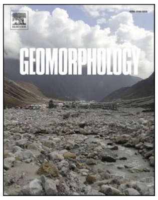
Geomorphology 490 (2025) 110012

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.journals.elsevier.com/geomorphology



Tectonic and climatic controls on the regionally anomalous geomorphic character and behaviour of the Upper Mōtū River, Aotearoa New Zealand

Jacqui McCord[a,*], Gary Brierley[a], Jon Tunnicliffe[a], Ian Fuller[b], Mike Marden[c], Colin Mazengarb[d]

[a] *School of Environment, University of Auckland, Private Bag 92019, Auckland, 1142, New Zealand*
[b] *School of Agriculture and Environment, Massey University, Private Bag 11222, Palmerston North, 4442, New Zealand*
[c] *Private Researcher, 48 Hillview Terrace, Mangapapa, Gisborne, 4010, New Zealand*
[d] *Private Researcher, 27 Golf Links Road, Geilston Bay, 7015, Tasmania, Australia*

ARTICLE INFO

Keywords:
Valley confinement
Terrace
Landscape pattern
Landscape evolution

ABSTRACT

Interpreting patterns of landforms is key to geomorphic understandings of landscapes. This study applies Stage One of the River Styles Framework to describe and explain contemporary river character, behaviour and patterns of river types in the Upper Mōtū Catchment on the East Coast of Aotearoa New Zealand. The Mōtū Catchment is regionally anomalous as it stores large volumes of sediment within a perched drainage basin at high elevations in the landscape. Landscape memory exerts a primary control upon contemporary process interactions in the Upper Mōtū Catchment. Geologic and climatic controls upon landscape configuration determine contemporary sediment sources and connectivity relationships, in turn influencing landscape responses to human disturbance and resulting patterns and rates of sediment flux. Tectonic uplift has shaped the relief and valley configuration while the lithological fabric created structural weakness that the river has exploited to form the current drainage pattern. Significant accommodation space has been created on valley floors in the upper catchment. Quaternary climate change instigated phases of valley floor aggradation and reworking that created a complex sequence of river terraces upstream of a knickpoint (Mōtū Falls) in the upper catchment. Terraces now act as confining margins for the laterally adjusting river. Contemporary headcut incision and channel expansion are the dominant contemporary sediment sources in this river system. In contrast to other river systems in the region where targeted revegetation of hillslopes is the key to process-based restoration programmes, bed control structures and a continuous riparian vegetation corridor are required to address sediment issues in the Upper Mōtū Catchment.

1. Introduction

Rivers are finely attuned to consume their own energy as they make use of the space that is available to them to transport sediments and adjust their form along erodible corridors (e.g., Eaton and Millar, 2017; Nanson and Huang, 2017; Piégay et al., 2005). Hence, accommodation space and valley width are key determinants of river character and behaviour (i.e., River Styles; Brierley and Fryirs, 2005; Fryirs et al., 2016). Anthropogenic activities that deny a river the space to which it has become accustomed create strangled rivers that concentrate flow energy and diminish habitat availability, often with profound off-site impacts and legacy effects (Brierley et al., 2023). In response, space to move and freedom space interventions now endeavour to regenerate river systems (Biron et al., 2014; Buffin-Bélanger et al., 2015; Ciotti et al., 2021; Nelson et al., 2024). In turn, catchment-scale patterns of accommodation space along river courses are key to Natural Flood Management programmes (e.g., Lane, 2017). Hence, understanding reach-, catchment- and region-wide patterns of accommodation space, and connectivity relationships, are key to process-based river management practices that work with the river (Brierley and Fryirs, 2022).

Geologic, climatic and anthropogenic factors that determine the character, behaviour and evolution of river systems play out in a catchment-specific manner (Brierley et al., 2013). Geologic controls refer primarily to the influence of tectonic setting and lithology on topography and relief (uplift, landscape dissection, drainage density) and the erodibility of the landscape (e.g., Burbank and Pinter, 1999).

---

* Corresponding author.
E-mail addresses: Jacqui.mccord@auckland.ac.nz (J. McCord), g.brierley@auckland.ac.nz (G. Brierley), j.tunnicliffe@auckland.ac.nz (J. Tunnicliffe), I.C.Fuller@massey.ac.nz (I. Fuller), Mardenm@landcareresearch.co.nz (M. Marden), gis4geotechs@outlook.com (C. Mazengarb).

https://doi.org/10.1016/j.geomorph.2025.110012
Received 10 March 2025; Received in revised form 8 September 2025; Accepted 9 September 2025

This, in turn, fashions patterns of valley confinement and the accommodation space that supports storage of alluvial sediments, recognising that river capture may create underfit or overfit streams in some instances (e.g., Buckley et al., 2024; Craw et al., 2016; Dury, 1964; Duvall et al., 2020). Climatic influences upon discharge and vegetation cover set the regime conditions under which each river operates. Changes to flow and sediment regimes, and adjustments to base level conditions, alter the aggradational-degradational regime of a river, creating terraces and reworking deposits stored on the valley floor (e.g., Crosby and Whipple, 2006; Leopold and Bull, 1979). These considerations, in turn, influence forms and impacts of human land use and disturbance to landscapes, and the consequences that ensue (e.g., Downs and Piégay, 2019; Gregory, 2006).

East Coast catchments on the North Island of Aotearoa New Zealand have some of the highest rates of sediment generation and flux per unit area in the world (Hicks et al., 2011). Fuller et al. (2023) show how variability in dominant sediment sources underpins marked differences in the contemporary geomorphic behaviour of adjacent river systems in this region. In large part this reflects lithological controls upon the prominence of different forms of hillslope sediment input (localized gully-mass movement complexes and systematic shallow landslides). However, in stark contrast to adjacent catchments (the Waiapu, Hikuwai/Uawa, Waimatā and Waipaoa river systems), active reworking of valley floor deposits is the dominant contemporary sediment source in the Mōtū Catchment (Fig. 1; Fuller et al., 2023; Vale et al., 2021). Here we present an account of the geologic and climatic history of the Mōtū River to explain how significant sediment stores have accumulated in the low-gradient, wide valley (high accommodation space) headwater setting of the Upper Mōtū Catchment, thereby explaining this regionally anomalous situation.

Specific aims of this paper are to:

1) Show how geologic controls determine patterns of accommodation space in the Mōtū Catchment.
2) Outline climatic controls on terrace formation within the wide valley settings of the upper catchment.
3) Apply Stage 1 of the River Styles framework (Brierley and Fryirs, 2005) to relate contemporary character river and behaviour to patterns of accommodation space (valley width and slope).
4) Demonstrate implications for river management applications.

2. Regional setting

The Mōtū River is 178 km long and drains a catchment area of 1373

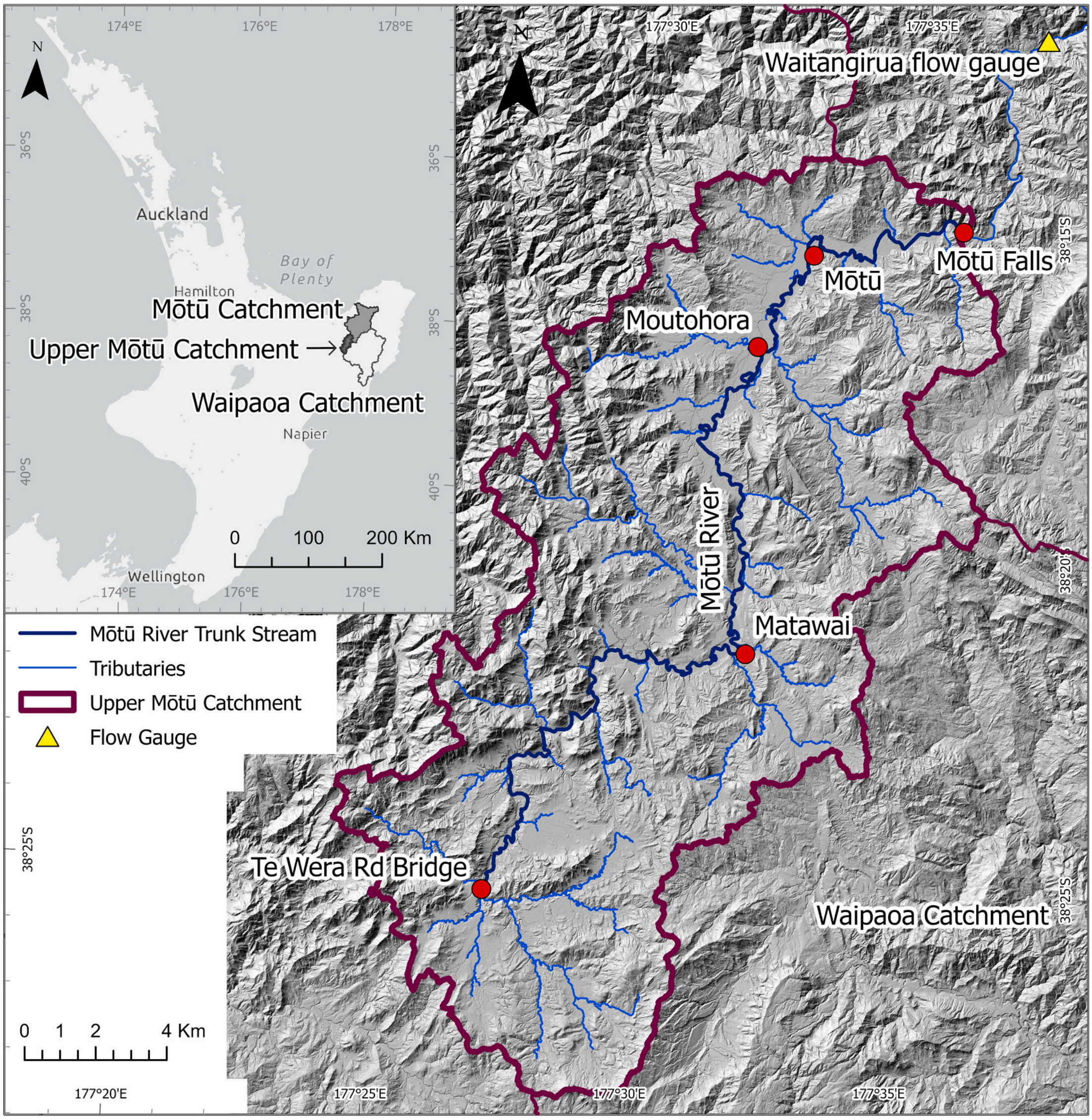


Fig. 1. The Upper Mōtū Catchment with key locations annotated. Inset map situates the Mōtū and Upper Mōtū Catchment, North Island, Aotearoa New Zealand.

km^2. It begins in the Raukūmara Ranges and flows northeast to the Bay of Plenty (Fig. 1). The Mōtū Falls, at an elevation of 462 m, divides the sediment stores in wide valley settings of the Upper Mōtū Catchment (246 km^2) from the lower catchment where the river flows through a confined gorge to the Pacific Ocean. The channel long profile is stepped, with the lowest stream gradient in the upper catchment immediately upstream of Mōtū Falls (Fig. 2).

The East Coast region has a temperate climate. Average annual rainfall at Mōtū township (1981 to 2010; Chappell, 2016) is 2158 mm/yr. Higher rainfall occurs in upper parts of the Raukūmara Range (Fig. 1). The maximum daily recorded rainfall (194 mm) occurred in March 1988 associated with ex-tropical Cyclone Bola. Peak discharge of 603 m^{3}s^{-1} at Waitangirua flow gauge occurred during this event (Fig. 1). Based on data since 1960, the 2.3 year return flood event is 260 m^{3}s^{-1}.

2.1. *Tectonic setting and lithology*

The axial Raukūmara Range lies at the frontal arc of the Hikurangi Subduction margin where the Indo-Australia plate is being subducted below the Pacific Plate. Uplift of the ranges began during the Miocene to Pliocene (Jiao et al., 2015; Nicol et al., 2007). Late Quaternary uplift rates are estimated at up to 4 mm/yr under the central ranges, reducing to the northeast and southwest (Litchfield and Berryman, 2006). The Upper Mōtū Catchment lies to the east of the axial range and flows north-eastward into a high standing gorge. The subdued and mature topography indicates that uplift has created a perched drainage basin. The sandstones at Mōtū Falls act as a barrier between this perched landscape and the deeply incised river system downstream. Uplift of the range likely initiated incision in the neighbouring Waipaoa Catchment to the southeast. It is hypothesized that the catchment divide has progressively moved north-westward, pirating parts of the Mōtū (Fig. 1).

The geology of the Upper Mōtū River (Fig. 3) has been documented by Isaac (1977) and summarised by Mazengarb and Speden (2000). The Late Jurassic to Early Cretaceous basement Pahau terrane that forms the rugged Raukūmara Ranges is the oldest lithologic unit in the Matawai District. Steeply dipping, tightly folded, indurated sandstones and mudstones are an extension of the North Island ‘axial ranges’ to the south. The Pahau terrane sediments are overlain unconformably by the Cretaceous Matawai Group (Mazengarb and Harris, 1994). West of the Moutohora Fault, in stratigraphical order, the oldest member of the Matawai Group, the Koranga Formation, comprises a gently dipping resistant conglomerate and sandstone. Remnants of the Koranga formation cap the Pahau terrane and form resistant ridges and bluffs in a belt several kilometres wide. The Te Wera Formation unconformably overlies Koranga Formation and locally rests directly on Pahau terrane. It is comprised predominantly of sandstone with minor conglomerate beds that form strike ridges locally. Te Wera Formation grades up into the Karekare Formation, a unit that forms the bulk of the Matawai Group (in terms of stratigraphic thickness). Karekare Formation is mainly comprised of mudstone with thinly bedded sandstone/mudstone packets. Karakare mudstones are friable and more easily eroded than underlying units. They tend to form more subdued landscapes, while the alternating sandstone/mudstone packets are more resistant to erosion. The Mōtū Falls have formed over a more resistant sandstone-dominated unit of the Karekare Formation with minor conglomerate. The Karekare Formation is widespread to the east of the Moutohora Fault. The Matawai Group is in turn overlain by the Tinui Group of Late Cretaceous to Paleocene Age that comprises the mudstone-dominated Whangai Formation.

Near-vertical faults with downthrow to the east trend approximately north-south, dissecting the Jurassic to Cretaceous strata, the most prominent being Moutohora and Kotare Faults. Although there is no evidence of recent displacement along these faults, displacement has occurred on adjacent faults to the northwest (Mazengarb and Speden, 2000). Multiple deformation events have folded and tilted the underlying strata (Mazengarb and Harris, 1994). The Matawai and Tinui Groups have been folded into anticlinal and synclinal structures with a north to south trend north of Matawai, and a northeast to southwest trend to the west of Te Wera Road Bridge (Fig. 1). This complex geologic history exerts a key control upon valley settings and contemporary river character and behaviour in the region. While the estimated annual sediment yield for the Waiapu catchment is 35 Mtyr^{-1}, the Motu catchment has an estimated annual sediment yield of 3.5 Mtyr^{-1} (Hicks et al., 2011).

2.2. *Quaternary history*

Climate-induced phases of sediment accumulation on valley floors, and subsequent incision, have created flights of river terraces across much of the North Island of New Zealand (Clement and Fuller, 2007; Litchfield and Berryman, 2005, 2006). Cool climatic shifts caused tree line retreat, enhanced erosion in headwater tributaries, and sediment build up on valley floors (Berryman et al., 2000; Suggate, 1990). Re-

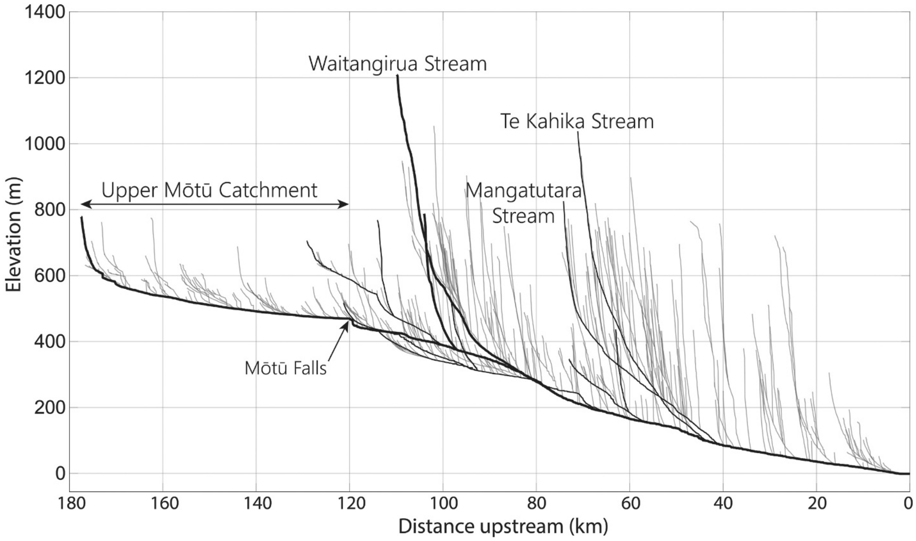


Fig. 2. Longitudinal profile of the Mōtū River and tributaries derived from a 1 m LiDAR DEM. Image drafted using procedures outlined by Schwanghart and Scherler (2014).

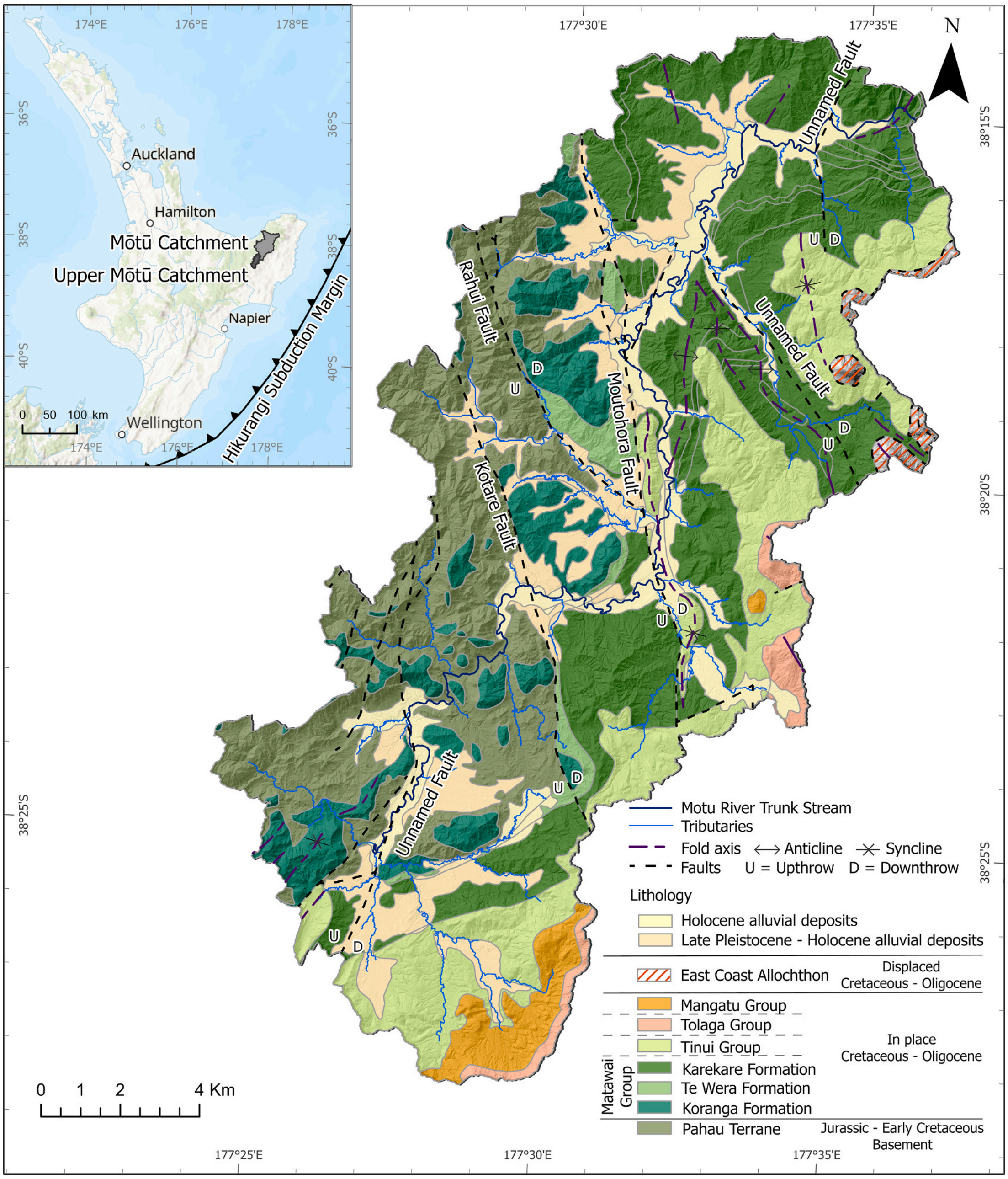


Fig. 3. Overview of the lithology and structural features of the Upper Mōtū River (Mazengarb and Speden, 2000). From oldest to youngest, the main lithological units that make up the Mōtū Catchment are: the Pahau terrane (indurated sandstones and mudstones), and the Matawai Group consisting of the Koranga Formation (conglomerate and sandstone), Te Wera Formation (sandstone and minor conglomerate) and Karekare Formation (mudstone and thinly bedded sandstone/sandstone packets).

establishment of woody vegetation during interglacial periods reduced sediment generation (Marden et al., 2021; McGlone et al., 1984), while enhanced rainfall increased stream power and sediment transport potential, triggering downcutting through valley fill deposits (Berryman et al., 2000; Grant, 1985). In the East Coast region, four terraces represent cool climatic periods through the Pleistocene (Berryman et al., 2000; Litchfield and Berryman, 2005). Pronounced warming following the Last Glacial Maximum triggered incision which became the dominant process during the Holocene (Marden et al., 2008, 2014). Alongside this, commencement of volcanic activity in the Taupō Volcanic Zone around 2 Ma ago introduced large volumes of sediment to North Island catchments (Wilson et al., 1995). This likely induced an aggradation response followed by a phase of reworking along many rivers (Clement and Fuller, 2007; Marden et al., 2014).

2.3. *Settlement history and land use*

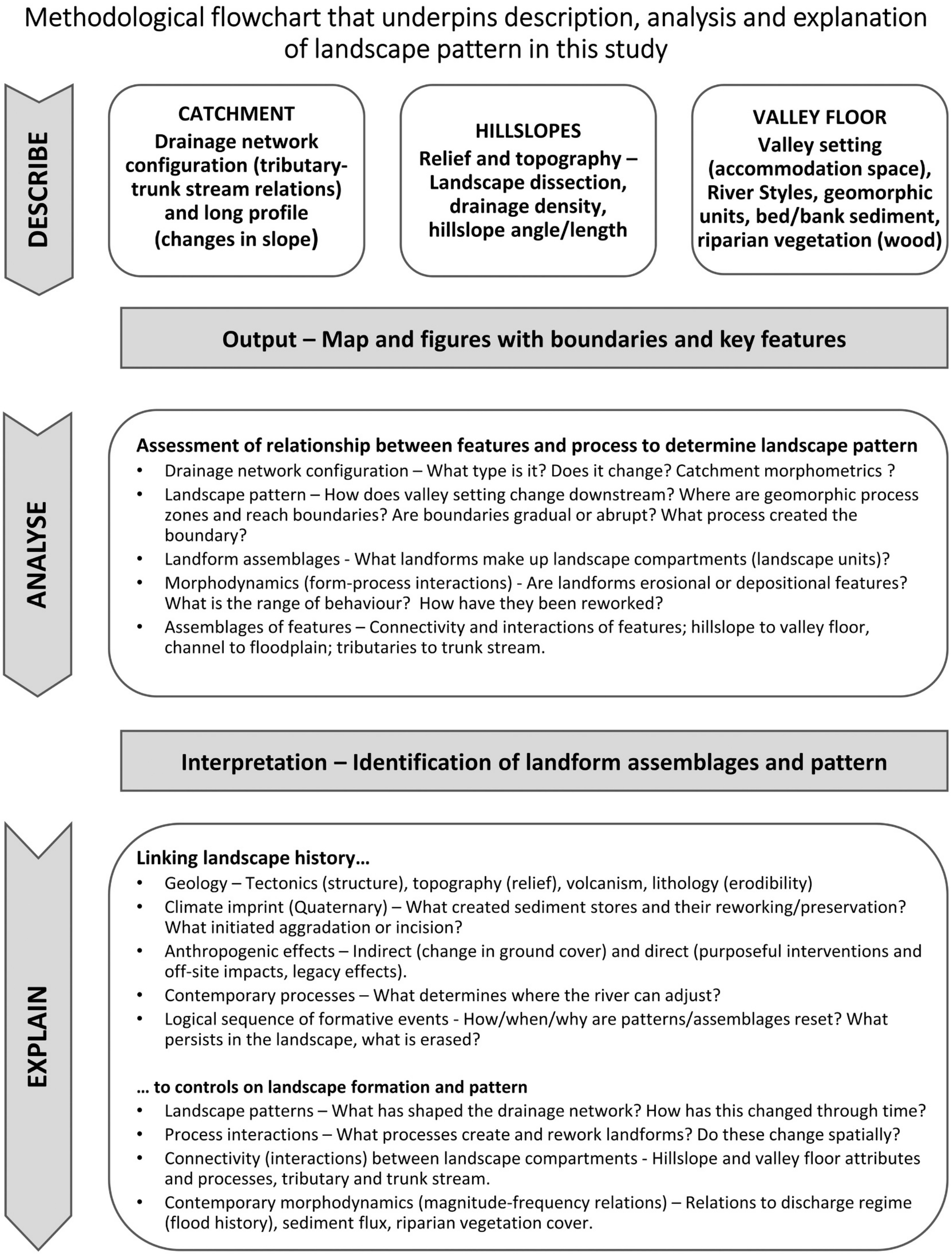
Prior to European settlement, mature forest of rimu, matai, kahikatea, and tawa covered the Upper Mōtū Catchment, but the bush was progressively cleared and the land converted to pasture following the founding of Mōtū township in 1887 (Twisleton, 2007). Today, the upper catchment comprises 65 % pasture and 29 % hardwood forest. Sediment fingerprint analysis revealed that channel banks contribute 95 % of in-channel sediment and 96 % of flood sediment in the Upper Mōtū Catchment, with negligible evidence for contemporary sediment flux from hillslope failures and mass movement (Vale et al., 2021).

3. Methods

Stephen Trudgill (2003, p. 32) noted that “Much of geomorphic enquiry entails the search for mechanism, pattern and logic.” However, as Peter Haggett (1965, p. 2) commented, “… pattern and order exist in knowing what to look for, and how to look.” Observation is a key skill in geomorphic fieldwork (Church, 2013; Rhoads and Thorn, 1996), using abductive reasoning to ‘read the landscape’ and unravel controls upon landscape forms, processes and evolutionary traits (Brierley et al., 2021; Fryirs and Brierley, 2013), here we relate field-based investigations to analyses of remotely sensed information to interpret landscape patterns in the Mōtū Catchment.

Fig. 4 summarises the approach to analysis of landscape pattern used in this study. Step 1 describes landforms and landscape features at the catchment scale, differentiating features on hillslopes and the valley floor. Step 2 analyses relationships between features to identify patterns. Step 3 relates contemporary patterns to their historical context (i.e., geological, climatic and anthropogenic controls).

Remote sensing analysis undertaken using a 1 m resolution DEM (2020) was used to derive the drainage network configuration, long profile and topography. Identification, mapping and interpretation of landscape features and patterns was analysed based on the shape/geometry of these features, their position and elevation in the landscape, the definition/shape of landform boundaries, and their juxtaposition to



CATCHMENT
Drainage network configuration (tributary-trunk stream relations) and long profile (changes in slope)

HILLSLOPES
Relief and topography – Landscape dissection, drainage density, hillslope angle/length

VALLEY FLOOR
Valley setting (accommodation space), River Styles, geomorphic units, bed/bank sediment, riparian vegetation (wood)

Output – Map and figures with boundaries and key features

Assessment of relationship between features and process to determine landscape pattern

- Drainage network configuration – What type is it? Does it change? Catchment morphometrics ?
- Landscape pattern – How does valley setting change downstream? Where are geomorphic process zones and reach boundaries? Are boundaries gradual or abrupt? What process created the boundary?
- Landform assemblages - What landforms make up landscape compartments (landscape units)?
- Morphodynamics (form-process interactions) - Are landforms erosional or depositional features? What is the range of behaviour? How have they been reworked?
- Assemblages of features – Connectivity and interactions of features; hillslope to valley floor, channel to floodplain; tributaries to trunk stream.

Interpretation – Identification of landform assemblages and pattern

Linking landscape history…

- Geology – Tectonics (structure), topography (relief), volcanism, lithology (erodibility)
- Climate imprint (Quaternary) – What created sediment stores and their reworking/preservation? What initiated aggradation or incision?
- Anthropogenic effects – Indirect (change in ground cover) and direct (purposeful interventions and off-site impacts, legacy effects).
- Contemporary processes – What determines where the river can adjust?
- Logical sequence of formative events - How/when/why are patterns/assemblages reset? What persists in the landscape, what is erased?

… to controls on landscape formation and pattern

- Landscape patterns – What has shaped the drainage network? How has this changed through time?
- Process interactions – What processes create and rework landforms? Do these change spatially?
- Connectivity (interactions) between landscape compartments - Hillslope and valley floor attributes and processes, tributary and trunk stream.
- Contemporary morphodynamics (magnitude-frequency relations) – Relations to discharge regime (flood history), sediment flux, riparian vegetation cover.

Fig. 4. Approach to landscape analysis used in this study.

other landscape features (Wheaton et al., 2015). Field verification supported this analysis. Reach boundaries were defined in relation to patterns of valley confinement and assemblages of channel and floodplain geomorphic units along the valley floor (Brierley and Fryirs, 2005; Fryirs and Brierley, 2018), following procedures developed in the River Styles Framework (Brierley and Fryirs, 2005). This work was restricted to streams of 3rd order and above (after Wheeler et al., 2022). Alongside analyses of landscape dissection and drainage density, the shape, length and angle of bedrock hillslopes and colluvial features were used to assess hillslope connectivity to the valley floor (Fryirs et al., 2007). This included analysis of the presence and absence of terraces and fans at valley margins. The Wolman Walk method was used to measure bed material size at 16 representative field sites, incorporating each River Style (Wolman, 1954).

Cross-section analysis of the width of the valley bottom, valley floor and valley margins was conducted over intervals of 300 m or less down valley, following procedures and definitions outlined by Fryirs et al. (2016) (Fig. 5). Channel slope, contemporary sinuosity and sinuosity of historical longest flow path (based on the presence of chute cutoffs of paleo-meanders) was calculated for each River Style. Alluvial terraces were mapped along the longitudinal profile of the main stem of the Upper Mōtū River (Fig. 9). Background knowledge of the geological, climatic and anthropogenic history was then used to explain landscape patterns.

4. Results

The distribution of River Styles in the Upper Mōtū Catchment is shown in Fig. 6. The upper catchment has a trellis drainage network configuration, with a southwest to northeast orientation. The headwaters converge into the main stem immediately upstream of Te Wera Road bridge (Fig. 1). Here the Mōtū River flows northeast within a partly confined valley, with an average slope of 0.003 m/m. Pronounced kinks in stream alignment coincide with a narrowing of the valley at a chokepoint (Fig. 6). Downstream of the chokepoint, the Mōtū River initially flows eastward. At Matawai, the river swings to the north, then veers eastward to Mōtū Falls. Downstream of the chokepoint, the valley progressively widens from partly confined with an average slope of 0.0021 m/m, to laterally unconfined valley with an average slope of 0.0009 m/m. The valley then progressively narrows to a gorge adjacent to the falls.

Eight River Styles were identified in the Upper Mōtū Catchment (Fig. 6 and Supplementary Data). The tributaries of the Mōtū River generally have a downstream transition from a **Confined, bedrock margin-controlled River Style** or **Partly confined, bedrock margin-controlled River Style** into a **Confined, terrace margin-controlled River Style.** As the tributaries approach the main stem, they generally transition to a **Partly confined, planform-controlled, terrace constrained River Style**. The **Laterally unconfined, passive meandering River Style** is typical of tributaries where channels are infilled with stored alluvium. No relationship between tributary/trunk connectivity and changes in River Styles is evident (Fig. 6).

The main stem of the Mōtū River, extending from just upstream of the Te Wera Road Bridge to partway between Matawai and Moutohora, is a **Partly confined, planform-controlled, terrace constrained River Style** (Fig. 7a). In these reaches, terraces restrict lateral channel migration. Instream geomorphic units include riffle-run sequences and point bars. The floodplains are discontinuous with ledges (flat topped, bank attached units that reflect channel expansion (Fryirs and Brierley, 2013) at channel margins. Low elevation terraces are laterally discontinuous, asymmetrical (un-paired) and non-linear, with paleo-meanders preserved on the surfaces (see Fig. 5).

The **Partly confined, planform-controlled, terrace constrained River Style** is disrupted for a short length by the **Confined, bedrock margin-controlled River Style** (minimum valley margin width approximately 12 m; Fig. 7b). This transitions into the **Confined, terrace margin-controlled River Style** as the valley gradually widens. Bedrock and terrace margins limit the potential for channel adjustment through the chokepoint. Point bars, ledges and floodplain pockets are the dominant geomorphic units.

The average width of the active valley bottom is 44 m within the **Partly confined, planform controlled, terrace constrained River Style**, but the average valley floor width is 260 m. Asymmetrical channels with ledges are inset within a macrochannel. Unpaired low-level terraces and paleo-meanders are common (Fig. 8). These features indicate contemporary incision, channel expansion and downstream translation of bends, as lateral movement of the contemporary channel is locally constrained (Nicoll and Hickin, 2010). In contrast, paleo-meanders on the higher floodplain surface indicate that lateral adjustment was more prominent in the past. Comparing the stream length today with the longest paleo-flow path (river length today plus paleo-meanders), channel length has reduced by 12 % in the reach upstream of Matawai township, compared to a 39 % reduction in the reach downstream of Matawai township. Average slope of the Mōtū River changes from 0.0024 m/m for the reach upstream of Matawai to 0.0014 m/m in the reach downstream of Matawai.

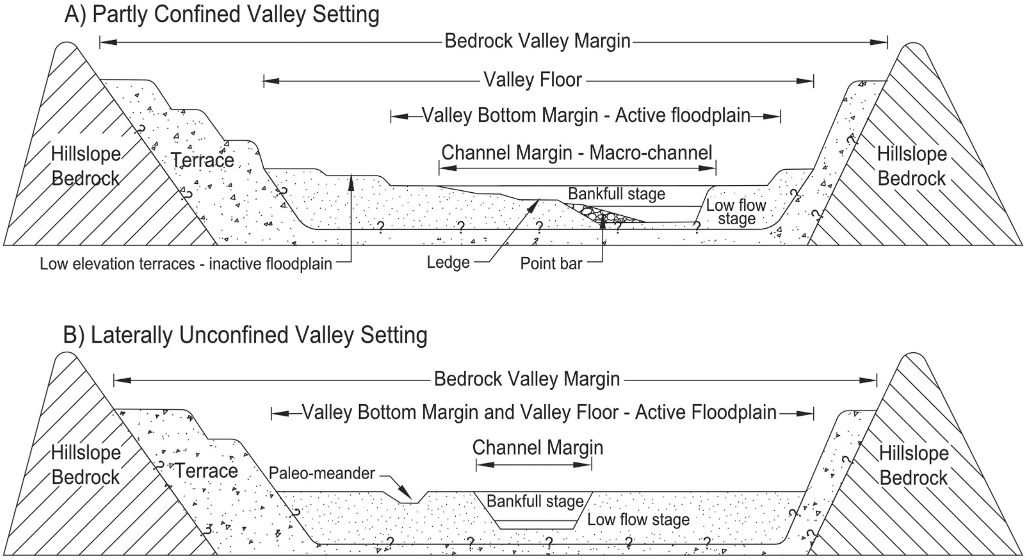


Fig. 5. Schematic diagram of key landforms and confining margin terminology for partly confined and laterally unconfined valley settings (see text for details).

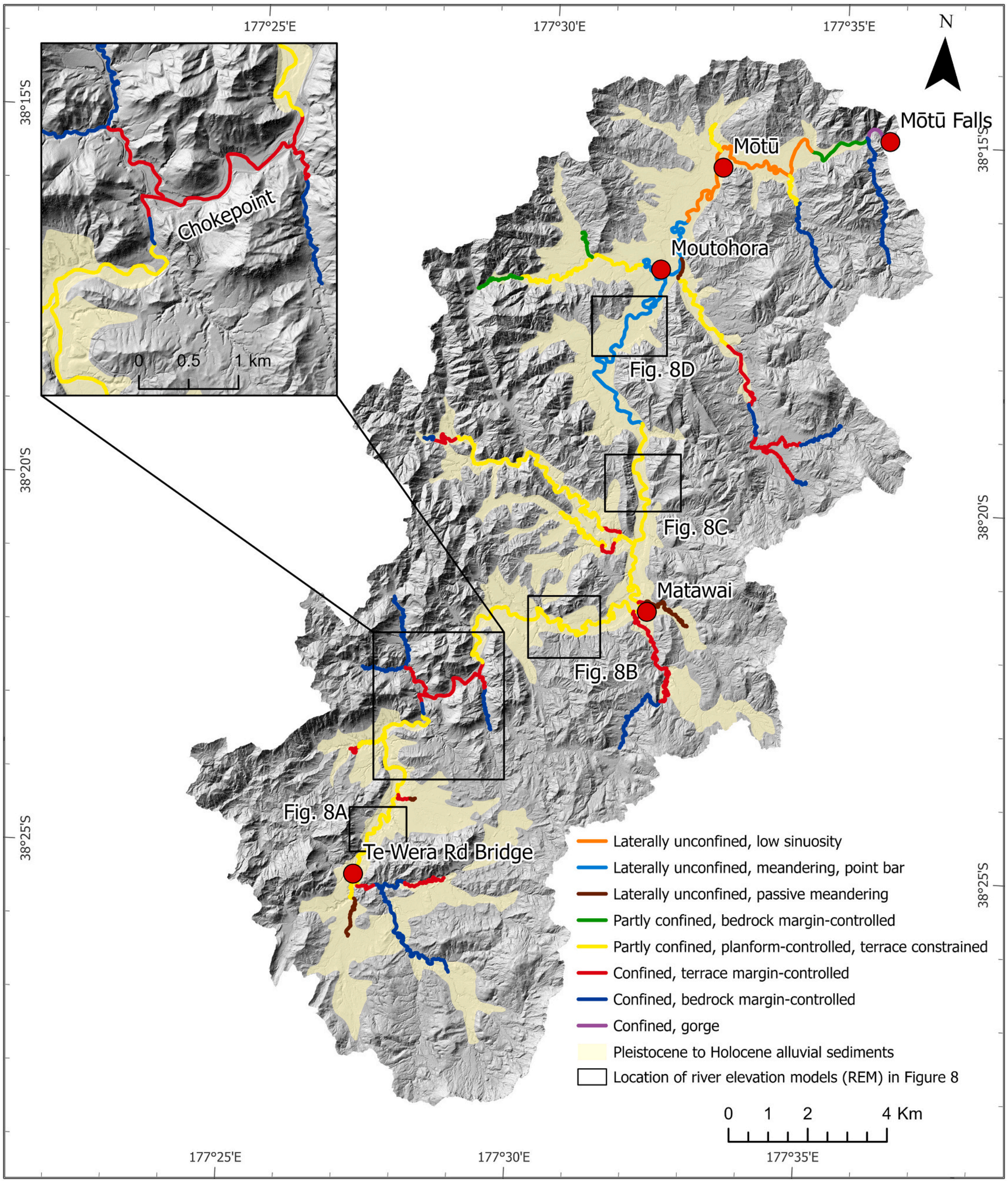


Fig. 6. Distribution of River Styles in the Upper Mōtū Catchment. Alluvial sediment stores are found along partly confined and laterally unconfined River Styles.

Approximately 28 km downstream, the Mōtū River transitions to the **Laterally unconfined, meandering, point bar River Style** (Fig. 7c) and then into the **Laterally unconfined, low sinuosity River Style**. Ledges and low-elevation terraces are not evident in this laterally unconfined setting. The bank height progressively increases downstream, and the frequency of point bars reduces as the channel becomes less sinuous, entrenched and symmetrical, inset within continuous floodplains with paleo-meanders. Terraces at valley margins exert no influence on lateral adjustment in these reaches.

Approaching Mōtū Falls, bedrock margins narrow with a gradual transition into the **Partly confined, bedrock margin-controlled River Style** (Fig. 7d). The channel is symmetrical and entrenched, and runs are the dominant geomorphic unit. In contrast, sculpted geomorphic units characterize the **Confined, gorge River Style** adjacent to the falls.

Flights of terraces along valley margins of the Upper Mōtū River are laterally discontinuous and asymmetrical. They are best preserved where the valley margins are widest, often coincident with tributary confluence zones where long-term incision of the main stem has truncated tributary adjacent fills (Fig. 9). Upstream of the chokepoint, up to five terrace steps rise above the valley floor, with up to 40 m elevation difference between the highest terrace and the contemporary channel. Here, the elevation difference is greater between the upper terraces at up to 14 m (Terraces 1, 2 and 3), relative to between Terrace 3 and the low-level terraces at approximately 3 to 5 m). Just one remnant terrace is evident within the chokepoint (Fig. 9). Downstream of the chokepoint, terraces extend for several kilometres beyond Matawai township. Moving downstream, the overall elevation difference between the upper terrace and river level decreases from 35 to 25 m. Only small remnants of terraces remain at a slight narrowing of the valley at 16–18 km downvalley (Fig. 9). In the laterally unconfined reach beyond 18 km downvalley, the three terrace levels reduce to one (Fig. 9) and the overall height of terraces continues to decrease downstream from 25 m to 15 m

Fig. 7. Characteristic examples of the primary River Styles along the Upper Mōtū River. A) Partly confined, planform-controlled, terrace constrained River Style upstream of the chokepoint; B) Looking downstream towards the start of the chokepoint; C) Laterally unconfined, meandering, point bar River Style; D) Partly confined, bedrock margin-controlled River Style upstream of Mōtū Falls.

above river level. Individual terraces have an elevation difference of up to 10 m. The valley floor becomes progressively elevated above the river level downstream.

As a result of vertical aggradation and channel entrenchment, low-elevation terraces are evident in partly confined and chokepoint reaches. However, they are not observed in the laterally unconfined reaches immediately upstream of Mōtū Falls. The reduced connectivity between the floodplain and the entrenched channel indicate that channel incision and expansion processes propagated upstream in response to lowered base level (Simon, 1989).

5. Geological controls on patterns of landforms and River Styles in the Upper Mōtū Catchment

Fig. 10 and Table 1 characterize primary patterns of valley width (accommodation space) and associated assemblages of valley floor landforms and River Styles in Upper Mōtū Catchment in relation to five process zones. The boundaries between the zones are gradational. They primarily reflect changes to valley setting and accommodation space, as this is the key determinant of the pattern and persistence of terraces, which in turn influences the character and behaviour of the contemporary river. Three tributary patterns of River Styles reflect the presence or absence of valley fill, and the progression of upwards incision into tributary fills (Fig. 10).

The transition from a partly confined valley with discontinuous floodplains (a transfer zone) to a laterally unconfined valley with continuous floodplains (an accumulation zone) corresponds to a reduction in average slope from 0.0021 m/m to 0.0009 m/m (Montgomery, 1999; Fig. 6). In partly confined reaches, the confining margin varies between bedrock and terraces. Terrace preservation seemingly correlates with the width of the bedrock margin (Limaye and Lamb, 2016). The terraces are most evident at truncated tributary fills where the upper terrace level edge corresponds to the bedrock margin width on either side of the valley.

Geological imprints exert a variable control upon river alignment and the distribution of contemporary processes in the five zones that make up the Upper Mōtū Catchment (Table 2). The wide valleys create accommodation space where sediment accumulation can occur. The suite of terraces indicates a long-term tendency towards incision in response to uplift and/or climatic changes (Litchfield and Berryman, 2006). Terrace distribution, in turn, influences forms and rates of contemporary river adjustment (i.e., the pattern of River Styles along the Upper Mōtū River).

Boundary conditions that shape the pattern of contemporary geomorphic process zones in the Upper Mōtū Catchment are primarily products of geologic (tectonic, structure, lithology) and climate (terrace formation, distribution and preservation) controls. Implicitly, these controls play out over different timescales. Tectonic uplift of the ranges perched the ancestral Mōtū River high in the landscape, juxtaposing different lithologies with variable erosivity. The contemporary drainage network and valley alignment frequently map to fault lines, indicating that exploitation of structural weaknesses in the rock created preferential flow paths (Roy et al., 2015). Downthrow of faults to the east promotes the contemporary northeasterly direction of flow. The river also tends to follow the direction of fold axes. Accordingly, the trunk stream flows parallel to the strike direction of lithological layers, as indicated by the northward swing of the river at Matawai township.

Mōtū Falls coincides with the outcropping of comparably more resistant sandstone, forming a knickpoint. It sets a local base level to which the upper Mōtū River has adjusted its longitudinal profile (Leopold and Bull, 1979). This less erodible unit has arrested rates of downcutting into bedrock. In response, lateral river migration in upstream reaches has widened the valley (Whipple and Tucker, 1999) to provide accommodation space for sediment to accumulate.

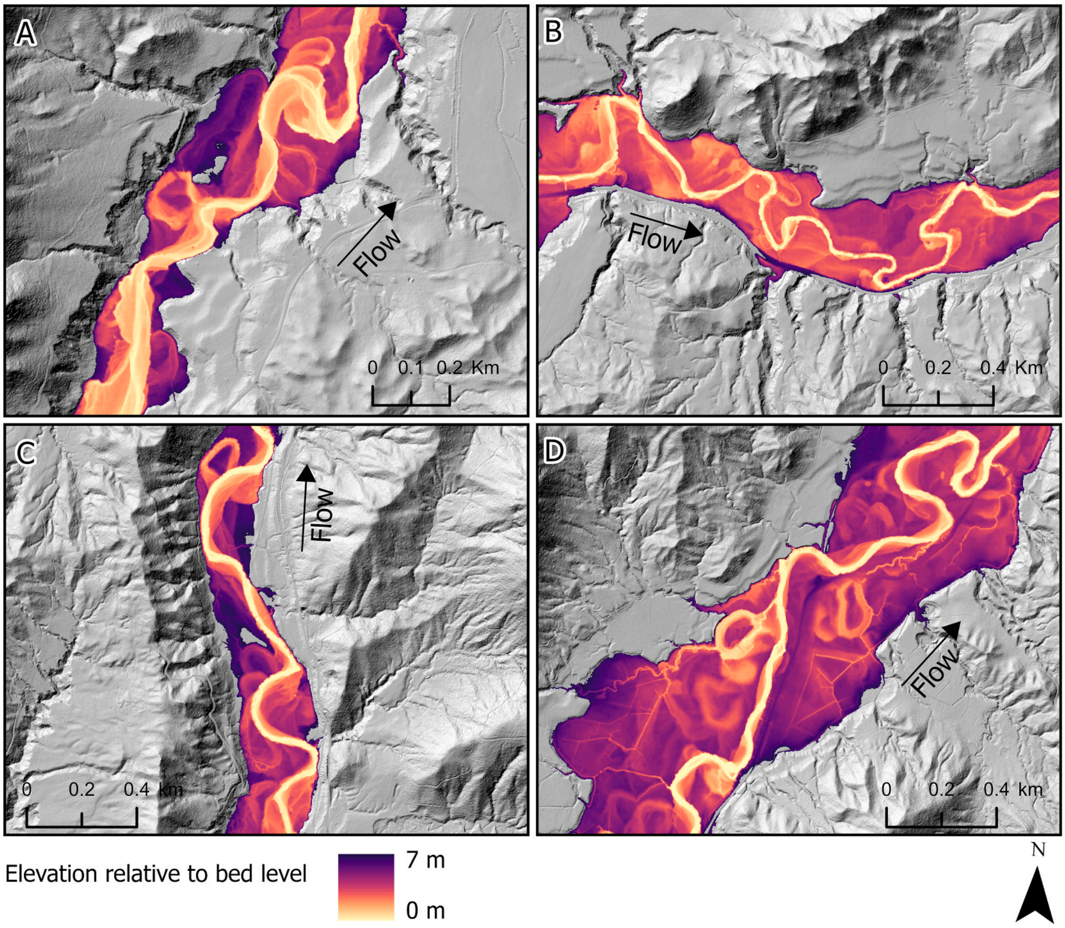


Fig. 8. Relative Elevation Models highlighting paleo-meanders and contemporary channel pattern on the valley floor (sites are located on Fig. 6). A) Upstream of the chokepoint, channel migration is limited by bedrock and terrace margins B) Between the chokepoint and Matawai, there is reduced occurrence of paleo-meanders. C) Narrower zone 16–18 km down valley, where terraces have been erased due to narrower bedrock and paleo-meanders are frequent. D) Laterally unconfined valley with frequent paleo-meanders across the valley floor.

The downstream change in lithology from the more resistant Pahau terrane upstream to the more erosive Matawai Group at the Kotare Fault (Fig. 3) has enabled greater planation of the river and an overall widening of the valley. However, this planation is disrupted at two locations. At the chokepoint, there are no faults or folds to exploit. The pre-uplift geology is inferred to have the Pahau terrane overlain by the Koranga Formation, the latter being the least erosive. As the material weathered, the drainage network dissected the Koranga Formation to create a superimposed drainage pattern (e.g., Cotton, 1958). Within the chokepoint, the greater resistance of the Koranga Formation to erosion and the lack of structural weakness promoted downcutting over lateral planation as the dominant process within this reach.

Outcrops of the Whangai Formation 16–18 km down-valley of Matawai township are more resistant to river incision than the Karekare Formation. Slight narrowing of the valley indicates a slower rate of lateral planation and valley widening. The resulting width is less than the meander width of the ancestral river which effectively removed terraces from the landscape in this location (i.e., erasure has occurred; Brierley, 2010).

Terraces buffer (disconnect) sediment delivery from hillslopes to valley floors along much of the Upper Mōtū River (Fryirs et al., 2007). The chokepoint in Zone 2 and the Mōtū Falls (Zone 5) create bottlenecks that enable aggradation and sediment storage in upstream reaches (Gran and Czuba, 2017). This geological control upon patterns of accommodation space and slope is reflected in a marked increase in terrace height upstream of the chokepoint and pronounced sediment accumulation upstream of Mōtū Falls. Differences in terrace height in Zone 1 indicate that an additional 25 m of incision has occurred and suggests that at the time of maximum aggradation, the valley floor was steeper in this zone compared to today (Fig. 9). Downcutting may have occurred through bedrock to create strath terraces or into valley fill to create alluvial terraces (Merritts et al., 1994). Downstream changes in the number and size of terraces may reflect floodplain reworking, a pause in incision downstream due to an influx of sediment eroded from upstream (Schumm, 1991) or tectonic uplift (Litchfield and Berryman, 2006).

The imprint of geologic and climatic controls exerts a primary influence upon forms and rates of landscape response to anthropogenic disturbance. Land clearance doubtless increased the release of sediment from hillslopes. However, much of this sediment has subsequently been re-stored on fans and terraces in the wide valley settings. Landscape sensitivity to anthropogenic disturbance has been more pronounced on the valley floor. Here, removal of roughness elements (riparian vegetation and wood) in the riparian zone has accentuated riverbed incision and subsequent channel expansion, creating headcuts, ledges and low terrace surfaces (cf., Brooks et al., 2003). Reworking of sediment stored in terraces and in low elevation terraces is the primary source of sediment for the Mōtū River (Vale et al., 2021). Enlarged channel capacity, in turn, has reduced the frequency of flood inundation on adjacent surfaces.

6. Discussion and concluding comment

While chronologic control is key to interpretations of the sequence and timing of phases of geomorphic history and rates of process activity,

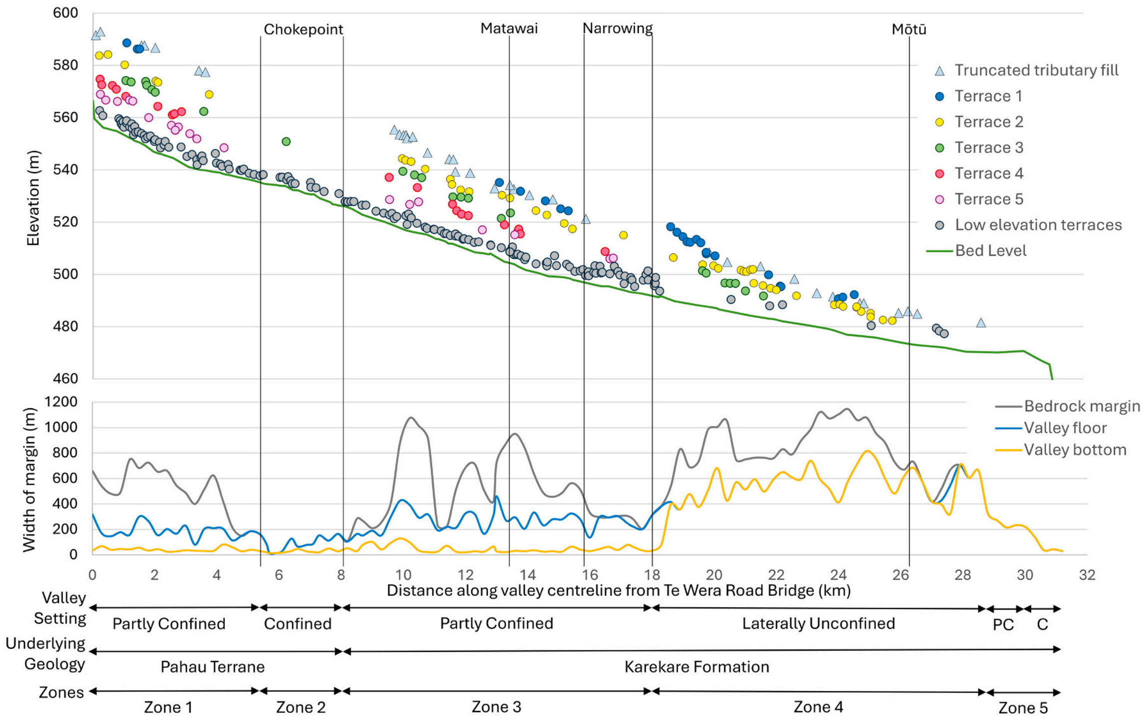


Fig. 9. Longitudinal profile of the Upper Mōtū River with the elevation of the terraces (Tc1 to Tc5) and low elevation terraces, derived from the DEM. The correlation of terrace elevations is based on a visual assessment; no dating has been undertaken. The width of the valley bottom, valley floor and bedrock margin show the correlation between the persistence of terraces and the bedrock valley margin width.

much can be gleaned from analysis of spatial patterns of landforms to determine sediment sources, stores and connectivity relationships. Findings from this study show how the imprint of landscape history has fashioned anomalous process relationships in Upper Mōtū Catchment relative to adjacent river systems (Fuller et al., 2023). The imprint of geologic, climatic and anthropogenic memory (Brierley, 2010) is manifest in four inter-related ways in this instance. First, geologic controls have determined patterns of accommodation space, with large valley width upstream of Mōtū Falls (Figs. 6 and 10). Drainage configuration (valley alignment, tributary-trunk stream relations), drainage density and downstream changes in valley width (including chokepoints) are products of uplift, tectonic structure, fault-fold patterns and lithology. Second, the significant accommodation space presented opportunities to develop and preserve a long-term record of sediment accumulation and reworking as a result of climate controls. Changes to the aggradational-degradational balance over time have created distinct flights of major terraces that act as major sediment stores (Figs. 9 and 10). Third, terraces, fans and tributary fills now play a dual role in the contemporary sediment budget. They act as confining margins that determine the space within which flow energy reworks valley floor sediments. They also buffer hillslope sediment supply to the contemporary channel (i.e., they inhibit lateral hillslope-valley floor connectivity; Fryirs et al., 2007). Fourth, marked changes to channel geometry/planform associated with channel bed incision and widening processes (Fig. 8) are products, in part at least, of anthropogenic memory, as forest clearance and land use changes reduced riparian vegetation cover, loading of wood and associated valley floor roughness. Reworking of valley fill deposits by headward incision and subsequent channel expansion (Simon, 1989) is now the dominant contemporary sediment source in this system (Vale et al., 2021).

Although the cut-and-fill evolutionary history of the Upper Mōtū river system is quite distinct from other catchments in the East Coast region (Fuller et al., 2023), intriguing parallels can be made with cut-and-fill rivers in tableland and escarpment-dominated landscapes in passive margin tectonic settings of southeastern Australia (e.g., Fryirs and Brierley, 2001). Unravelling catchment-specific understandings of patterns of landforms is required to appraise sediment sources/stores and (dis)connectivity relationships (i.e., buffering capacity) of a given river system, rather than giving undue attention to overly-generalised assumptions regarding tectonic and climatic controls upon contemporary sediment sources and the ease with which sediments are likely to be conveyed through river systems (cf., Buckley et al., 2024; Fryirs et al., 2007; Poeppl et al., 2020). Two distinct scales and phases of cut-and-fill history are evident in the Upper Mōtū Catchment: longer-term controls on terrace formation, and contemporary incision, head cut activity and channel expansion. Understanding controls upon cut-and-fill river activity is key to effective management of some New Zealand rivers.

Interpretation of geological controls on landscape patterns and evolutionary traits provides critical insights to guide predictions of landscape futures, and associated implications for management applications (Brierley et al., 2021). Management practices that work with the river, applying process-based understandings that tackle issues at source and at scale, build upon explanations of where rivers get their sediments from (Brierley and Fryirs, 2022). This incorporates insights into the role of downstream changes in accommodation space (valley width, slope and patterns of terraces) and associated longitudinal and lateral connectivity relationships upon patterns and rates of sediment storage and flux (Fuller et al., 2023; Poeppl et al., 2020).

Upstream transitions in the pattern of geomorphic units indicate that the likely front of headcut incision in the Upper Mōtū catchment currently lies at the transition from the **Laterally unconfined, meandering, point bar River Style**, to the **Laterally unconfined, low sinuosity River Style**. A second front is suspected in the vicinity of Matawai township, indicated by changes in the frequency of paleo-meanders in the **Partly confined, planform-controlled, terrace constrained River Style**. As valley floors and tributary fills contain vast sediment stores that can be reworked and evacuated, bed control structures and a continuous riparian vegetation corridor are required to address sediment issues in the Upper Mōtū Catchment. This contrasts to other catchments in the region where reforestation of highly erodible

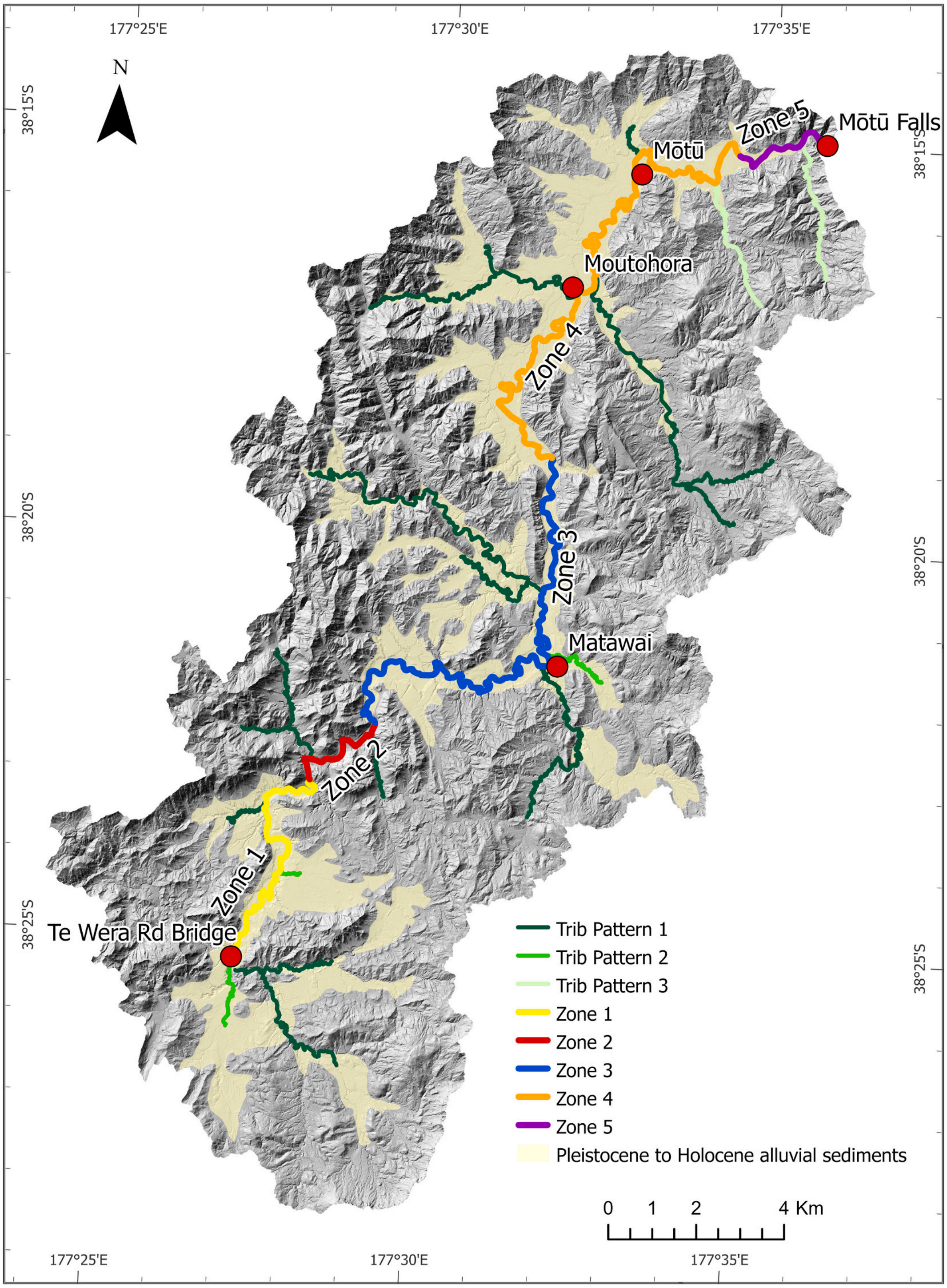


Fig. 10. The five zones (Zones 1 to 5) of the Upper Mōtū River, defined by the pattern of valley setting, hillslope/terrace/tributary fill features and geomorphic units on the valley floor. Patterns in tributaries (Trib Pattern 1 to 3) reflect upstream changes in River Style.

hillslopes is required to mitigate large mass movement complexes that are generating vast quantities of sediment (Fuller et al., 2023). In a sense, the less dramatic geomorphic responses to anthropogenic disturbance in the Mōtū Catchment relative to other river systems in the East Coast region highlight the importance of understanding contextual, catchment-specific considerations to explain landscape morphodynamics and contemporary sediment flux in any given catchment (Brierley et al., 2013; Wohl et al., 2024). This has profound implications for fit-for-purpose, process-based management applications that build upon such understandings (Fuller et al., 2023).

CRediT authorship contribution statement

Jacqui McCord: Writing – original draft, Visualization, Methodology, Conceptualization. **Gary Brierley:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Jon Tunnicliffe:** Writing – original draft, Visualization, Supervision. **Ian Fuller:** Writing – review & editing. **Mike Marden:** Writing – review & editing. **Colin Mazengarb:** Writing – review & editing.

Table 1
Key attributes of process zone compartments that make up the Upper Mōtū Catchment, thereby defining landscape pattern.

	Zone 1	Zone 2 (Chokepoint)	Zone 3	Zone 4	Zone 5
Slope (m/m)	0.003	0.0026	0.0021	0.0009	0.00004
Terrace Steps	Up to 5	Not present	Up to 5	Up to 3	Not present
Terrace height above channel	40 m high	Not present	35-25 m high	25–15 m high	Not present
Valley Setting	Partly confined	Confined	Partly confined	Laterally unconfined	Partly confined to confined
Confining/ Constraining Margin	Terraces	Bedrock	Terraces	Not present	Bedrock
Contemporary Process zone	Transfer zone - incisional	Transfer zone	Transfer - incisional	Accumulation Zone - incisional	Accumulation to throughput zone
Floodplains	Discontinuous	Floodplain pockets	Discontinuous	Continuous	Discontinuous to floodplain pockets
Instream geomorphic units	Riffles Point bar	Run Point bar	Point bar	Run	Run Forced riffles
Floodplain geomorphic units	Low elevation terraces Ledges	Floodplain pocket stripping	Low elevation terraces Paleo-meanders	Paleo-meanders Floodplain reworking	Floodplain pockets
Contemporary behaviour	Incision and widening	Incision	Incision and widening	Incision and widening	Widening

Table 2
Summary of controls on landscape patterns in each zone of the Mōtū River. The lithology and geological imprints control where accommodation space and terraces can form. This now exerts a variable control on contemporary river adjustment.

	Lithology	Geological control on accommodation space	Controls on contemporary channel adjustment
Zone 1	Pahau Terrane (less erosive)	Fault and fold aligned drainage network. Moderately wide valley, sediment stored in up to 5 terraces	Terraces confined channel margins
Zone 2	Pahau Terrane (less erosive)	Narrow bedrock margin with limited sediment storage	Bedrock margin restricts lateral adjustment
Zone 3	Karekare Formation (more erosive)	Fault and fold aligned drainage network. Moderately wide valley, sediment stored in up to 5 terraces	Terraces confine channel margins
Zone 4	Karekare Formation (more erosive)	Fault and fold aligned drainage network. Wide valley floor, sediment stored in up to 3 terraces and on valley floor	Laterally unconfined (alluvial) channel adjustment
Zone 5	Karekare Formation (more erosive)	Narrow bedrock margin with limited sediment storage	Bedrock margin restricts lateral adjustment

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Janic Slupski from Gisborne District Council for his support during the undertaking of this study. Elliot Stevens at the University of Auckland provided assistance with fieldwork. We also thank the Marsden-funded 'Let the River Speak' at the University of Auckland (Anne Salmond, Dan Hikuroa, Billie Lythberg). Guidance from the review process enhanced communication of key messages in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2025.110012.

Data availability

No data was used for the research described in the article.

References

Berryman, K., Marden, M., Eden, D., Mazengarb, C., Ota, Y., Moriya, I., 2000. Tectonic and paleoclimatic significance of Quaternary river terraces of the Waipaoa river, east coast, North Island, New Zealand. N. Z. J. Geol. Geophys. 43 (2), 229–245. https://doi.org/10.1080/00288306.2000.9514883.

Biron, P.M., Buffin-Bélanger, T., Larocque, M., Choné, G., Cloutier, C.A., Ouellet, M.A., Demers, S., Olsen, T., Desjarlais, C., Eyquem, J., 2014. Freedom space for rivers: a sustainable management approach to enhance river resilience. Environ. Manag. 54 (5), 1056–1073. https://doi.org/10.1007/s00267-014-0366-z.

Brierley, G.J., 2010. Landscape memory: the imprint of the past on contemporary landscape forms and processes. Area 42 (1), 76–85. https://doi.org/10.1111/j.1475-4762.2009.00900.x.

Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publishing, Malden, MA. https://doi.org/10.1002/9780470751367.

Brierley, G.J., Fryirs, K.A., 2022. Truths of the riverscape: moving beyond command-and-control to geomorphologically informed nature-based river management. Geosci. Lett. 9 (1), 14. https://doi.org/10.1186/s40562-022-00223-0.

Brierley, G.J., Fryirs, K.A., Cullum, C., Tadaki, M., Huang, H.Q., Blue, B., 2013. Reading the landscape: integrating the theory and practice of geomorphology to develop place-based understandings of river systems. Prog. Phys. Geogr. Earth Environ. 37 (5), 601–621. https://doi.org/10.1177/0309133313490007.

Brierley, G.J., Fryirs, K.A., Reid, H., Williams, R., 2021. The dark art of interpretation in geomorphology. Geomorphology 390, 107870. https://doi.org/10.1016/j.geomorph.2021.107870.

Brierley, G.J., Hikuroa, D., Fuller, I.C., Tunnicliffe, J., Allen, K., Brasington, J., Friedrich, H., Hoyle, J., Measures, R., 2023. Reanimating the strangled rivers of Aotearoa New Zealand. WIREs Water 10 (2), e1624. https://doi.org/10.1002/wat2.1624.

Brooks, A.P., Brierley, G.J., Millar, R.G., 2003. The long-term control of vegetation and woody debris on channel and flood-plain evolution: insights from a paired catchment study in southeastern Australia. Geomorphology 51 (1–3), 7–29. https://doi.org/10.1016/S0169-555X(02)00323-9.

Buckley, J., Hodge, R.A., Slater, L.J., 2024. Bedrock rivers are steep but not narrow: hydrological and lithological controls on river geometry across the USA. Geology 52 (7), 522–526. https://doi.org/10.1130/G51627.1.

Buffin-Bélanger, T., Biron, P.M., Larocque, M., Demers, S., Olsen, T., Choné, G., Ouellet, M.A., Cloutier, C.A., Desjarlais, C., Eyquem, J., 2015. Freedom space for rivers: an economically viable river management concept in a changing climate. Geomorphology 251, 137–148. https://doi.org/10.1016/j.geomorph.2015.05.013.

Burbank, Pinter, 1999. Landscape evolution: the interactions of tectonics and surface processes. Basin Res. 11 (1), 1–6. https://doi.org/10.1046/j.1365-2117.1999.00089.x.

Chappell, P.R., 2016. The climate and weather of Gisborne. In: NIWA Science and Technology Series, p. 70.

Church, M., 2013. Refocusing geomorphology: field work in four acts. Geomorphology 200, 184–192. https://doi.org/10.1016/j.geomorph.2013.01.014.

Ciotti, D.C., Mckee, J., Pope, K.L., Kondolf, G.M., Pollock, M.M., 2021. Design criteria for process-based restoration of fluvial systems. BioScience 71 (8), 831–845. https://doi.org/10.1093/biosci/biab065.

Clement, A.J., Fuller, I.C., 2007. Fluvial responses to environmental change in the North Island, New Zealand, during the past c. 30 ka recorded in river terrace sequences: a review and model for river behaviour. N. Z. J. Geol. Geophys. 50 (2), 101–116. https://doi.org/10.1080/00288300709509824.

Cotton, C.A., 1958. Geomorphology: An Introduction to the Study of Landforms, 7th ed. Whitcombe & Tombs.

Craw, D., Upton, P., Burridge, C.P., Wallis, G.P., Waters, J.M., 2016. Rapid biological speciation driven by tectonic evolution in New Zealand. Nat. Geosci. 9 (2), 140–144. https://doi.org/10.1038/ngeo2618.

Crosby, B.T., Whipple, K.X., 2006. Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand. Geomorphology 82 (1–2), 16–38. https://doi.org/10.1016/j.geomorph.2005.08.023.

Downs, P.W., Piégay, H., 2019. Catchment-scale cumulative impact of human activities on river channels in the late Anthropocene: implications, limitations, prospect. Geomorphology 338, 88–104. https://doi.org/10.1016/j.geomorph.2019.03.021.

Dury, G.H., 1964. Principles of underfit streams. In: US Geological Survey Professional Paper 452-A. United States Government Printing Office.

Duvall, A.R., Harbert, S.A., Upton, P., Tucker, G.E., Flowers, R.M., Collett, C., 2020. River patterns reveal two stages of landscape evolution at an oblique convergent margin, Marlborough Fault System, New Zealand. Earth Surf. Dyn. 8 (1), 177–194. https://doi.org/10.5194/esurf-8-177-2020.

Eaton, B., Millar, R., 2017. Predicting gravel bed river response to environmental change: the strengths and limitations of a regime-based approach. Earth Surf. Process. Landf. 42 (6), 994–1008. https://doi.org/10.1002/esp.4058.

Fryirs, K.A., Brierley, G.J., 2001. Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: implications for geomorphic river recovery. Geomorphology 38 (3–4), 237–265. https://doi.org/10.1016/S0169-555X(00)00093-3.

Fryirs, K.A., Brierley, G.J., 2013. Geomorphic Analysis of River Systems: An Approach to Reading the Landscape, 1st ed. John Wiley & Sons, Chichester, UK; Hoboken, NJ. https://doi.org/10.1002/9781118305454.

Fryirs, K.A., Brierley, G.J., 2018. What's in a name? A naming convention for geomorphic river types using the River Styles Framework. PloS One 13 (9), e0201909. https://doi.org/10.1371/journal.pone.0201909.

Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai, M., 2007. Buffers, barriers and blankets: the (dis)connectivity of catchment-scale sediment cascades. CATENA 70 (1), 49–67. https://doi.org/10.1016/j.catena.2006.07.007.

Fryirs, K.A., Wheaton, J.M., Brierley, G.J., 2016. An approach for measuring confinement and assessing the influence of valley setting on river forms and processes. Earth Surf. Process. Landf. 41 (5), 701–710. https://doi.org/10.1002/esp.3893.

Fuller, I.C., Brierley, G.J., Tunnicliffe, J., Marden, M., McCord, J., Rosser, B., Hikuroa, D., Harvey, K., Stevens, E., Thomas, M., 2023. Managing at source and at scale: the use of geomorphic river stories to support rehabilitation of Anthropocene riverscapes in the East Coast Region of Aotearoa New Zealand. Front. Environ. Sci. 11, 1162099. https://doi.org/10.3389/fenvs.2023.1162099.

Gran, K.B., Czuba, J.A., 2017. Sediment pulse evolution and the role of network structure. Geomorphology 277, 17–30. https://doi.org/10.1016/j.geomorph.2015.12.015.

Grant, P.J., 1985. Major periods of erosion and alluvial sedimentation in New Zealand during the Late Holocene. J. R. Soc. N. Z. 15 (1), 67–121. https://doi.org/10.1080/03036758.1985.10421743.

Gregory, K.J., 2006. The human role in changing river channels. Geomorphology 79 (3–4), 172–191. https://doi.org/10.1016/j.geomorph.2006.06.018.

Haggett, P., 1965. Locational Analysis in Human Geography. Edward Arnold, London.

Hicks, D.M., Shankar, U., McKerchar, A.I., Basher, L., Lynn, I., Page, M., Jessen, M., 2011. Suspended sediment yields from New Zealand rivers. J. Hydrol. N. Z. 50 (1), 81–142.

Isaac, M., 1977. Mesozoic Geology of the Matawai District. Ph. D. Thesis. University of Auckland.

Jiao, R., Seward, D., Little, T.A., Kohn, B.P., 2015. Unroofing of fore-arc ranges along the Hikurangi Margin, New Zealand: Constraints from low-temperature thermochronology. Tectonophysics 656, 39–51. https://doi.org/10.1016/j.tecto.2015.06.004.

Lane, S.N., 2017. Natural flood management. WIREs Water 4 (3), e1211. https://doi.org/10.1002/wat2.1211.

Leopold, L.B., Bull, W.B., 1979. Base level, aggradation, and grade. Proc. Am. Philos. Soc. 123 (3), 168–202.

Limaye, A.B., Lamb, M.P., 2016. Numerical model predictions of autogenic fluvial terraces and comparison to climate change expectations. J. Geophys. Res. Earth 121 (3), 512–544. https://doi.org/10.1002/2014JF003392.

Litchfield, N.J., Berryman, K., 2005. Correlation of fluvial terraces within the Hikurangi margin, New Zealand: implications for climate and baselevel controls. Geomorphology 68 (3–4), 291–313. https://doi.org/10.1016/j.geomorph.2004.12.001.

Litchfield, N.J., Berryman, K., 2006. Relations between postglacial fluvial incision rates and uplift rates in the North Island, New Zealand. J. Geophys. Res. Earth 111 (F2), 2005JF000374. https://doi.org/10.1029/2005JF000374.

Marden, M., Mazengarb, C., Palmer, A., Berryman, K., Rowan, D., 2008. Last glacial aggradation and postglacial sediment production from the non-glacial Waipaoa and Waimata catchments, Hikurangi Margin, North Island, New Zealand. Geomorphology 99 (1–4), 404–419. https://doi.org/10.1016/j.geomorph.2007.12.003.

Marden, M., Betts, H., Palmer, A., Taylor, R., Bilderback, E., Litchfield, N.J., 2014. Post-Last Glacial Maximum fluvial incision and sediment generation in the unglaciated Waipaoa catchment, North Island, New Zealand. Geomorphology 214, 283–306. https://doi.org/10.1016/j.geomorph.2014.02.012.

Marden, M., Holt, K., Ryan, M., Carrasco, J., Marsaglia, K., Kirby, M., Palmer, A., 2021. Stratigraphy and vegetation signals from an upland, landslide-dammed, paleolake during the Last Glacial-Interglacial Transition, Waipaoa Sedimentary System, Hikurangi Margin, eastern North Island, New Zealand. N. Z. J. Geol. Geophys. 65 (1), 220–241. https://doi.org/10.1080/00288306.2021.1947327.

Mazengarb, C., Harris, D., 1994. Cretaceous stratigraphic and structural relations of Raukumara Peninsula, New Zealand: stratigraphic patterns associated with the migration of a thrust system. Ann. Tecton. 8, 100–118.

Mazengarb, C., Speden, I.G., 2000. Geology of the Raukumara area. In: Institute of Geological & Nuclear Sciences 1:250 000 Geological Map 6. Institute of Geological & Nuclear Sciences.

McGlone, M.S., Howorth, R., Pullar, W.A., 1984. Late Pleistocene stratigraphy, vegetation and climate of the Bay of Plenty and Gisborne regions, New Zealand. N. Z. J. Geol. Geophys. 27 (3), 327–350. https://doi.org/10.1080/00288306.1984.10422302.

Merritts, D.J., Vincent, K.R., Wohl, E.E., 1994. Long river profiles, tectonism, and eustasy: a guide to interpreting fluvial terraces. J. Geophys. Res. Solid Earth 99 (B7), 14031–14050. https://doi.org/10.1029/94JB00857.

Montgomery, D.R., 1999. Process domains and the river continuum 1. JAWRA J. Am. Water Resour. Assoc. 35 (2), 397–410. https://doi.org/10.1111/j.1752-1688.1999.tb03598.x.

Nanson, G.C., Huang, H.Q., 2017. Self-adjustment in rivers: evidence for least action as the primary control of alluvial-channel form and process. Earth Surf. Process. Landf. 42 (4), 575–594. https://doi.org/10.1002/esp.3999.

Nelson, A.D., Collins, V.D., Payne, J.S., Abbe, T.B., 2024. Proactive river corridor definition: recommendations for a process-based width optimization approach illustrated in the context of the coastal Pacific Northwest. WIREs Water 11 (3), e1711. https://doi.org/10.1002/wat2.1711.

Nicol, A., Mazengarb, C., Chanier, F., Rait, G., Uruski, C., Wallace, L., 2007. Tectonic evolution of the active Hikurangi subduction margin, New Zealand, since the Oligocene. Tectonics 26 (4). https://doi.org/10.1029/2006TC002090.

Nicoll, T.J., Hickin, E.J., 2010. Planform geometry and channel migration of confined meandering rivers on the Canadian prairies. Geomorphology 116 (1–2), 37–47. https://doi.org/10.1016/j.geomorph.2009.10.005.

Piégay, H., Darby, S.E., Mosselman, E., Surian, N., 2005. A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion. River Res. Appl. 21 (7), 773–789. https://doi.org/10.1002/rra.881.

Poeppl, R.E., Fryirs, K.A., Tunnicliffe, J., Brierley, G.J., 2020. Managing sediment (dis)connectivity in fluvial systems. Sci. Total Environ. 736, 139627. https://doi.org/10.1016/j.scitotenv.2020.139627.

Rhoads, B.L., Thorn, C.E., 1996. Observation in geomorphology. In: Rhoads, B.L., Thorn, C.E. (Eds.), The Scientific Nature of Geomorphology. Wiley, pp. 21–56.

Roy, S.G., Koons, P.O., Upton, P., Tucker, G.E., 2015. The influence of crustal strength fields on the patterns and rates of fluvial incision. J. Geophys. Res. Earth 120 (2), 275–299. https://doi.org/10.1002/2014JF003281.

Schumm, S.A., 1991. To Interpret the Earth: Ten Ways to be Wrong. Cambridge University Press.

Schwanghart, W., Scherler, D., 2014. Short Communication: TopoToolbox 2 – MATLAB-based software for topographic analysis and modeling in Earth surface sciences. Earth Surf. Dyn. 2 (1), 1–7. https://doi.org/10.5194/esurf-2-1-2014.

Simon, A., 1989. A model of channel response in disturbed alluvial channels. Earth Surf. Process. Landf. 14, 11–26. https://doi.org/10.1002/esp.3290140103.

Suggate, R.P., 1990. Late Pliocene and Quaternary glaciations of New Zealand. Quat. Sci. Rev. 9, 175–197. https://doi.org/10.1016/0277-3791(90)90017-5.

Trudgill, S., 2003. Meaning, knowledge, constructs and fieldwork in physical geography. In: Roy, A., Trudgill, S. (Eds.), Contemporary Meanings in Physical Geography: From What to Why? Arnold, pp. 25–46.

Twisleton, D., 2007. The Motu and beyond: The Way it Was. Dick Twisleton.

Vale, S., Smith, H., Marden, M., 2021. Upper Mōtū Catchment Sediment Sources Study. Contract Report: LC3937. Manaaki Whenua - Landcare Research, p. 21.

Wheaton, J.M., Fryirs, K.A., Brierley, G.J., Bangen, S.G., Bouwes, N., O'Brien, G., 2015. Geomorphic mapping and taxonomy of fluvial landforms. Geomorphology 248, 273–295. https://doi.org/10.1016/j.geomorph.2015.07.010.

Wheeler, N., Pingram, M., David, B., Marson, W., Tunnicliffe, J., Brierley, G.J., 2022. River adjustments, geomorphic sensitivity and management implications in the Waipā catchment, Aotearoa New Zealand. Geomorphology 410, 108263. https://doi.org/10.1016/j.geomorph.2022.108263.

Whipple, K.X., Tucker, G.E., 1999. Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs. J. Geophys. Res. Solid Earth 104 (B8), 17661–17674. https://doi.org/10.1029/1999JB900120.

Wilson, C.J., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M., 1995. Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. J. Volcanol. Geotherm. Res. 68 (1–3), 1–28. https://doi.org/10.1016/0377-0273(95)00006-G.

Wohl, E., Rathburn, S., Dunn, S., Iskin, E., Katz, A., Marshall, A., Means-Brous, M., Scamardo, J., Triantafillou, S., Uno, H., 2024. Geomorphic context in process-based river restoration. River Res. Appl. 40 (3), 322–340. https://doi.org/10.1002/rra.4236.

Wolman, M.G., 1954. A method for sampling coarse river-bed material. Trans. Am. Geophys. Union 35 (6), 951–956.