Research Article

Insights from long-term variations in gravel riverbed topography as an indicator of vegetation–morphology interactions

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Abstract

Flooding shapes the fluvial landforms by interacting with the development of riparian vegetation. However, the quantitative evaluation of the effects of flooding on fluvial landscapes often relies on snapshot physical parameters regarding hydrological processes, as typified by shear stress on the bed surface. Flooding events over time regulate riparian vegetation, and introducing a long-term perspective into river environmental assessment could complement understanding the vegetation–morphology interactions. In this study, we estimated the long-term variations in channel topography (geomorphological variations) of a gravel riverbed of the Chikuma River. We used cross-sectional profiles of the river channel from 1959 to 2010 as an indicator of vegetation–morphology interactions and examined the effects of geomorphological variations on the fluvial landscape. Our results show that boreal and herbaceous vegetated areas had significant smaller geomorphological variations than those with active channels and gravel bars in the river. Temporal changes in the elevation of the river channel reduced after riparian vegetation was established and riverbed stabilisation could enable riparian forests to develop. We, therefore, identify geomorphological variations as an explanatory factor for fluvial landforms. The index could support river management with a long-term view of channel evolution with vegetation–morphology interaction.

Keywords Channel evolution · Channel topography · Flood disturbance · Riverbed stability · Sedimentation process · Vegetation succession

1 Introduction

Flooding shapes the fluvial landforms and habitat gradients for the establishment and development of riparian vegetation [1–5]. Consequently, the flow regime is critical in the formation of plant communities [6–10], seed banks [11–13] and nutrient dynamics [14–18]. Riparian vegetation consistently adjusts to flood disturbances and sedimentation process (erosion and deposition of sediments) driven by the flooding history to maintain a dynamic equilibrium, with new conditions correlated with the elevation relative to the river water level [19–24]. However, the strong hydrological controls on colonisation, composition and the development of the riparian vegetation are not entirely passive [25–27]. Riparian vegetation increases flow resistance, inducing sediment deposition, bank stability from the root systems and narrower and deeper channels [28–30]. Consequently, fluvial landscapes are formed by vegetation–morphology interactions.

In hydrological approaches, flood pulse is quantified through physical processes, as typified by shear stresses on the bed surface. The shear stress can capture the instantaneous energy proportional to the elevation of the river channel, showing high values with deeper water depth

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and faster flow velocity of a flooding event [31–35]. However, it is challenging to quantify vegetation responses to floods and long-term changes in the fluvial landscape retroactively. In another approach, long-term variations in channel topography could indicate the current fluvial landscape differently from shear stress by reflecting the long-term interaction of physical and biological processes.

A quantitative indicator of the long-term interactions of physical and biological processes in river systems should enhance our understanding of the current fluvial landscapes, reflecting the flooding history and assist river management. First, we estimated the long-term variations in the channel topography of the Chikuma River by using cross-sectional profiles of the river channel from 1959 to 2010 to evaluate vegetation–morphology interactions. We examined the effects of geomorphological variations on the fluvial landscapes (active channel, gravel bar, herbaceous vegetation and riparian forest) regarding the elevation of the river channel. Additionally, we evaluated the relationship between the geomorphological variations and stand basal area of the riparian forest. The long-term variations in channel topography could account for fluvial landscapes and provide a long-term viewpoint for understanding the vegetation–morphology interactions.

2 Materials and methods

2.1 Study sites

The study was conducted at four sites along the Chikuma River, Nagano Prefecture, Central Japan, located at 248.5, 249.5, 250.5 and 251.0 km upstream from the river mouth (Fig. 1). The Chikuma River is the upper part of the longest river in Japan, i.e. the Shinano River (length: 367 km, watershed area: 11,900 km^2), which originate from Mt. Kobushi (2475 m a.s.l.) and flow into the Sea of Japan [36]. The riverbed consists mainly of cobbles (64–256 mm) with fine sediment deposits (< 2 mm in diameter) [37]. The D_{60} (grain diameter at 60% passing the grain size distribution curve) is 50–60 mm [36]. The river slope ranges from 4.5 to 5.0%, and the river width is approximately 400 m between dikes consisting of 30% active channels and 70% sediment bars under base-flow conditions. The boreal vegetation has expanded since the 1980s because of compound cross-sectioning in the channel [38]. At this time, the mean annual precipitation was 890.8 mm, and the mean annual temperature was 11.9 °C at the Ueda meteorological observatory located 8 km from the study site for the years 1981–2010 [39]. The mean water discharge from 1959 to 2010 was 61.6 m^3 s^{-1} at the Kuiseke gauging station, 15 km downstream of the study site [40, 41], and storm events occurred more frequently from June to October (Fig. 2).

2.2 Channel topography

We set four transverse lines 248.5, 249.5, 250.5 and 251.0 km from the river mouth in December 2010 to coincide with river cross-sectional profiles surveyed by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). We then conducted a topographic levelling survey using a laser-controlled land-levelling system to delineate the river cross-sectional profiles at 10-m intervals along these lines (Fig. 1). Moreover, we recorded the river channel condition (active channel, gravel bar, herbaceous vegetation or riparian forest) under the base-flow condition (no precipitation 5 days before the survey) by field observation and aerial photographs. The cross-sectional profiles of the four transverse lines in 1959, 1964, 1969, 1976, 1981, 1982, 1985, 1988, 1992, 1995, 2000 and 2004 were obtained from the MLIT.

We estimated temporal changes in the elevation of the river channel in each survey year (riverbed fluctuation) by using the difference between the elevations at the points of reference and those from previous survey years in each river channel condition (active channels, gravel bars, herbaceous vegetation and riparian forests). Moreover, we classified the location of riparian forests from 25, 50 and 75 percentiles of the stand basal area of riparian forests to consider the differences in the number and size of trees depending on the timing of colonisation and the establishment periods of the riparian forests. The negative and positive values of the riverbed fluctuation refer to the erosion and deposition of sediments, respectively. We represent the long-term variations in river channel elevation at any point on the cross-sectional files between 1959 and 2010 (geomorphological variation) in the following equation:

$$\text{Geomorphological variation} = \left[\Sigma \left(E_i - \mu \right)^2 / (n - 1) \right]^{0.5},$$

where E_i denotes each elevation at each reference point on the same 10-m interval point of the cross-sectional profiles of any year, μ is the average E_i and n is the number of E_i values (here, 13 in number). Higher values of the index indicate larger riverbed topographical changes with the sedimentation process, while lower values indicate more stabilisation of the riverbed.

We estimated the mean water levels from 2006 to 2010 (i.e. the mean elevation of the water surface at the mean discharge above sea level for over 5 years) at each site using the mean-specific discharges, river slopes, cross-sectional areas, Gauckler–Manning coefficient (0.04 sm$^{-1/3}$) and Manning formula [42] to perform a comprehensive analysis of the four study sites by relativising the elevation to the mean water levels at each site. The
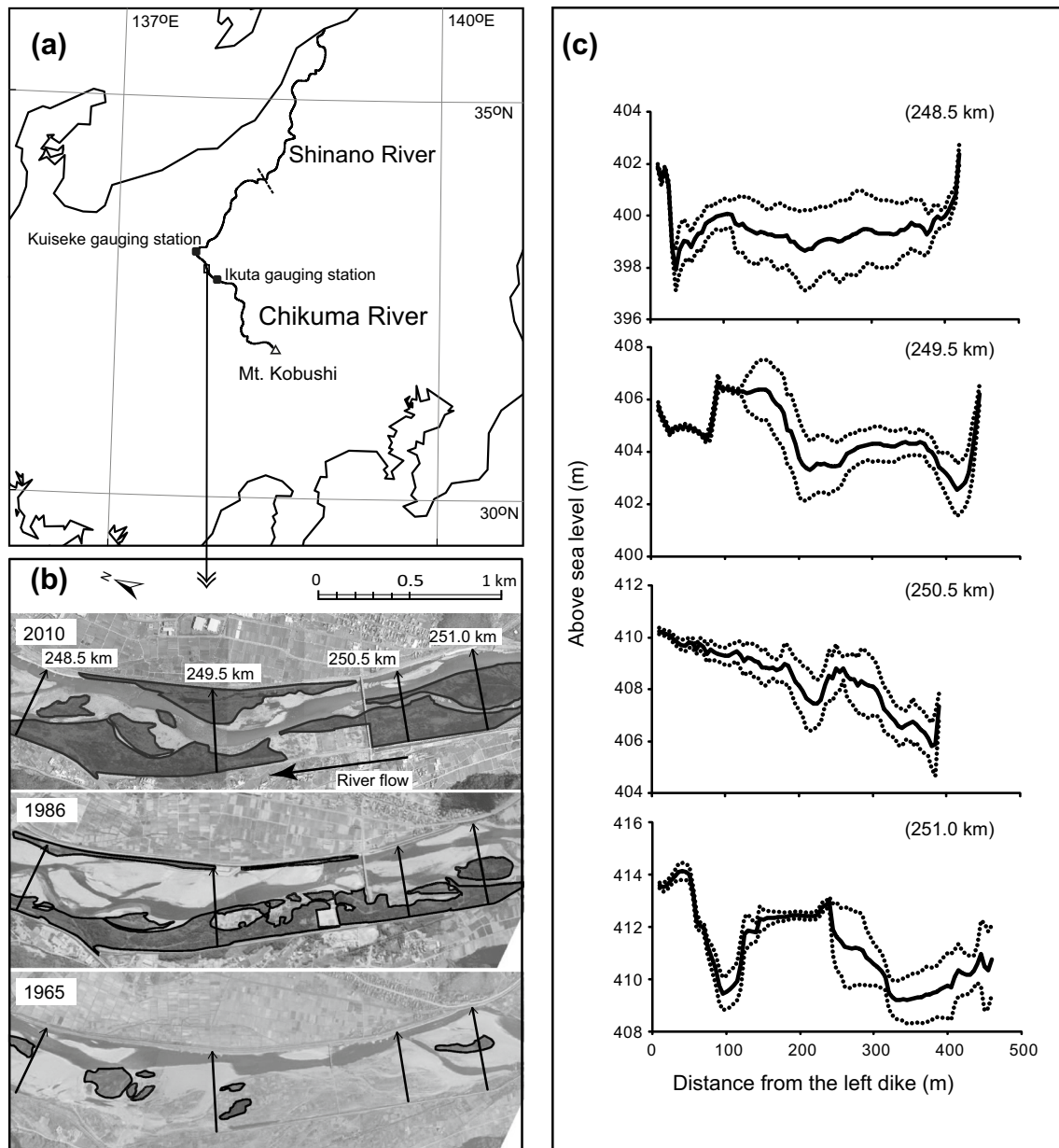
Fig. 1 **a** Locations of study sites in the Chikuma River. **b** Aerial photographs of the study sites in 2010, 1986 and 1965. The arrowed lines and numbers in the river channel represent the cross sections from the left to right dikes and each distance from the river mouth, respectively. The shaded areas indicate the riparian forests. **c** River cross-sectional profiles of the Chikuma River from 1959 to 2010 at the four cross sections, 248.5, 249.5, 250.5 and 251.0 km from the river mouth. The solid and dotted lines indicate the means and standard deviations, respectively

mean-specific discharges from 2006 to 2010 (i.e. the average over 5 years of water discharge per unit area of the upstream watershed) were estimated from each drainage area of the sites and the discharge data from the nearest two gauging stations of the Kuiseke and Ikuta [41]. There is no dam between the gauging stations. The elevation relative to the mean water level at each site was estimated by subtracting the mean water level from the elevation of the river channel.

2.3 Riparian vegetation

We recorded the diameter at a breast height (DBH) of 1.3 m over the bark (9.0 ± 6.0 cm, mean $\pm$ standard deviation, $n = 2740$), and the position of all riparian trees (1510 ± 1110 stems ha^{-1}) along 12 belt transects (10 m $\times$ channel width) at four transverse topographical survey lines (for three replicates per transverse topographical survey line) in December 2010. We then

estimated the basal area of riparian forest from the DBH in each 10×10 m^2 along each transect, and the mean basal area was 14.5 ± 8.6 m^2 ha^{-1}. The most abundant species in the riparian forest were black locust (*Robinia pseudoacacia* L.), constituting $90 \pm 10\%$ of all the trees based on the stand basal area. The other species were willow (*Salix gilgiana* Seemen) and tree of heaven (*Ailanthus altissima* [Mill.] Swingle). The 25, 50 and 75 percentiles of the basal area were 7.5, 12.4 and 19.2 m^2 ha^{-1}, respectively. The herbaceous vegetation consisted mainly of runner reed (*Phragmites japonica* Steud.) and curly top knotweed (*Persicaria lapathifolia* L.).

2.4 Statistical analysis

To determine the differences in geomorphological variation among fluvial landscapes (active channel, gravel bar, herbaceous vegetation and riparian forest), we performed an analysis of covariance (ANCOVA), setting the fluvial landscape as a fixed factor and an elevation relative to the mean water level as a covariate, using all the data on the 12 belt transects at four transverse topographical survey lines. For ANCOVA involving a significant effect of fluvial landscape, multiple mean comparisons were made using Tukey's honest significant difference (HSD) test. The correlation between geomorphological variation and basal area of riparian forests was analysed using Pearson's product–moment correlation coefficient. For all tests, $p < 0.05$ indicated a statistically significant difference. All analyses were conducted using R ver. 3.5.3 [43].

Fig. 3 Changes in riverbed fluctuations of the Chikuma River since ▶ 1959 at **a** active channels ($n = 47$), **b** gravel bars ($n = 47$), **c** herbaceous vegetation ($n = 9$), **d** < 25 percentile of riparian forest basal area ($n = 15$, youngest), **e** 25–50 percentile of riparian forest basal area ($n = 14$), **f** 50–75 percentile of riparian forest basal area ($n = 14$), **g** > 75 percentile of riparian forest basal area ($n = 15$, oldest). Each site category of fluvial landscapes (active channels, gravel bars, herbaceous vegetation and riparian forests) is based on the status of the floodplain in 2010. The variations at riparian forests were classified according to the quartile basal area. The means and standard deviations are shown

3 Results and discussion

The riparian forests are established at relatively small riverbed fluctuations and depressed the riverbed fluctuations compared to active channels, gravel bars and herbaceous vegetation (Fig. 3). Minimal variation (< 0.2 m) in the riverbed fluctuation existed at riparian forests between 2004 and 2010 (Fig. 3) despite that the largest discharge (2076 m^3 s^{-1}) at the gauging station since 1959 was observed on 19 July 2006 (Fig. 2). In contrast, the high-flow event showed large variations in the riverbed fluctuations at active channels, gravel bars and herbaceous vegetation (Fig. 3). The bed stabilisation could be influenced by biological feedback via the binding effects of the roots of the riparian vegetation, increasing the bank's resistance to erosion [5, 26, 28–31]. We found that the riverbed fluctuations decreased earlier with a larger basal area of riparian forests (Fig. 3), suggesting that the development of riparian forests further stabilised the riverbed. The vegetation–morphology interactions could generate positive

Fig. 2 Average daily discharge hydrograph of the Chikuma River at the Kuiseke gauging station from 1959 to 2010. The arrowed lines indicate the topographical surveys. Since the 1980s when the riparian forests were expanded, large floods have occurred periodically
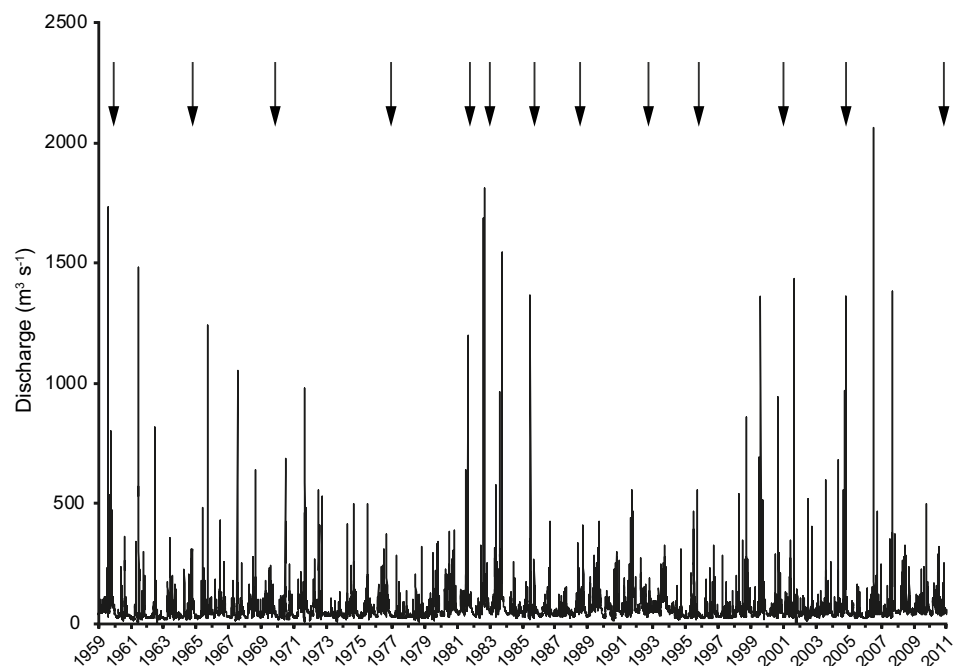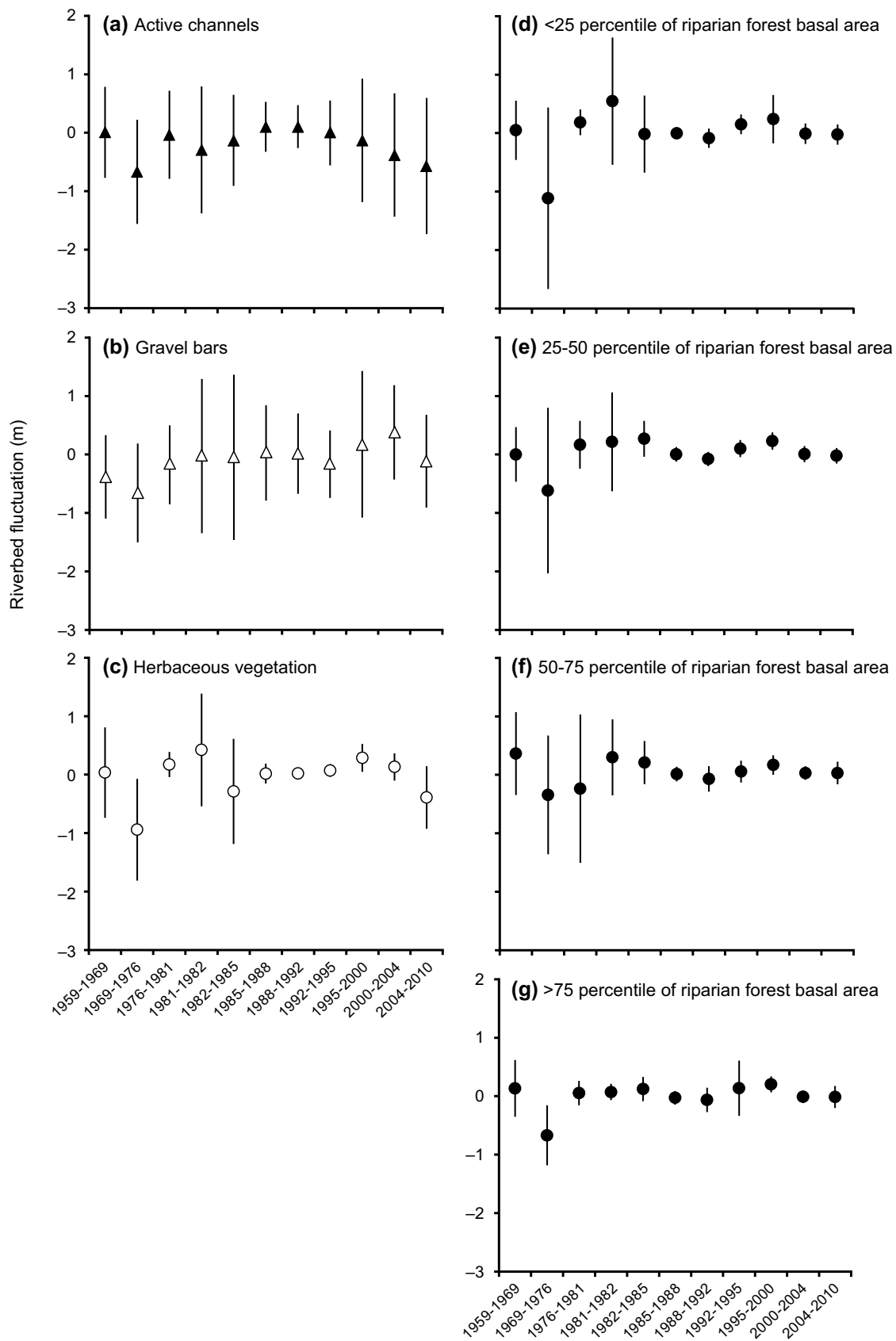
Table 1 Results of ANCOVA for geomorphological variations among fluvial landscapes (active channels, gravel bars, herbaceous vegetation and riparian forests) in the Chikuma River

	Active channels	Gravel bars	Herbaceous vegetation	Riparian forests	df	Fluvial landscape		Elevation	
						F	P	F	P
	($n=47$)	($n=45$)	($n=11$)	($n=58$)					
Geomorphological variation (m)	0.99 ± 0.29^a	0.91 ± 0.40^a	0.59 ± 0.21^b	0.41 ± 0.39^b	4, 156	4.60	0.004	27.21	< 0.001

ANCOVA was performed using the elevation relative to the mean water level as a covariate and the fluvial landscape as a fixed factor. The values represent means and standard deviations. Different letters indicate a significant difference among fluvial landscapes (Tukey's HSD, $p < 0.05$)
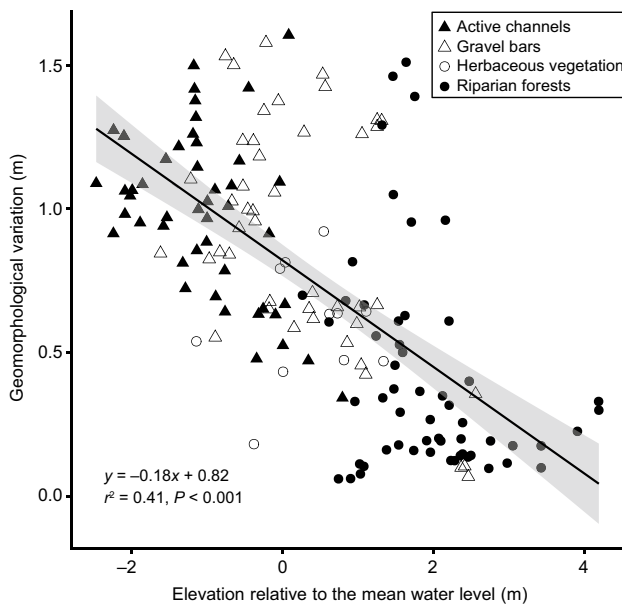

Fig. 4 Relationship between the elevation of river channels relative to the mean water level and the geomorphological variation in the Chikuma River. The solid and shaded regions represent the regression line and a 95% confidence interval, respectively

feedback of bed stabilisation when bed it enables riparian forest to establish.

The ANCOVA results showed that the geomorphological variation as a developed index of long-term variations in the gravel riverbed topography significantly differed among the fluvial landscapes (Table 1). The riparian forests and herbaceous vegetated areas also had significantly smaller geomorphological variation than active channels and gravel bars (Fig. 4 and Table 1). Geomorphological variation was negatively correlated with the elevation of the river channel relative to the mean water level (Table 1). This relationship corresponds with the decrease in the magnitude of shear stress at higher elevations along floodplains during flooding [16, 31, 32]. Consequently, a high-flow event might not even erode sediments or create gravel beds by washing or breaking down riparian forests at higher floodplain elevations because of the binding effects of the roots [26, 28, 44]. Therefore, the riparian forests tend to survive at relatively high floodplain elevations of the compound cross-sectioning in the river channel (Fig. 4), despite the periodic occurrence of large floods (Fig. 2). However, no clear relationship was present between the geomorphological variation and basal area of the riparian forests ($p = 0.486$), probably due to the reproduction by stump sprouting and root suckering of black locust, toppled by floods or logging operations of river management [32, 45]. The geomorphological variation may facilitate the prediction of locations to establish riparian forests; however, it is not a limiting factor for the biomass of species that reproduce asexually.

In contrast to boreal and herbaceous vegetated areas, active channels and gravel bars at lower floodplain elevations maintained the large riverbed fluctuations (Fig. 3) and geomorphological variations (Fig. 4 and Table 1). The large values of the geomorphological variation indicate the short disturbance-free periods for vegetation growth (window of opportunity [46]) and the small binding effects of the roots when vegetation existed in the past. The long-term variations in the channel topography driven by floods suggest a major control of the vegetation colonisation and have the potential to be complementary to the windows of opportunity concept [46, 47]. Additionally, the implications of the magnitude of the developed geomorphological index may differ for each river, which is related to the river slope, grain size and investigation periods and intervals for the river cross-sectional profiles; further investigation is required for this generalisation. When the same mechanisms of the flood-driven sedimentation processes and the bed stabilisation by vegetation colonisation intervene in the geomorphological variations as explanatory factors, long-term variations in channel topography could account for the fluvial landscape and provide a long-term view for understanding the interaction of physical and biological processes in river systems.

On the other hand, the long-term variations in the channel topography are affected by both natural flood disturbances and human activity on river–riparian gradients. These artificial impacts include human-induced channel

alteration on a scale of years to decades, for example, decades of erosion control, gravel mining and other activities for stabilising water and sediment flow in watersheds [48–50]. Further investigation of the causal relationships between the geomorphological variation and temporal changes in the overall sediment yield in river systems and the separation effects of human-induced channel alteration could enable a quantitative analysis for geomorphological variation.

4 Conclusion

The fluvial landscapes (active channels, gravel vars, herbaceous vegetation and riparian forests) formed by the flood history had different long-term variations in the gravel riverbed topography, such as geomorphological variations estimated by cross-sectional profiles over the 50 years. Active channels and gravel bars had large geomorphological variations, and the temporal variations in the channel topography were maintained over the entire period in the river. In contrast, boreal and herbaceous vegetated areas had significantly smaller geomorphological variations than those with active channels and gravel bars and the temporal variations in the channel topography reduced after riparian vegetation was established. The geomorphological variation could indicate vegetation–morphology interactions and introduce a long-term view of the channel evolution under dynamic equilibrium into river environmental assessment.

Compliance with ethical standards

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

References

1. Junk WJ, Bayley PB, Sparks RE (1989) The flood pulse concept in river–floodplain systems. Can Spec Publ Fish Aquat Sci 106:110–127
2. Lytle DA, Poff NL (2004) Adaptation to natural flow regimes. Trends Ecol Evol 19:94–100
3. Tockner K, Lorang MS, Stanford JA (2010) River flood plains are model ecosystems to test general hydrogeomorphic and ecological concepts. River Res Appl 26:76–86
4. Siev S, Yang H, Sok T, Sovannara U, Song L, Kodikara D, Oeurng C, Hul S, Yoshimura C (2018) Sediment dynamics in a large shallow lake characterized by seasonal flood pulse in Southeast Asia. Sci Total Environ 631–632:597–607
5. Politti E, Bertoldi W, Gurnell A, Henshaw A (2018) Feedbacks between the riparian Salicaceae and hydrogeomorphic processes: a quantitative review. Earth Sci Rev 176:147–165
6. Sakio H (2005) Effects of flooding on growth of seedlings of woody riparian species. J For Res 10:341–346
7. Takahashi M, Nakamura F (2011) Impacts of dam-regulated flows on channel morphology and riparian vegetation: a longitudinal analysis of Satsunai River, Japan. Landsc Ecol Eng 7:65–77
8. Rocha J, Hughes SJ, Almeida P, Garcia-Cabral I, Amich F, Crespí AL (2015) Contemporary and future distribution patterns of fluvial vegetation under different climate change scenarios and implications for integrated water resource management. Ecol Res 30:989–1003
9. Xiu C, Gerisch M, Ilg C, Henle K, Ouyang Z (2015) Effects of hydrologic modifications to riparian plant communities in a large river system in northern China. Ecol Res 30:461–469
10. Xia H, Kong W, Li X, Zhang Y, Guo F, Sun OJ (2018) Variations in herbaceous vegetation structures and vegetation–environment relationships from floodplain to terrace along a large semi-humid river. Ecol Res 33:1049–1058
11. Morimoto J, Kominami R, Koike T (2010) Distribution and characteristics of the soil seed bank of the black locust (*Robinia pseudoacacia*) in a headwater basin in northern Japan. Landsc Ecol Eng 6:193–199
12. Hayashi H, Shimatani Y, Shigematsu K, Nishihiro J, Ikematsu S, Kawaguchi Y (2012) A study of seed dispersal by flood flow in an artificially restored floodplain. Landsc Ecol Eng 8:129–143
13. Osunkoya OO, Ali S, Nguyen T, Perrett C, Shabbir A, Navie S, Belgeri A, Dhileepan K, Adkins S (2014) Soil seed bank dynamics in response to an extreme flood event in a riparian habitat. Ecol Res 29:1115–1129
14. Akamatsu F, Shimano K, Denda M, Ide K, Ishihara M, Toda H (2008) Effects of sediment removal on nitrogen uptake by riparian plants in the higher floodplain of the Chikuma River, Japan. Landsc Ecol Eng 4:91–96
15. Ohte N (2012) Implications of seasonal variation in nitrate export from forested ecosystems: a review from the hydrological perspective of ecosystem dynamics. Ecol Res 27:657–665
16. Asaeda T, Rashid MH, Bakar RA (2015) Dynamic modelling of soil nitrogen budget and vegetation colonization in sediment bars of a regulated river. River Res Appl 31:470–484
17. Jiang Q, Xu Z, Hao Y, Dong H (2017) Dynamics of soil labile carbon and nitrogen pools in riparian zone of Wyaralong Dam in Southeast Queensland, Australia. J Soils Sediments 17:1030–1044
18. Pinay G, Black VJ, Planty-Tabacchi AM, Gumiero B, Décamps H (2000) Geomorphic control of denitrification in large river flood plains soils. Biogeochemistry 50:163–182
19. Dixon MD, Turner MG, Jin C (2002) Riparian tree seedling distribution on Wisconsin River sandbars: controls at different spatial scales. Ecol Monogr 72:465–485
20. Harner MJ, Stanford JA (2003) Differences in cottonwood growth between a losing and a gaining reach of an alluvial floodplain. Ecology 84:1453–1458
21. Cooper DJ, Dickens J, Hobbs NT, Christensen L, Landrum L (2006) Hydrologic, geomorphic and climatic processes controlling willow establishment in a montane ecosystem. Hydrol Process 20:1845–1864
22. Merritt DM, Scott ML, Poff NL, Auble GT, Lytle DA (2010) Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. Freshw Biol 55:206–225
23. Nilsson C, Jansson R, Kuglerová L, Lind L, Ström L (2013) Boreal riparian vegetation under climate change. Ecosystems 16:401–410

24. Catford JA, Morris WK, Vesk PA, Gippel CJ, Downes BJ (2014) Species and environmental characteristics point to flow regulation and drought as drivers of riparian plant invasion. Divers Distrib 20:1084–1096

25. Bertoldi W, Drake NA, Gurnell AM (2011) Interactions between river flows and colonizing vegetation on a braided river: exploring spatial and temporal dynamics in riparian vegetation cover using satellite data. Earth Surf Process Landf 36:1474–1486

26. Gurnell AM, Bertoldi W, Corenblit D (2012) Changing river channels: the roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. Earth Sci Rev 111:129–141

27. Surian N, Barban M, Ziliani L, Monegato G, Bertoldi W, Comiti F (2015) Vegetation turnover in a braided river: frequency and effectiveness of floods of different magnitude. Earth Surf Process Landf 40:542–558

28. Abernethy B, Rutherfurd ID (2001) The distribution and strength of riparian tree roots in relation to riverbank reinforcement. Hydrol Process 15:63–79

29. Gran K, Paola C (2001) Riparian vegetation controls on braided stream dynamics. Water Resour Res 37:3275–3283

30. Gran KB, Tal M, Wartman ED (2015) Co-evolution of riparian vegetation and channel dynamics in an aggrading braided river system, Mount Pinatubo, Philippines. Earth Surf Process Landf 40:1101–1115

31. Friedman JM, Auble GT (1999) Mortality of riparian box elder from sediment mobilization and extended inundation. Regul Rivers Res Manag 15:463–476

32. Asaeda T, Gomes PIA, Takeda E (2010) Spatial and temporal tree colonization in a midstream sediment bar and the mechanisms governing tree mortality during a flood event. River Res Appl 26:960–976

33. Kobayashi S, Amano K, Nakanishi S (2013) Riffle topography and water flow support high invertebrate biomass in a gravel-bed river. Freshw Sci 32:706–718

34. Lague D (2014) The stream power river incision model: evidence, theory and beyond. Earth Surf Process Landf 39:38–61

35. Shimizu Y, Nelson J, Ferrel KA, Asahi K, Giri S, Inoue T, Iwasaki T, Jang C-L, Kang T, Kimura I, Kyuka T, Mishra J, Nabi M, Patsinghasanee S, Yamaguchi S (2020) Advances in computational morphodynamics using the International River Interface Cooperative (iRIC) software. Earth Surf Process Landf 45:11–37

36. Ministry of Land, Infrastructure, Transport and Tourism, Japan (2009) Fundamental river management policy. http://www.mlit.go.jp/river/basic_info/jigyo_keikaku/gaiyou/seibi/index.html (**in Japanese**)

37. Akamatsu F, Ide K, Shimano K, Toda H (2011) Nitrogen stocks in a riparian area invaded by N-fixing black locust (*Robinia pseudoacacia* L.). Landsc Ecol Eng 7:109–115

38. Okino T, Chikuma River Research Group (2006) River ecosystems formed by flooding. The Shinano Mainichishinbun, Nagano (**in Japanese**)

39. Japan Meteorological Agency (2020) Climatic statistics. http://www.jma.go.jp/jma/index.html

40. Ministry of Land, Infrastructure, Transport and Tourism, Japan (2007) Precipitation and river discharge data base. Japan River Association, Tokyo

41. Ministry of Land, Infrastructure, Transport and Tourism, Japan (2020) Water information system. http://www1.river.go.jp/

42. Gordon ND, McMahon TA, Finlayson BL, Gippel CJ, Nathan RJ (2004) Stream hydrology: an introduction for ecologists. Wiley, West Sussex

43. R Core Team (2019) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

44. Gurnell A (2014) Plants as river system engineers. Earth Surf Process Landf 39:4–25

45. Akamatsu F, Makishima M, Taya Y, Nakanishi S, Miwa J (2014) Evaluation of glyphosate application in regulating the reproduction of riparian black locust (*Robinia pseudoacacia* L.) after clear-cutting, and the possibility of leaching into soil. Landsc Ecol Eng 10:47–54

46. Balke T, Herman PMJ, Bouma TJ (2014) Critical transitions in disturbance-driven ecosystems: identifying windows of opportunity for recovery. J Ecol 102:700–708

47. Hu Z, van Belzen J, van der Wal D, Balke T, Wang ZB, Stive M, Bouma TJ (2015) Windows of opportunity for salt marsh vegetation establishment on bare tidal flats: the importance of temporal and spatial variability in hydrodynamic forcing. J Geophys Res Biogeosci 120:1450–1469

48. Corenblit D, Steiger J, Tabacchi E (2010) Biogeomorphologic succession dynamics in a Mediterranean river system. Ecography 33:1136–1148

49. Swanson BJ, Meyer GA, Coonrod JE (2011) Historical channel narrowing along the Rio Grande near Albuquerque, New Mexico in response to peak discharge reductions and engineering: magnitude and uncertainty of change from air photo measurements. Earth Surf Process Landf 36:885–900

50. Formann E, Egger G, Hauer C, Habersack H (2014) Dynamic disturbance regime approach in river restoration: concept development and application. Landsc Ecol Eng 10:323–337