on earlier studies that only considered one external factor operating at a single spatial scale by analysing the effects of external factors operating at three different scales, i.e., large-scale (confinement), mid-scale (riparian vegetation) and small (local)-scale (woody debris, obstructions and impoundment). Indeed, this is the first study to consider multi-scale, multi-factor influences on geomorphic diversity in river channels. Secondly, the method adopted here is easy to apply to other fluvial systems insofar as the data required for analyses can be collected using either a digital global positioning system (DGPS) or a total station, and the analyses themselves involves simple arithmetic. The extension of this type of investigation to other river systems should further shed light on the relationships identified here and help to clarify the links between channel form, morphologic diversity and external controls.

There are, however, limitations to this study in that it takes a direct measurement and observation approach over relatively small spatial and temporal scales. Additionally, even though statistical analyses of channel morphology, and thus geomorphic diversity, offer insights into relationships among cross-sectional, long-profile, bedform and bar unit sequence variables, this approach is limited because the significant statistical associations do not necessarily signify that the relevant variables are causally related. In addition, only limited numbers of observations were available for some scale-factor pairings (especially for bar units). Finally, this study was based on bed surveys only. This means that when comparing the results of this study to others, the interpretation and findings may differ due to the fact that they used bankfull cross-sections and this study did not. As such, further field studies are required to expand upon our understanding of how specific controlling factors influence channel form.

6 Conclusion

The natural variability of geomorphic features, or geomorphic diversity, is an important component of fluvial systems that can indicate river health and influence the biological diversity within the channel. However, the causes of geomorphic diversity have often been neglected in previous studies. Indeed, those studies that have looked for the controlling factors on geomorphic structure within rivers have done so without any consideration of morphologic diversity. In addition, existing studies into the relationships between external factors and morphologic structure have tended to focus on only one factor (e.g., woody debris) and one scale (e.g., pools and riffles) at a time. The aim of this study, therefore, was to examine the multi-scale and multi-factor influences of physical and anthropogenic external factors (particularly confinement, riparian vegetation, woody debris, obstructions and anthropogenic impoundment) on the geomorphic structure and diversity of river systems at a range of scales, using the Turon River in Central West New South Wales as a case study.

The results of this study show that channel confinement has a significant impact on the magnitude and variability of channel characteristics, particularly in terms of the long-profile and channel cross-sectional form. In general, confined sections were found to be larger but less diverse than unconfined channels. In addition, the type of confinement was found to exert a strong influence on channel morphology and diversity, with valley, terrace and partially confined reaches containing cross-sections that were larger but less diverse and long-profiles with higher vertical variation than unconfined reaches.

Similarly, the presence and type of riparian vegetation was found to influence the morphology and diversity of long-profiles and, to a lesser extent, channel cross-sectional form. In this case, sections with only one bank of riparian vegetation cover were less asymmetric, less variable (i.e., less diverse) and contained long-profiles with higher vertical variation but lower angular variation than sections with both banks vegetated. In contrast, channels with limited riparian vegetation were smaller, less irregular, more diverse and contained long-profiles with smaller angular variation than channels with vegetated banks (i.e., grass, she-oak and/or blackberry cover). However, comparisons between channels with vegetated banks (i.e., channels with grassy cover and channels with she-oak/or blackberry cover) indicate reaches with grass cover are larger, more asymmetric, more diverse and contain long-profiles with smaller vertical variation and larger angular variation than reaches with she-oak and/or blackberry cover.

Woody debris, on the other hand, affects the diversity of cross-sections and bedforms within channels, more so than their size and structure. Sections within the Turon River study site containing woody debris were smaller, narrower and more diverse than sections devoid of woody debris. Additionally, when the type of woody debris present (i.e., in-channel or on-bank) was considered, in-channel woody debris reduced overall channel dimensions and increased channel diversity more than on-bank woody debris does.

Obstructions significantly impact upon channel morphology and diversity, affecting each of the channel components in some way. Sections containing obstructions were smaller, more diverse and contained longer, more asymmetric pool-riffle sequences than sections devoid of obstructions. These findings suggest that in-channel obstructions may be one of the key drivers of a channel's geomorphic diversity.

Finally, anthropogenic impoundment has a slight impact on the morphology and diversity of river systems. The causeway, located within the Turon River, was shown to impact on the dimensions and variability of cross-sections, bedforms and, to a lesser degree, long-profiles. Reaches most likely affected by the causeway (i.e., located within 50 m of it) were smaller, less diverse and had lower angular variation in their long-profiles than reaches further away. However, although reaches located upstream of the causeway were found to be larger and more diverse than reaches located downstream of the causeway, whether the impoundment is upstream or downstream of a particular location does not matter, from a channel size or diversity standpoint.

When these results are combined to give an overall view of the geomorphic diversity of the Turon River and the external factors that are accountable for it, they indicate that obstructions have the greatest influence on influence channel size and diversity. Obstructions were found to affect the dimensions and variability of the majority of cross-sectional and long-profile parameters studied and affected the magnitude of approximately half of the bedform and bar-unit dimensions. Other factors such as impoundments, confinement and riparian vegetation were also found to be important factors controlling the size, shape and diversity of the Turon River with their largest impact being on channel cross-sectional form and the long profile. Woody debris, on the other hand, was found to have little impact on channel character for any of the variables or scales investigated in this study with the exception of variability at the bedform scale.

Of the four classes of variables investigated (cross-section, long profile, bedform and bar unit), cross-sections were found to be the most affected by the external factors examined within this study. Therefore, cross-sections are the scale at which most channel change is likely to occur in response to the influences these factors place on the channel processes that shape channel morphology. This is true across nearly every factor and variable combination with only the variability of bedform structure being more highly controlled by other factors (namely woody debris and impoundments). Conversely, bar-units are the least affected scale, being only slightly influenced by woody debris and obstructions. Although obstructions resulted in approximately half of the bar-unit variables being significantly different in terms of their size and shape between obstructed and unobstructed channels, only two variables were found to have significantly different variabilities for the same comparison. Additionally, no significant differences were found for the dimensions of bar-units containing woody debris and those devoid of woody debris, while significant differences were found for the variabilities of only two out of the thirteen bar-unit parameters for this same comparison. Of the remaining two scales, the long profile was more sensitive to the factors studied here than were bedforms.

Another important finding of this study is that the variability of the channel parameters for each scale is influenced more than the size of the same parameters, which suggests that the combination of numerous external factors affects the structural diversity of channels more so than it does the morphology itself. The findings within this study also indicate that the influence of external factors on the magnitude and diversity of channel dimensions and morphology are reversed. In other words, large reaches have lower geomorphic diversity than smaller reaches. In both cases, this study represents the first time these relationships have been described in the literature.

As the first of its kind, this study has a number of qualities that improve the current state of knowledge on geomorphic diversity. Firstly, it improves on earlier studies that only examined one external factor and one scale by taking on a multi-scale, multi-factor approach. Secondly, the method is easy to apply to other fluvial systems. Thirdly, it provides insights into what factors or scales require further study. Next, it indicates that the influence of a combination of external factors results in a complex channel response that is evident at a range of scales (i.e., from cross-sections to bar-units). Finally, it has shown that geomorphically diverse systems can be the result of the complex interaction between external factors.

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Appendix 1 – Glossary of terms

Symbol/Abbreviation	Definition	Units
A	Downstream distance along the bed (i.e., distance between thalweg points)	m
A_2	Depth based cross-sectional asymmetry	dim
A_{h1}	Height based bedform asymmetry	dim
A_H	Height based pool-riffle sequence asymmetry	dim
A_L	Length based bedform asymmetry	dim
A_{L2}	Length based pool-riffle sequence asymmetry	dim
Avg.	Average	—
Bank.	Bank woody debris present	—
C	Hypothetical hypotenuse of the right-angled triangle containing angle θ	m
Conf.	Confinement present	—
CT	Chain-and-Tape (i.e., measure of the vertical variation in the thalweg)	dim
CV	Coefficient of variation	dim
D	Depth	m
$D_{avg.}$	Average depth	m
$D_{max.}$	Maximum depth	m
Down.	Downstream of causeway	—
H	Elevation difference between pool trough and riffle crest	m
H_p	Depth of the pool trough	m
H_r	Height of the riffle crest	m
In-Chan.	In-channel woody debris present	—
L	Length of the bedform or pool-riffle sequence	m
L_A	Distance downstream between points	m
L_p	Length of the pool	m
L_r	Length of the riffle	m
L_{r1}	Length of the pool or riffle entrance slope	m
L_{r2}	Length of the pool or riffle exit slope	m
L_S	Straight line distance between two consecutive points	m
L/W	Length-to-width ratio	dim
Max.	Maximum	dim
Min.	Minimum	dim
Mini.	Minimal vegetation present	—
N	Number of points in a transect	dim
Obs.	Obstructions present	—
Part. Val.	Partial valley confinement present	—
SO/BB	She-oak or blackberries present	—
Ter.	Terrace confinement present	—
Unconf.	Unconfined	—
Up.	Upstream of causeway	—
Val.	Valley confinement	—
VD	Vector Dispersion (i.e., measure of the angular variation in the thalweg)	dim
W	Width	m
W/D	Width-to-depth ratio	dim
χ	Distance between the point of maximum depth and the location of the channel centreline	m
Θ	angle of each thalweg point from the horizontal	°

'dim' indicates a dimensionless variable

Appendix 2 – Cross-sections

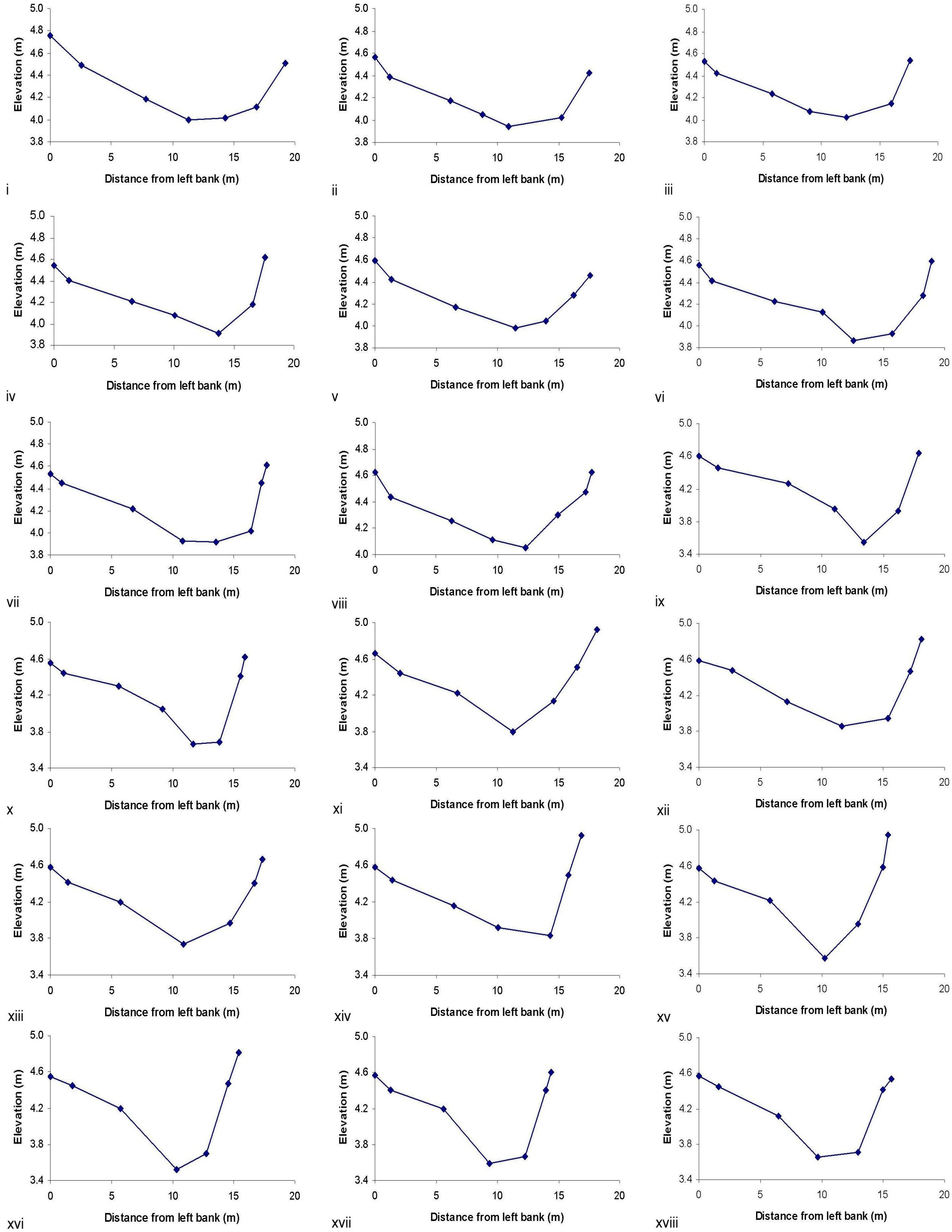


Figure 20: Visual representation of the 231 cross-sections surveyed within the study site. Roman numerals (i – ccxxxi) correspond to the cross-section number.

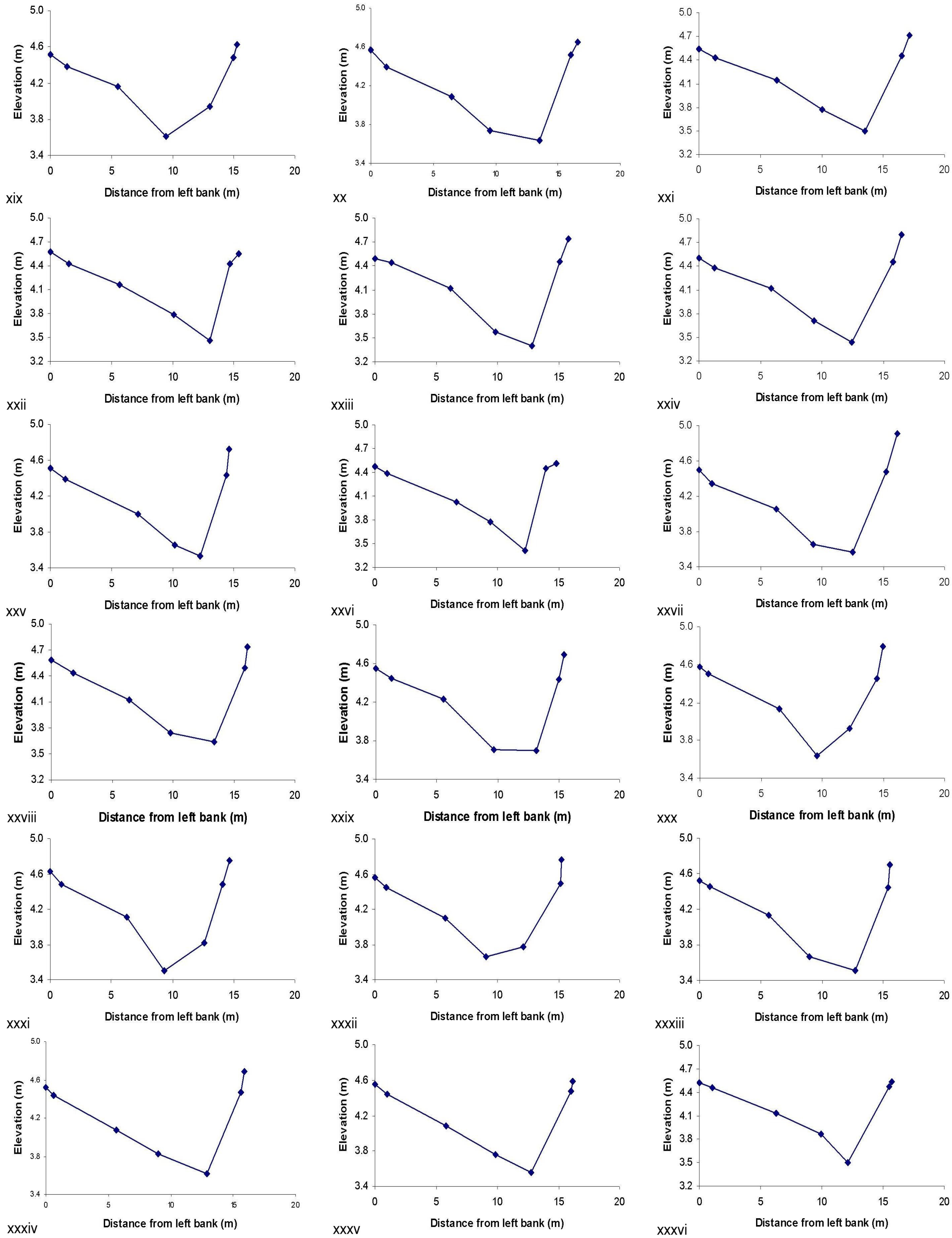
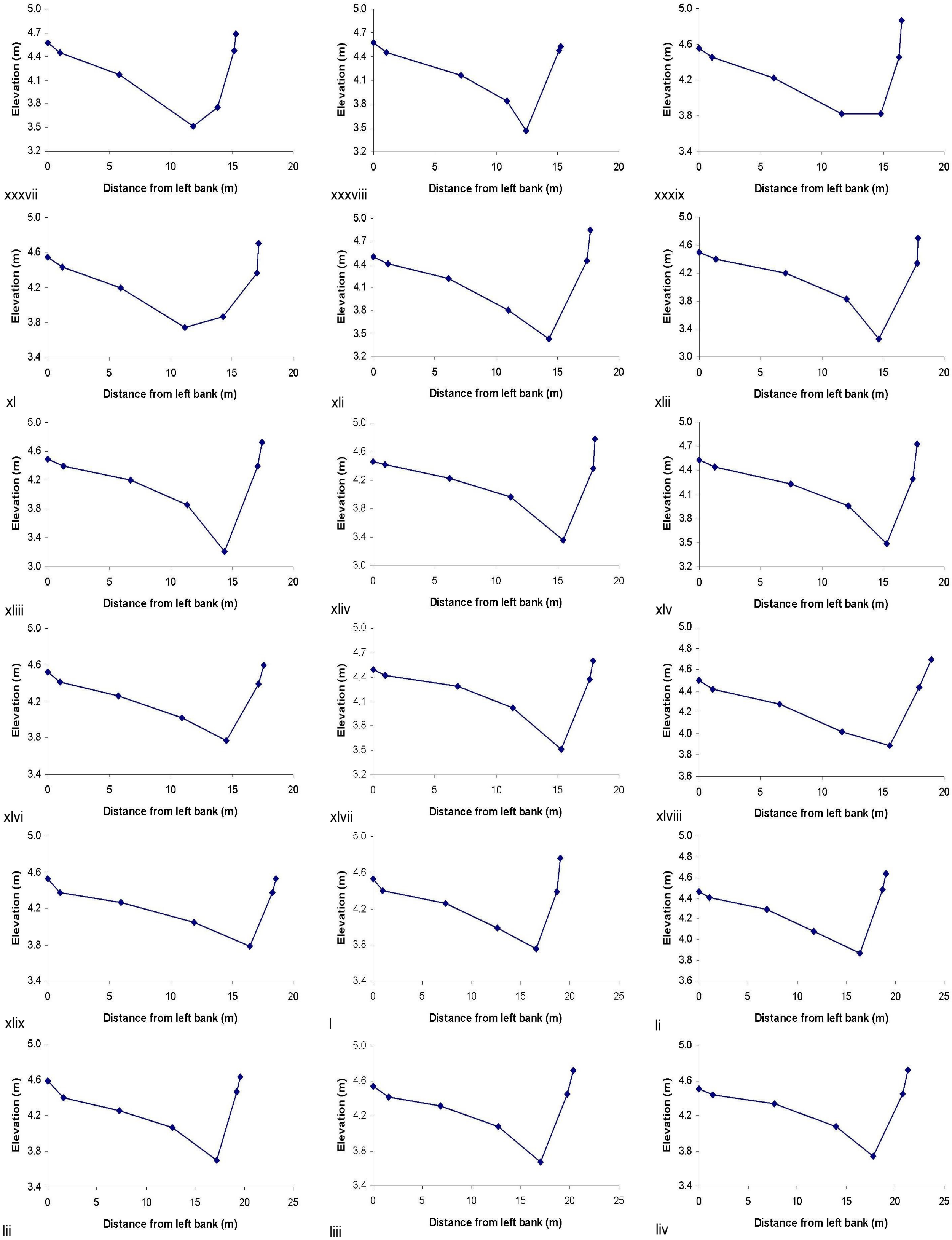


Figure 20 (cont): Visual representation of the 231 cross-sections surveyed within the study site. Roman numerals (i – ccxxxi) correspond to the cross-section number.



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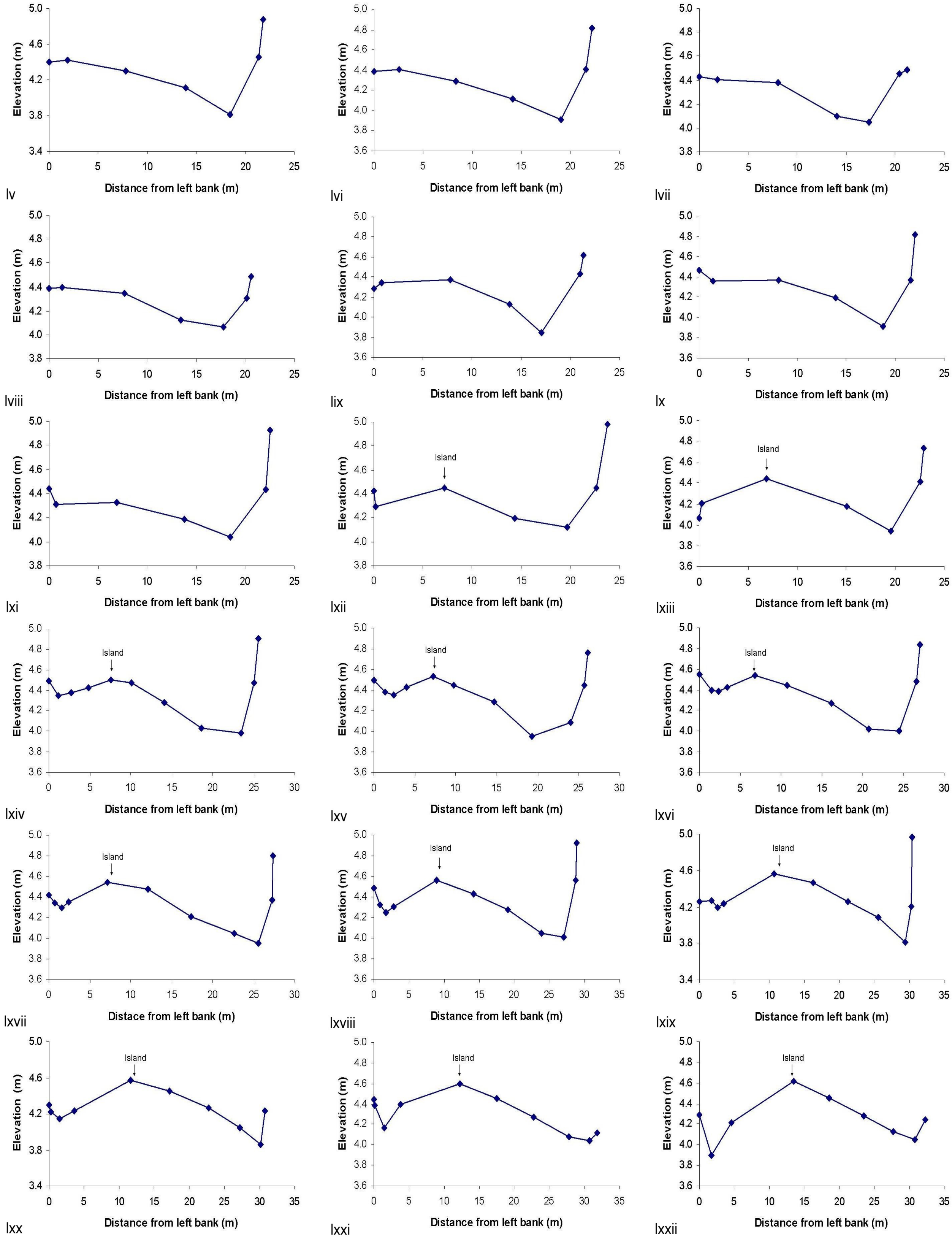


Figure 20 (cont): Visual representation of the 231 cross-sections surveyed within the study site. Roman numerals (i – ccxxxi) correspond to the cross-section number.

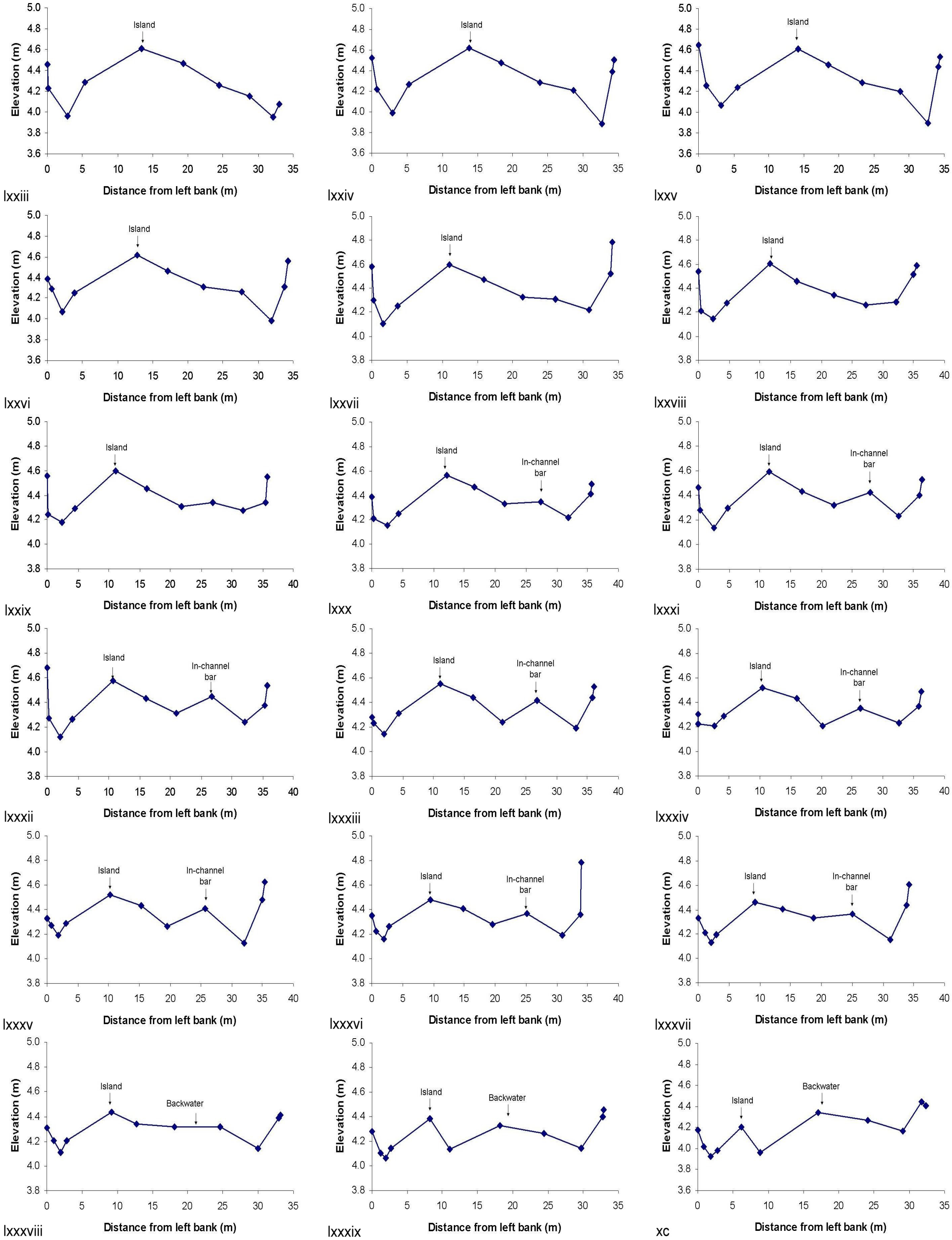
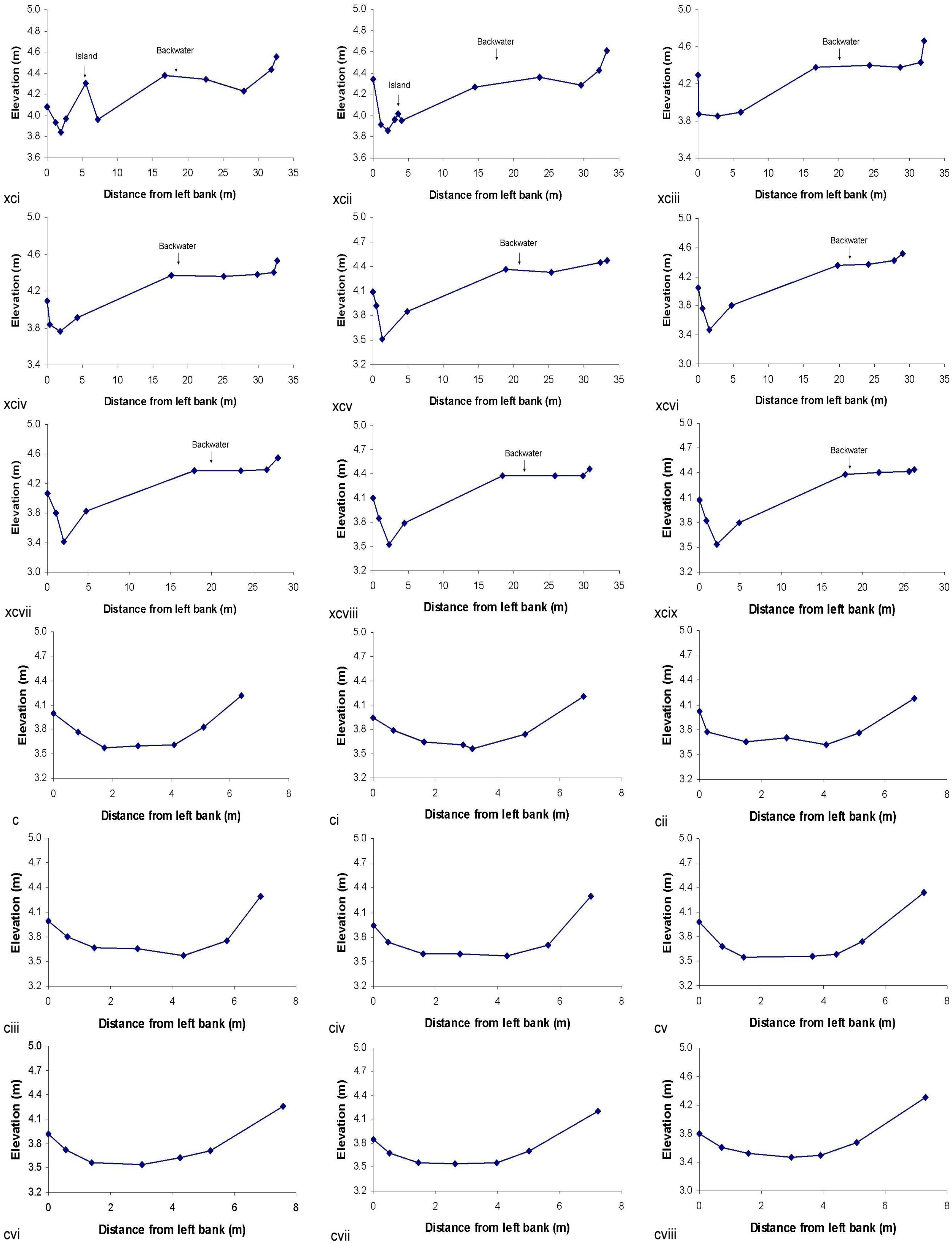


Figure 20 (cont): Visual representation of the 231 cross-sections surveyed within the study site. Roman numerals (i – ccxxxi) correspond to the cross-section number.



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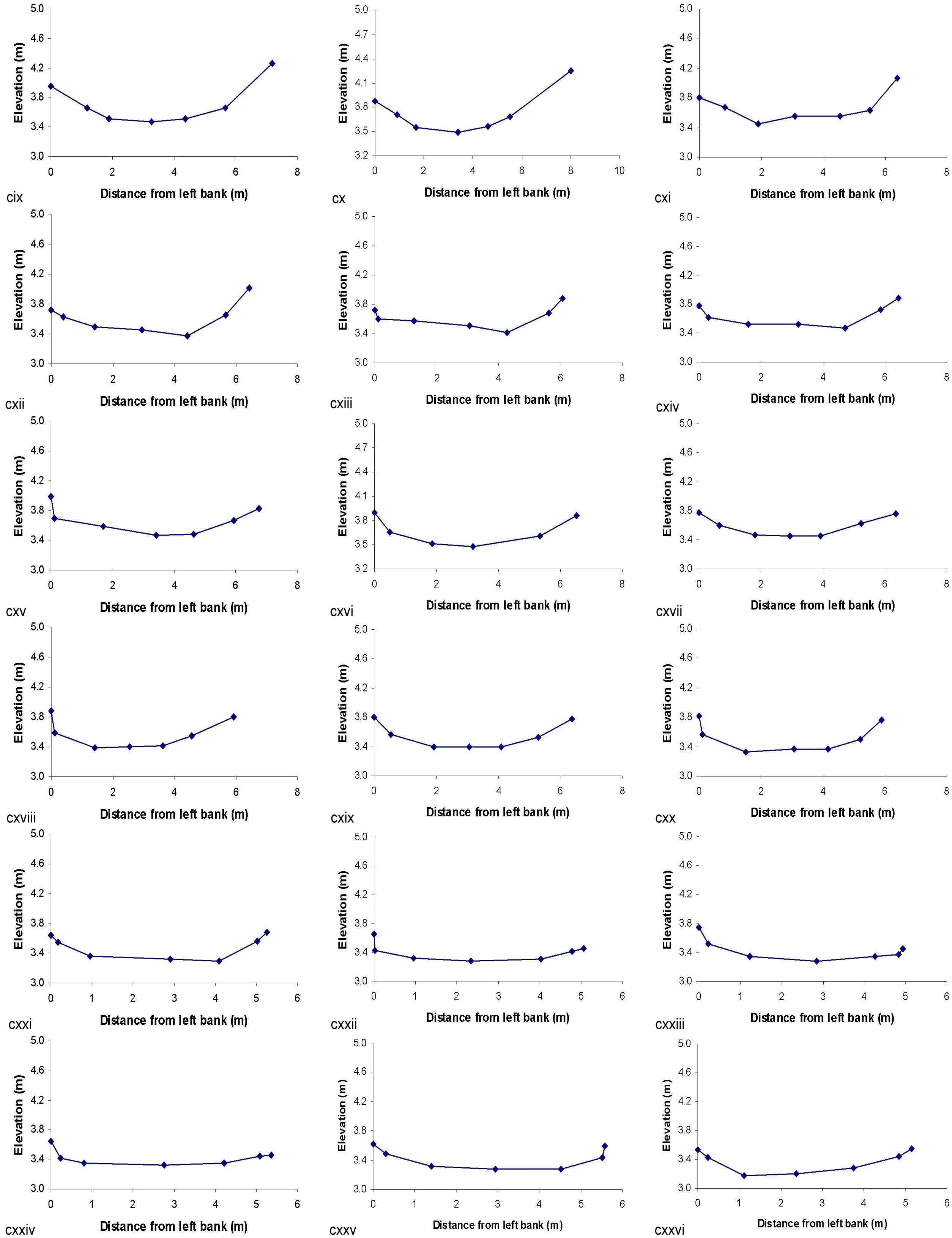

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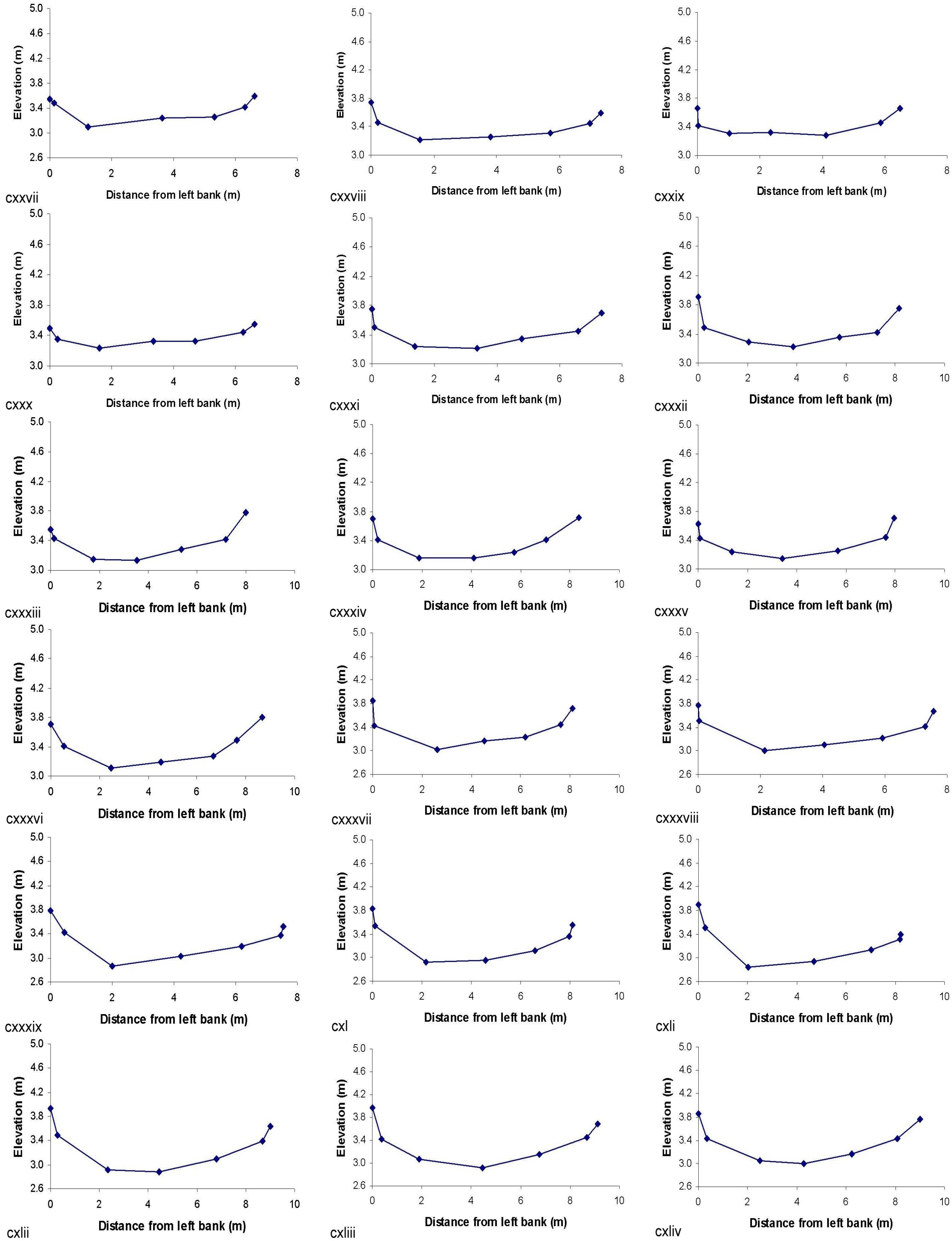

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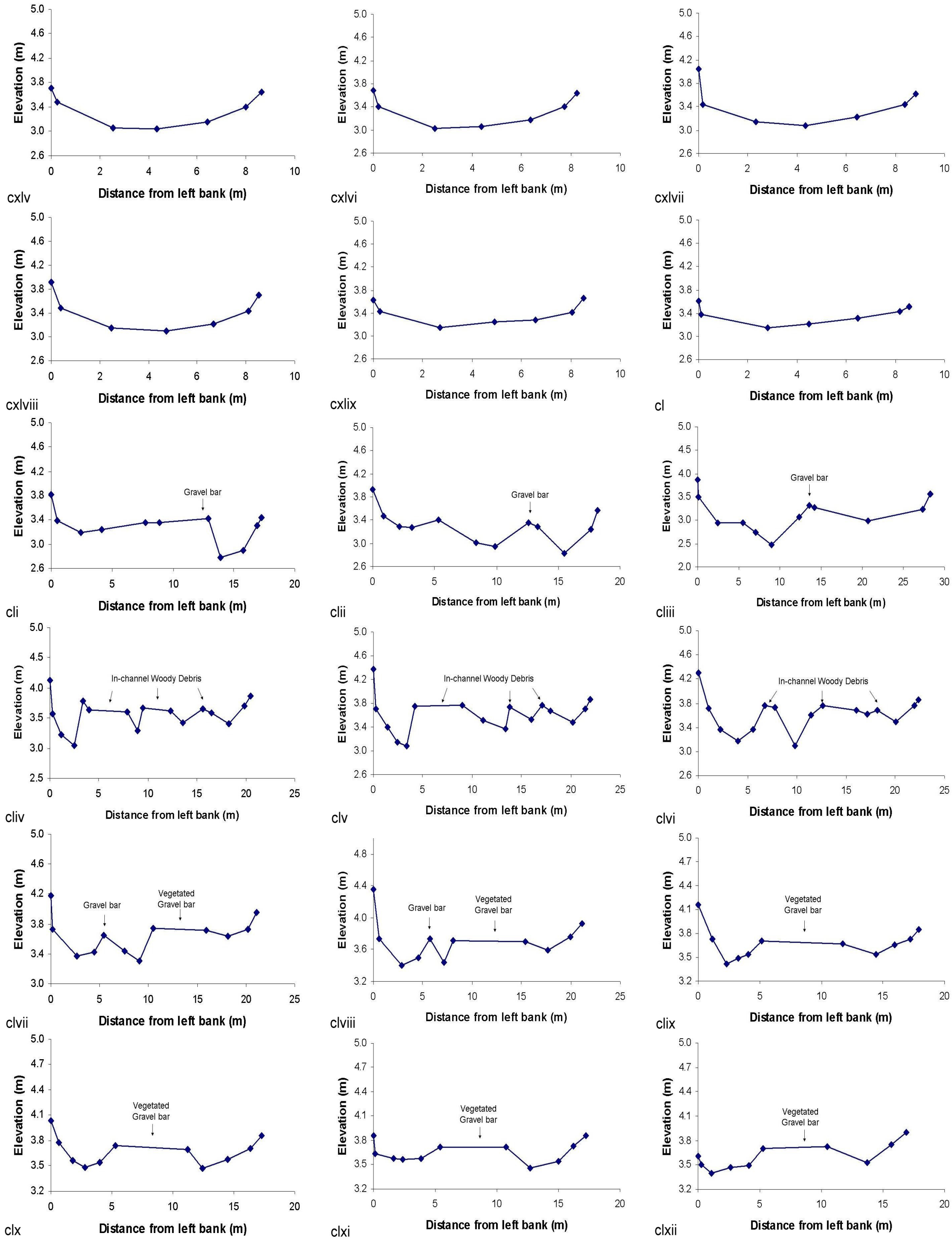
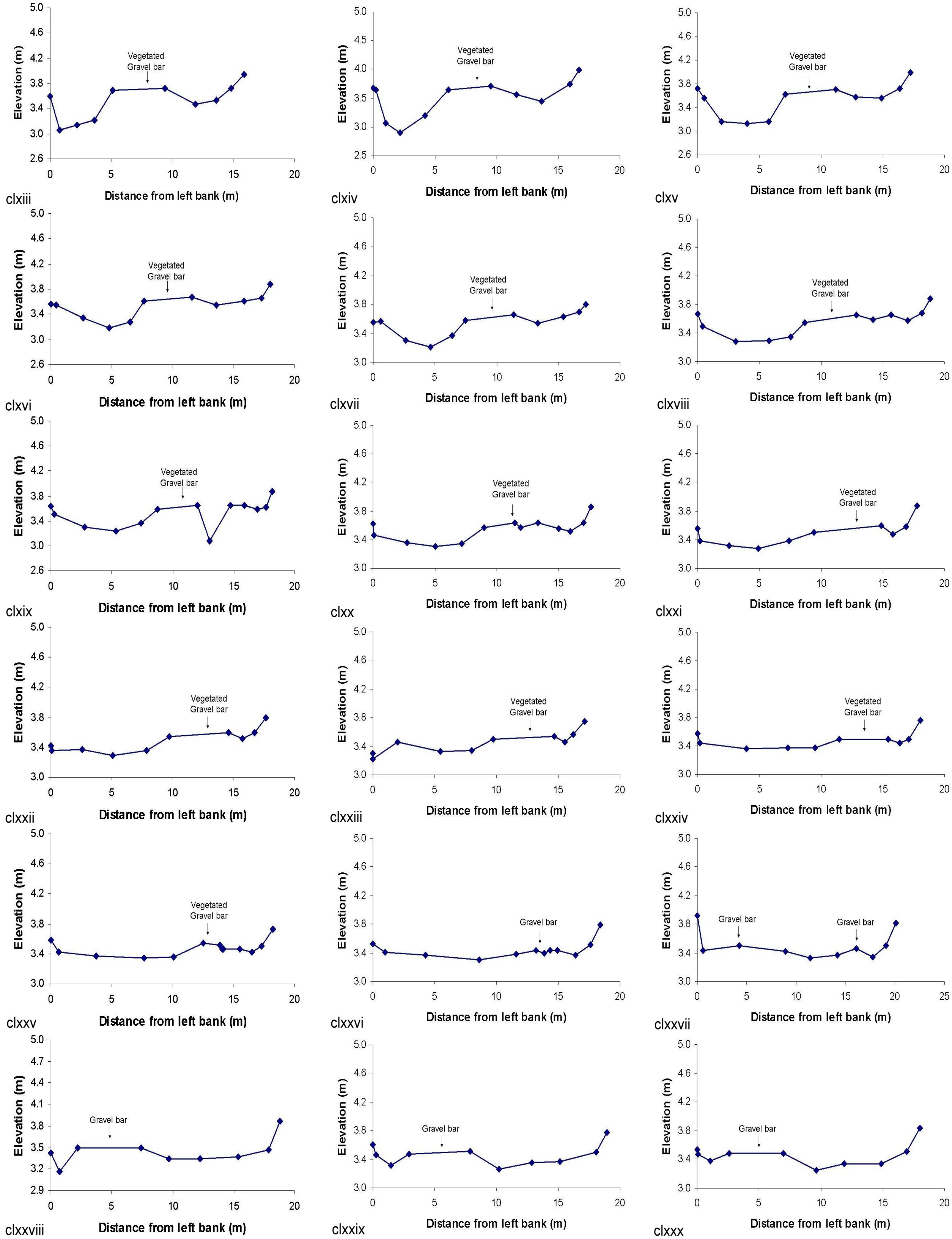


Figure 20 (cont): Visual representation of the 231 cross-sections surveyed within the study site. Roman numerals (i – ccxxxi) correspond to the cross-section number.



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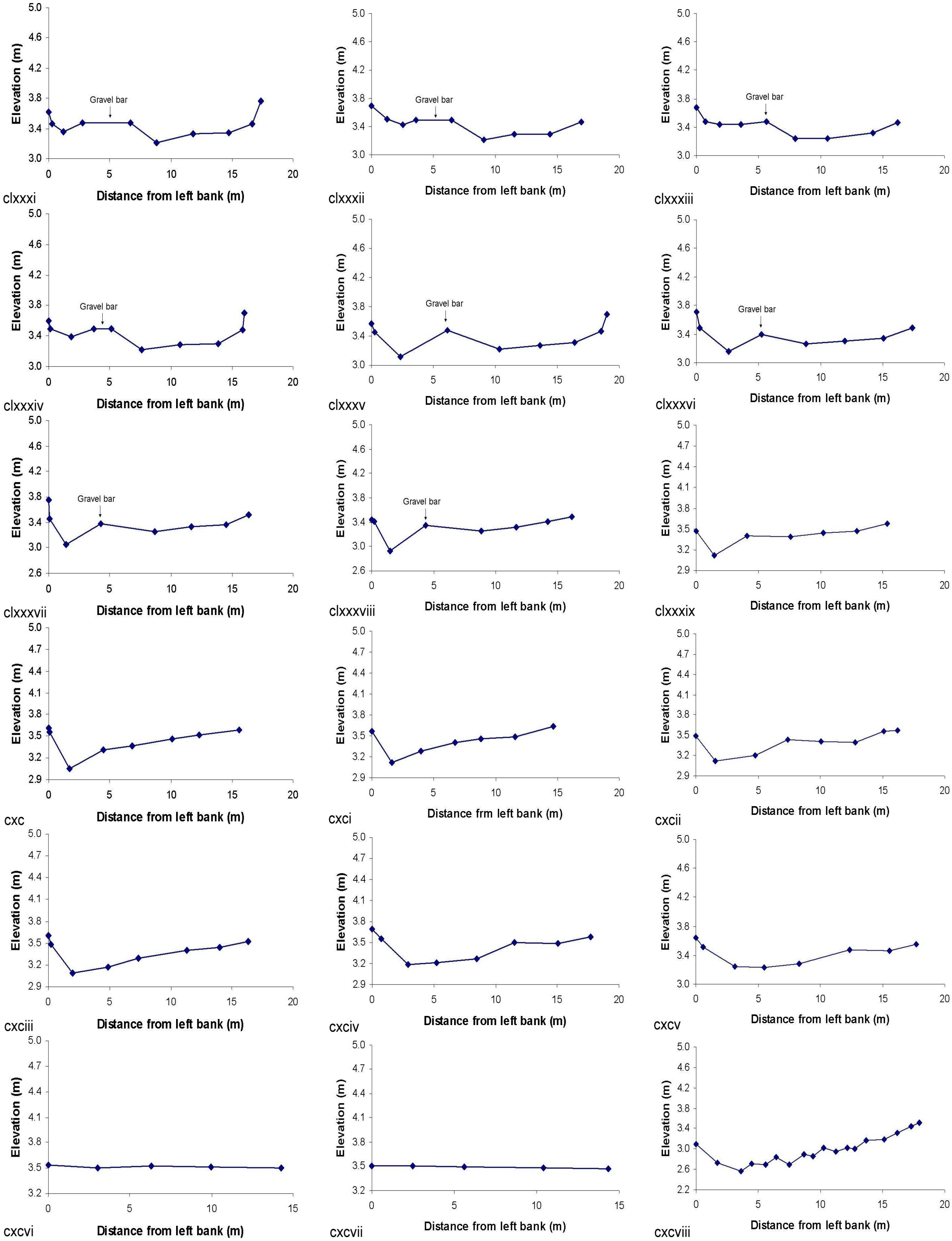

Figure 20 (cont): Visual representation of the 231 cross-sections surveyed within the study site. Roman numerals (i – ccxxxi) correspond to the cross-section number.

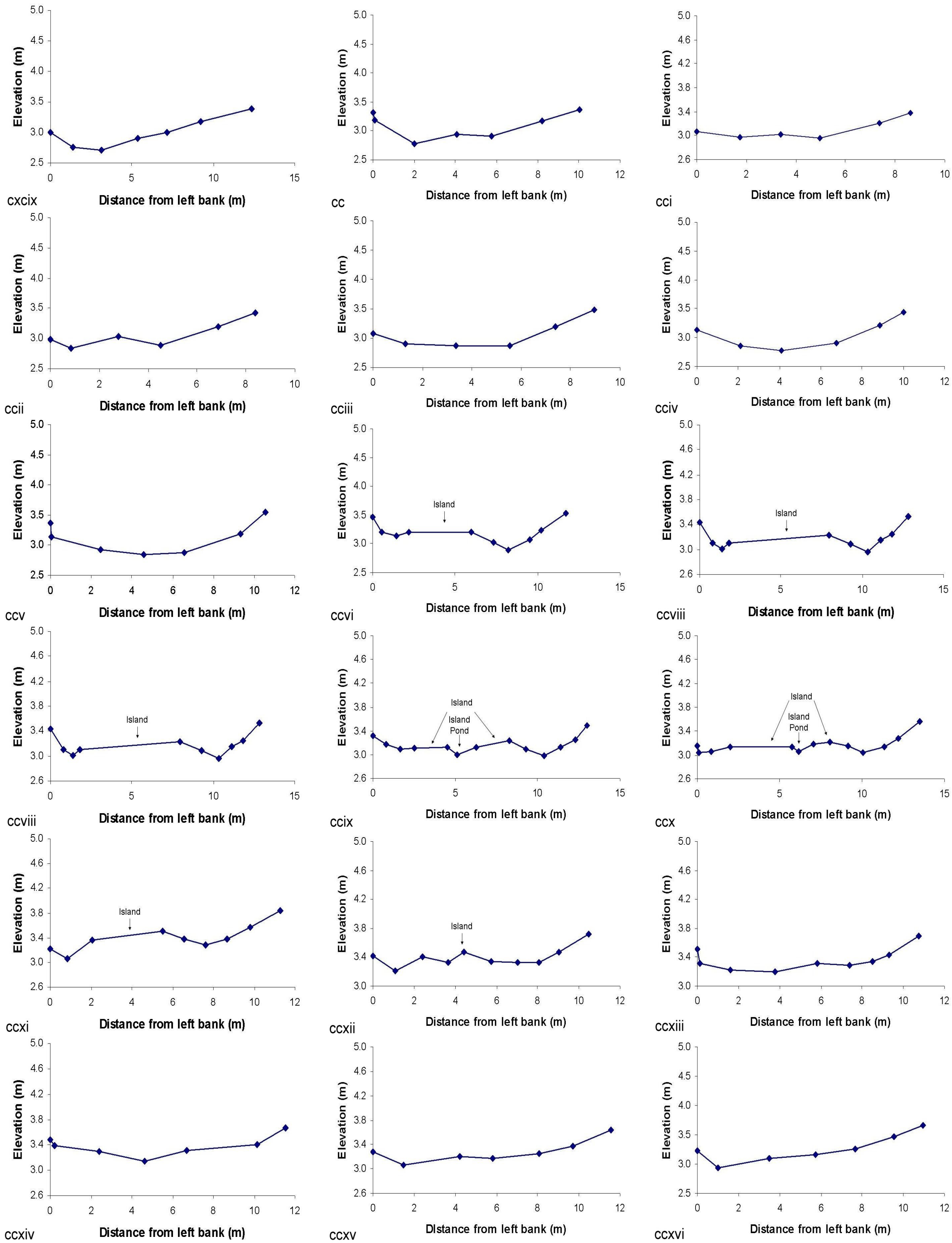

Figure 20 (cont): Visual representation of the 231 cross-sections surveyed within the study site. Roman numerals (i – ccxxxi) correspond to the cross-section number.

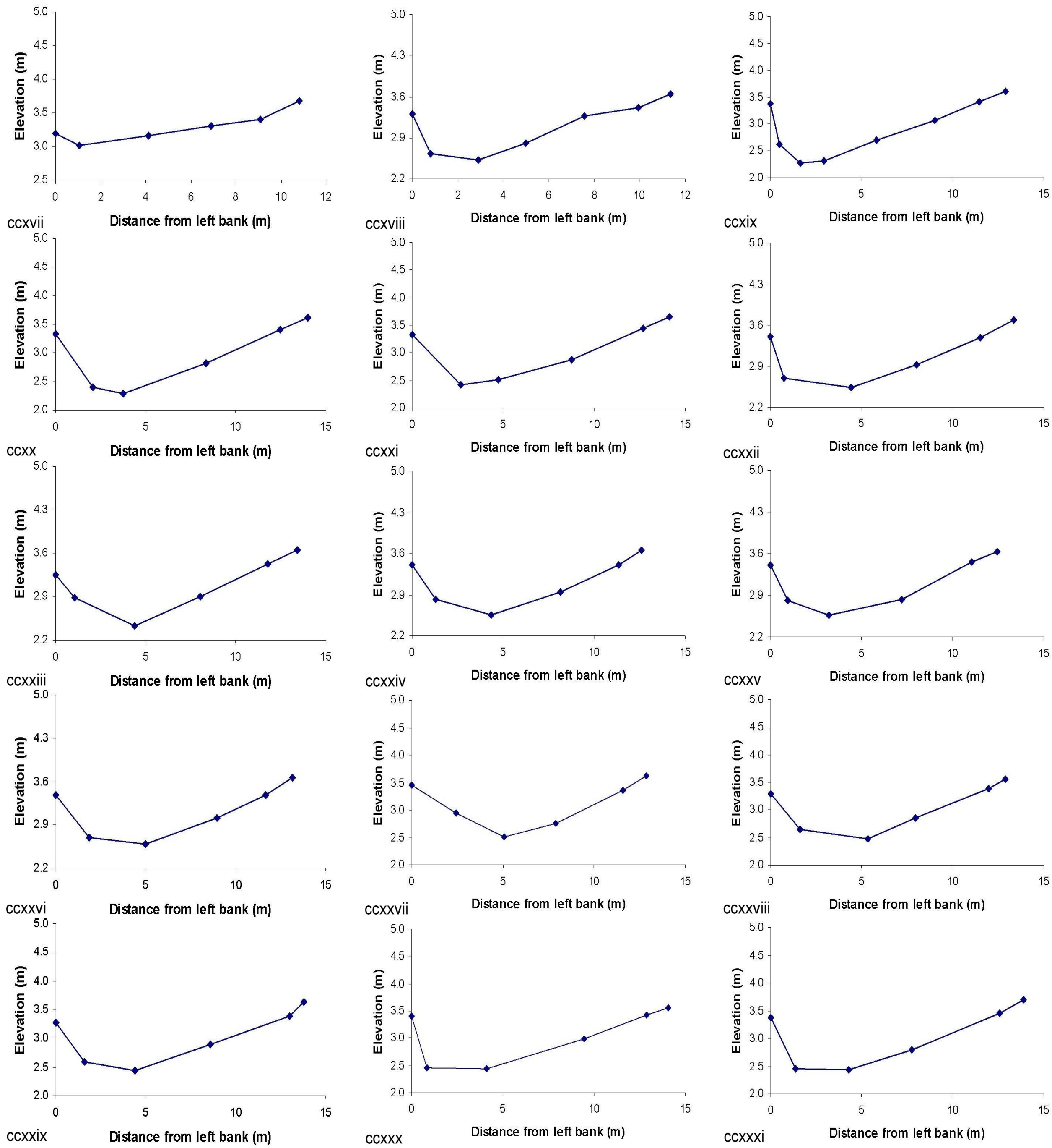

Figure 20 (cont): Visual representation of the 231 cross-sections surveyed within the study site. Roman numerals (i – ccxxxi) correspond to the cross-section number.

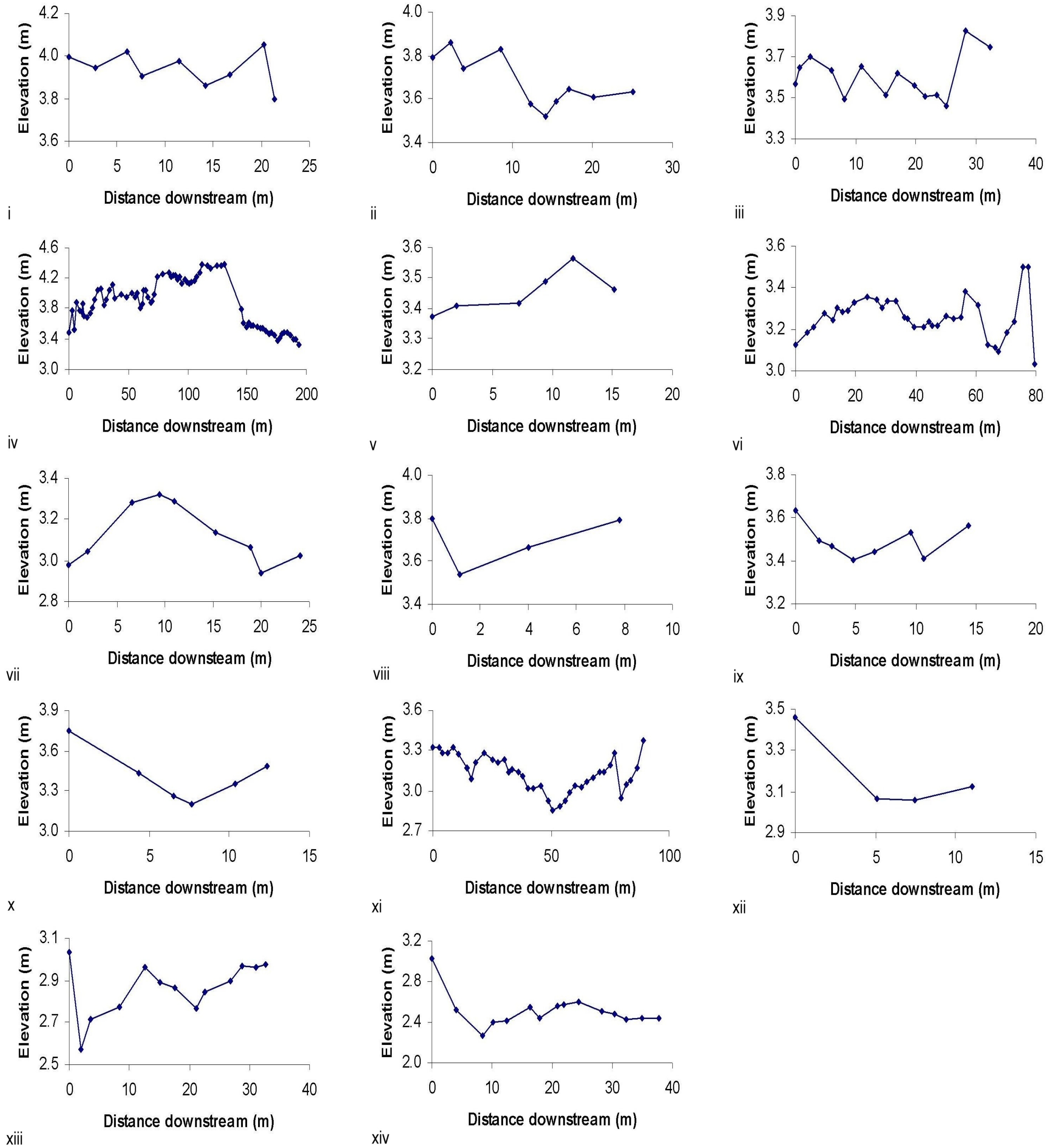

Figure 21: Visual representations of the pools (i – vii) and riffles (viii – xiv) found within the study site.

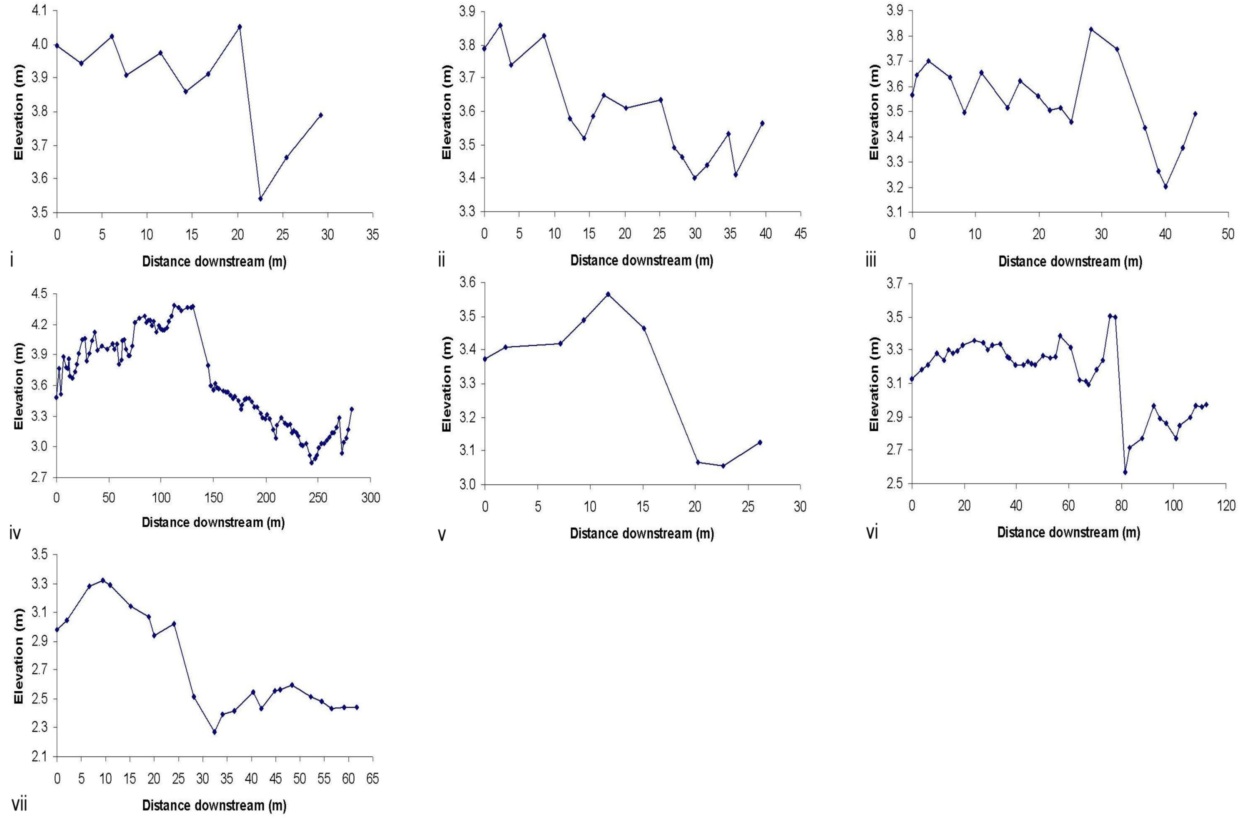

Figure 22: Visual representations of bar unit sequences (riffle-pool) found within the study site.