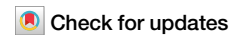


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# Rapid fluvial response to meter-scale coseismic coastal uplift during the 2024 Noto Peninsula earthquake



Takayuki Takahashi<sup>1</sup>✉, Takuro Ogura<sup>2,3</sup>, Kotaro Iizuka<sup>3,4</sup>, Yoshiya Iwasa<sup>5</sup>,  
Yuichi S. Hayakawa<sup>3,6</sup>, Tatsuto Aoki<sup>7</sup> & Nobuhisa Motta<sup>8</sup>

The response of river profiles to relative base-level change is a key topic in earth surface processes, but observations capturing these changes on unconsolidated deposits at a 1–10 years timescales are scarce. We monitored geomorphic changes at the Hakka River mouth after the 3.5-meter base-level fall caused by coseismic uplift of the 2024 Noto Peninsula earthquake, Japan. Utilizing uncrewed aerial vehicle surveys, we documented a maximum vertical riverbed lowering of 2 m and knickpoint upstream migration of 770-m within the first-year post-earthquake, primarily triggered by erosion during major floods that followed the earthquake. Our findings demonstrate that fluvial terraces can develop within a year or less, following co-seismic coastal uplift. However, the river has not yet reached a renewed graded stage because riverbed armoring resulting from sediment sorting during incision currently inhibits further incision. We suggest that the abandonment of alluvial plains and lowering and widening of the riverbed in the lower 10-km segment will continue over the next decade.

The interaction between tectonics and earth-surface processes, particularly fluvial dynamics, is fundamental to understanding the evolution of geomorphic landscapes<sup>1</sup>. River profiles are strongly controlled by base level. Vertical base-level changes are induced by tectonic crustal deformation and eustatic-isostatic sea-level fluctuations. For instance, local uplift or global cooling can trigger a relative base-level lowering, leading to downcutting (incision) in the lower river reaches.

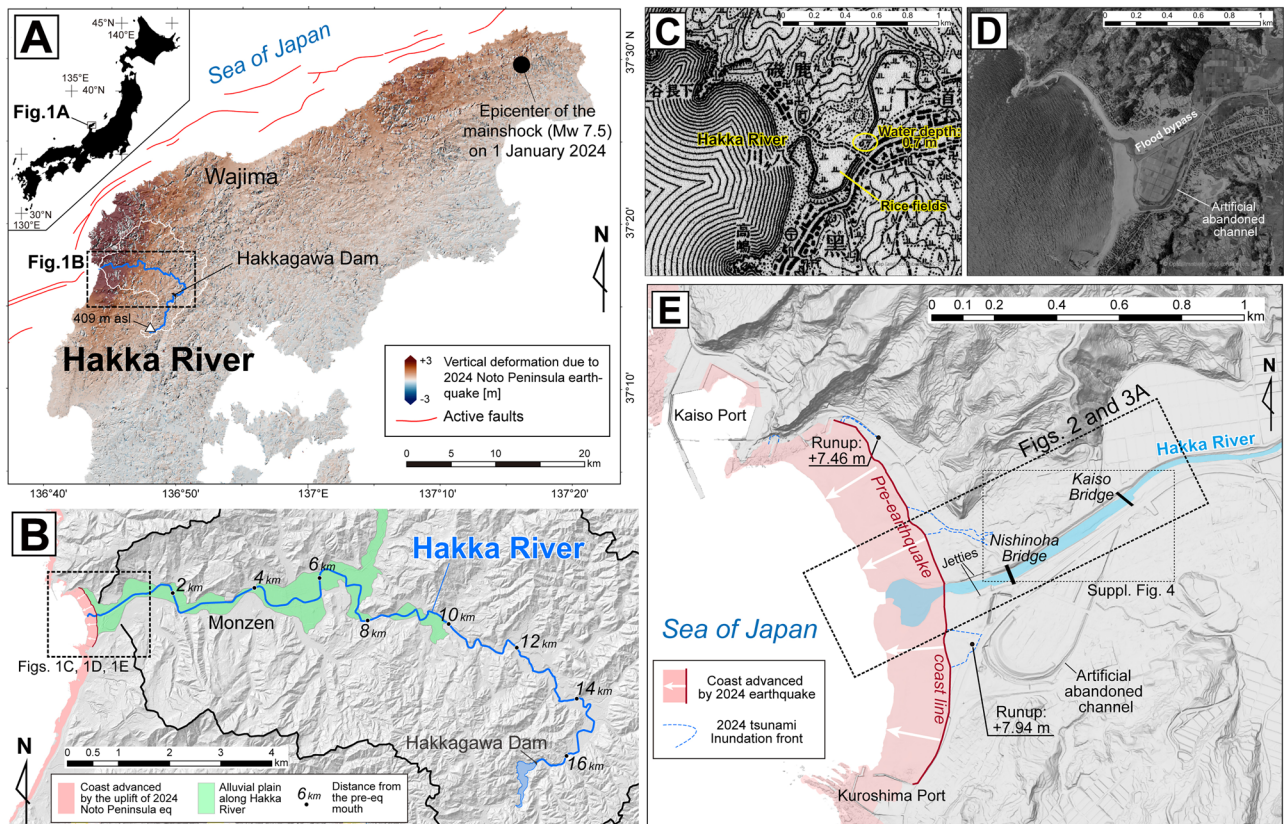
Incision initiated by local base-level drop proceeds through the formation and upstream migration of knickpoints<sup>2</sup>. Quantifying the retreat rate of knickpoints, often manifested as waterfalls or rapids, is crucial for understanding the fluvial response to external forcings, such as tectonic and climatic changes<sup>3,4</sup>. The horizontal migration rates of knickpoints in bedrock rivers are primarily controlled by water discharge, sediment flux, bedrock hardness, and knickpoint size and shape<sup>4–8</sup>, meanwhile the vertical rates in active tectonic settings are controlled by fault slip rate<sup>3</sup>.

Knickpoint retreat also leads to floodplain abandonment and subsequent fluvial terrace formation. Fluvial terraces, similar to marine terraces, often record base-level changes, allowing researchers to reconstruct paleoclimate changes and crustal deformation histories based on the elevations and ages of their treads<sup>7</sup>. However, the synchronicity between the formation

of coastal fluvial terraces continuing from marine terraces and the base-level lowering event that initiates marine terrace formation remains unverified, primarily due to the lack of detailed ages and preservation issues in fluvial and marine terraces<sup>3,9</sup>.

One approach to address this problem is to observe knickpoint migration over short timescales ( $10^0$ – $10^1$  years). While numerous flume experiments and models have been conducted<sup>10–13</sup>, direct field observations of the migration process are scarce. Events involving sudden base-level lowering, such as immediate coseismic uplift, surface rupture, or rapid lake-level drops, offer rare opportunities to observe the river profile response to relative base-level lowering and to quantify its rate<sup>14–16</sup>. A few studies have documented the response of river profiles and avulsion to coseismic surface rupture, including the 1959 Hebgen Lake Fault, US<sup>17</sup>; 1999 Chi-Chi, Taiwan<sup>18–22</sup>; 2008 Wenchuan, China<sup>23</sup>; and 2016 Kaikōura, NZ<sup>24</sup>. In most cases, knickpoints formed on bedrock rivers due to fault rupture migrated rapidly upstream within <10 years post-earthquake. However, observations of fluvial response to coseismic coastal uplift are more limited, with only a report relating to 1964 Alaska earthquake<sup>25</sup> to the best of our knowledge. Although a fast vertical incision followed by lateral erosion was observed along small Alaskan rivers flowing on unconsolidated deposits at the coast

<sup>1</sup>International Research Institute of Disaster Science, Tohoku University, Sendai, Japan. <sup>2</sup>Graduate School of Social Sciences, Hitotsubashi University, Tokyo, Japan. <sup>3</sup>Center for Spatial Information Science, The University of Tokyo, Tokyo, Japan. <sup>4</sup>School of Human Science and Environment, University of Hyogo, Himeji, Japan. <sup>5</sup>Faculty of Education, University of Teacher Education Fukuoka, Munakata, Japan. <sup>6</sup>Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Japan. <sup>7</sup>Institute of Human and Social Sciences, Kanazawa University, Kanazawa, Japan. <sup>8</sup>Graduate School of Education, Okayama University, Okayama, Japan. ✉e-mail: [t-takahashi@tohoku.ac.jp](mailto:t-takahashi@tohoku.ac.jp)



**Fig. 1 | Overview of the Noto Peninsula and Hakka River.** **A** Landform of Noto Peninsula displayed with the amount of vertical displacement by 2024 Noto Peninsula earthquake<sup>31</sup>. Only submarine active faults<sup>65,66</sup> related to the 2024 Noto Peninsula earthquake are displayed. The index map was made using PyGMT<sup>67</sup>. **B** Landforms of Hakka River drainages. Basemap is from 1-m mesh DEM of Geospatial information Authority of Japan (GSI)<sup>68</sup>. **C** Landform around Hakka River

mouth in 1910. From the former 1:50,000 Topological map of “Tsurugiji” in 1910<sup>42</sup> with the translation texts. **D** Orthophoto around the Hakka River mouth in 1960s. Edited from the GSI Tiles<sup>48</sup>. **E** Around the mouth of Hakka River. Coastal advanced (dried-up) area by coseismic uplift is from the data of Geographical Association of Japan<sup>39</sup>. The runup height and inundation area of the tsunami caused by 2024 Noto Peninsula earthquake is from Iwasa et al.<sup>50</sup>. Basemap is based on 1-m DEM of GSI<sup>68</sup>.

with >10 m coseismic uplift<sup>25</sup>, the monthly or daily landform changes were not fully recorded. Consequently, the formation processes of seafront fluvial terraces remain unclear, despite their potential to record coastal uplift histories. Furthermore, while knickpoint migration in unconsolidated deposits has been observed in a few cases<sup>16,25–29</sup>, the phenomenon is poorly understood due to limited field examples.

The 2024 Noto Peninsula earthquake ( $M_w$  7.5), which triggered a maximum coastal uplift of over 5 m<sup>30–33</sup>, provided a unique opportunity to observe fluvial response to meter-scale base-level lowering over short timescales. Nine months after the earthquake, the 2024 Okunoto heavy rainfall event triggered a flood, resulting in active fluvial erosion and sediment transport in the Noto Peninsula rivers<sup>34</sup>. Moreover, recent advancements in remote sensing technologies, including synthetic aperture radar (SAR), uncrewed aerial vehicle (UAV)-based photogrammetry, light detection and ranging (LiDAR), and real time kinematic global navigation satellite system (RTK-GNSS), enable high-definition landform measurements immediately after hazard events, immediately capturing daily to annual geomorphic changes<sup>16,35</sup>. High-definition and frequent measurement of post-seismic fluvial landform changes in the Noto Peninsula’s rivers is key to revealing the processes of fluvial response to base-level changes over short timescales.

We observed incision processes around the mouth of the Hakka River, located on the northwestern Noto Peninsula and uplifted by nearly 4 m, during the first year after the 2024 Noto Peninsula earthquake (Fig. 1). Through measurement and observation of the fluvial landform and deposits, we recorded knickpoint migration nearly 1 km upstream of the new river mouth in less than one year, which signifies rapid incision and episodic floodplain abandonment. Our results imply that a meter-scale

base-level drop can induce knickpoint migration upstream within an alluvial plain on a timescale of 1–10 years, which is recorded in the landform as fluvial terraces with a negligible time lag in geological timescales.

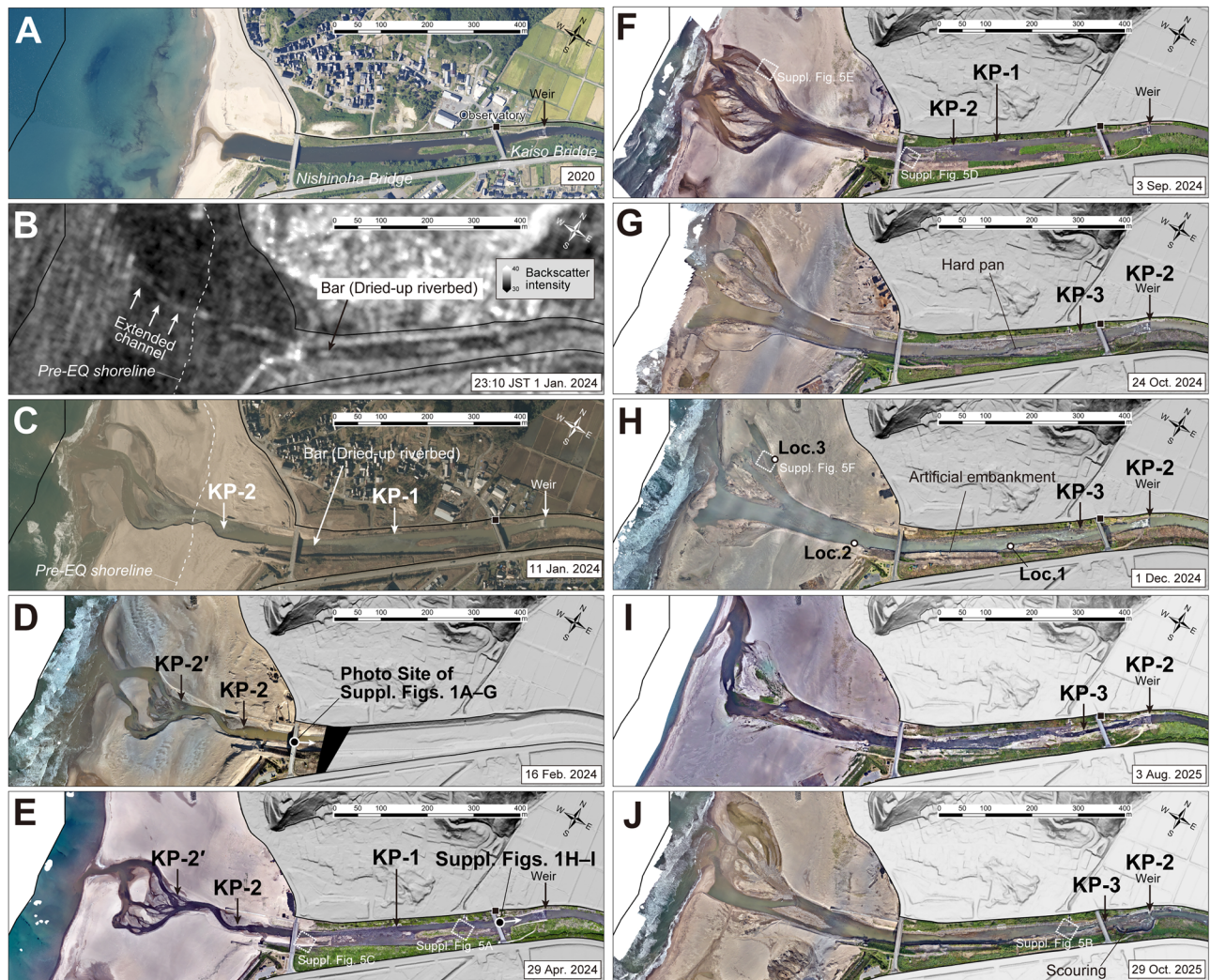
## Results and discussion

### Regional settings and hazards

The 2024 Noto Peninsula earthquake ( $M_w$  7.5) occurred at 16:10 JST on 1st January 2024 along the south-side-up reverse faults striking NE-SW and triggered the uplift in the northern and western area of the peninsula with a maximum uplift amount of 5.2 m<sup>31,32</sup>. Coastline advance transformed the modern bench and beach into a marine terrace level<sup>30–33</sup> and extended the channels of rivers whose mouths are located in the uplifted area in the northern part of the peninsula<sup>36</sup>. The coastline advance occurred concurrently with the earthquake before tsunami waves reached the coast<sup>37</sup>.

Furthermore, the so-called Okunoto heavy rain occurred on 20–22 September, 8.5 months after the Noto Peninsula earthquake, with a maximum accumulated precipitation of 501.0 mm in the Wajima area<sup>38</sup> (Fig. 1A), triggering floods on most rivers in the northern Noto Peninsula<sup>34</sup>.

The Hakka River, one of the largest rivers in the northwestern Noto Peninsula, has a drainage area of ~70 km<sup>2</sup> and a length of just over 20 km (Fig. 1A and B). Coseismic uplift of 3.9 m was measured at Kaisei Port, ~800 m north of the river mouth<sup>30</sup>. Coastal advance reached a maximum width of ~200 m at the shoal beach near Kuroshima Port (Fig. 1)<sup>31,36,39,40</sup>. Since the Hakka River is the largest river significantly impacted by both coseismic uplift and Okunoto heavy rain (3-day accumulated precipitation of 252.5 mm recorded near the river mouth in Monzen Town<sup>38</sup>), we consider it the most suitable field site to investigate fluvial response to coseismic uplift (Fig. 1).



**Fig. 2 | Orthophotos and a SAR image around the mouth of the Hakka River.** A GSI aerial orthophoto taken in 2020<sup>48</sup>; B An ALOS-2/Palsar-2 image at 23:10 JST (14:10 UTC), 1 January 2024<sup>40</sup>; C GSI aerial orthophoto on 11 January 2024<sup>48</sup>;

D Orthophoto on 16 February 2024<sup>49</sup>; E 29 April 2024; F 3 September 2024; G 24 October 2024; H 1 December 2024; I 3 August 2025; J 29 October 2025. The detailed information of each image was listed in Supplementary Table 3.

The drainage of the Hakka River peaks at an elevation of 409 m (Fig. 1A) and is mainly composed of volcanic and sedimentary rocks of Miocene age<sup>41</sup>. A gentle alluvial plain with a width of hundreds of meters is developed along the lower 10 km segment of the Hakka River (Fig. 1B). A topographical map in 1910<sup>42</sup>, before noticeable artificial deformation, displays the free-meandering channel of the Hakka River, the northward deviation of the Hakka River mouth, the land used for rice fields and the sandy ground around the mouth (Fig. 1C). These can be interpreted as a dune barrier, common along the Japan Sea<sup>43</sup>, and a wetland developed on a buried lagoon. The lowermost segment of the Hakka River was artificially straightened after a large flood occurred in 1959<sup>44</sup> (Fig. 1D). An artificial dam site is located 17 km upstream from the mouth (Fig. 1A and B) and some artificial structures are installed across the Hakka River channel on the alluvial plain (Fig. 1B). The riverbed before the earthquake was gentle and unlined, although both banks of this segment are artificially concreted<sup>45</sup>. There is a pair of jetties on both banks around the mouth, but the extended channel of post-earthquake flows on the dried-up beach without any artificial structures (Figs. 1E and 2A).

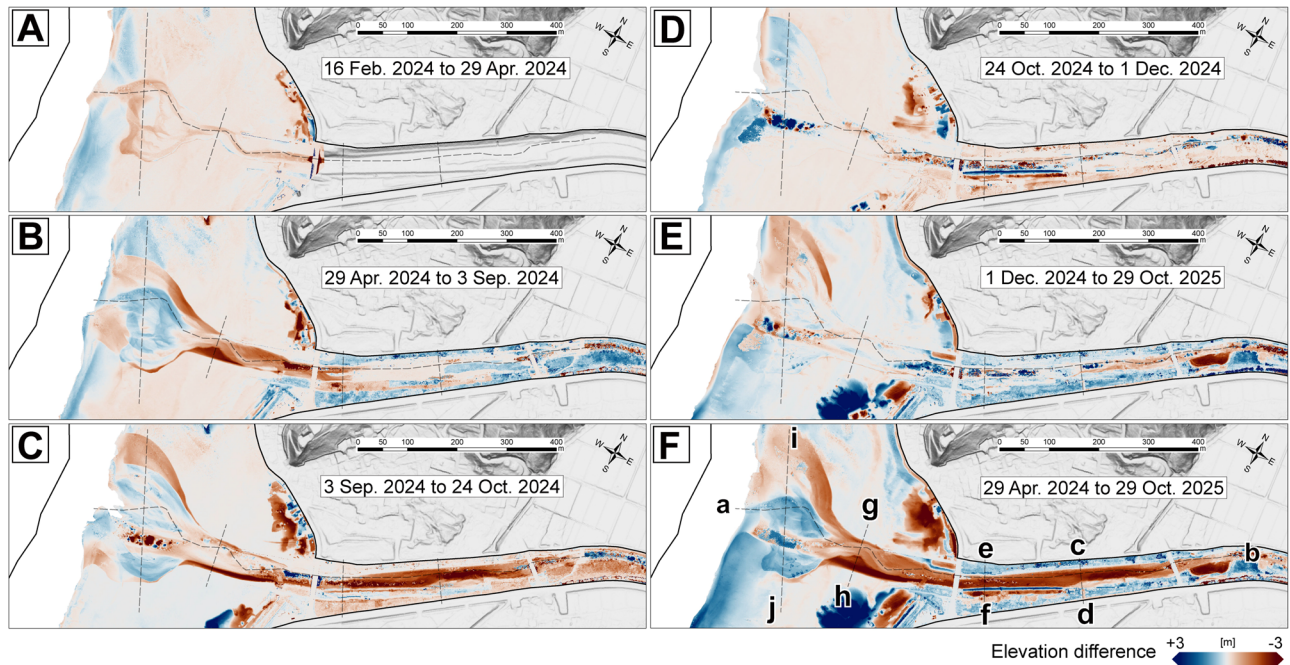
We monitored landform changes in the lowermost 1 km channel segment, starting from the post-earthquake river mouth (Figs. 1 and 2). This segment is spanned by two bridges: the upstream Kaiso Bridge and the downstream Nishinoha Bridge. A water-level monitoring station is situated on the right bank adjacent to the Kaiso Bridge (Figs. 1 and 2). The 1910

topographic map<sup>42</sup> indicates a Hakka River water depth of 0.7 m (Fig. 1C). The regional tidal range is only approximately 0.4 m<sup>30,46</sup>, therefore the effects of daily tidal change can be ignored.

### Geomorphic changes in the lower Hakka River after the earthquake

We tracked fluvial incision around the Hakka River mouth immediately post-earthquake using SAR and aerial photographs and UAV-based landform measurements. At first, a PALSAR-2 SAR image taken at 23:10 JST (14:10 UTC) on 1 January 2024<sup>47</sup> shows the extended channel on the emerged beach and confirms that the dried-up riverbed was formed upstream of Nishinoha Bridge, which cannot be found in the orthophoto of pre-earthquake (Fig. 2A, B). Two lips, interpreted as slope-break knick-points, were identified on the channel at around 730 m (KP-1) and 300–350 m (KP-2) upstream from the mouth in the orthophoto taken on 11 January (Fig. 2).

On 16 February 2024, KP-1 and KP-2 were confirmed at similar positions as on 11 January. By this time, the channel was flowing between the right bank and the artificial structure at the center of the riverbed, and the large parts of riverbed immediately upstream of the Nishinoha Bridge had dried up due to water-surface lowering (Fig. 2 and Supplementary Fig. 1A). This has been confirmed in the SAR image taken 7 hours after the earthquake and suggests that KP-1 was located 730 m upstream from the



**Fig. 3 | Changes in elevation around the Hakka River mouth.** Elevation differences were calculated by DEMs. **A** Between 16 February 2024<sup>59</sup> and 29 April 2024; **B** 29 April 2024 and 3 September 2024; **C** 3 September 2024 and 24 October 2024; **D** 24 October 2024 and 1 December 2024; **E** 1 December 2024 and 29 October 2025; **F** 29

April 2024 and 29 October 2025. The water surface area of the sea with incorrect relative elevation were masked. Note that the reddish and bluish colors indicate the elevation lowering and increasing, respectively.

mouth within just 7 hours of post-earthquake. Although KP-2 is hard to identify in the SAR image, its lip was found at 350 m upstream from the post-earthquake mouth, approximately 70 m upstream of the pre-earthquake shoreline on the GSI orthophoto taken on 11 January<sup>48</sup> (Fig. 2C). By February, KP-2—identifiable as a lip in the orthophoto and longitudinal profile—had migrated 50 m further up along the talweg, 120 m from the pre-earthquake shoreline (Figs. 2D and 3A). The channel segment downstream of KP-2 exhibited incised-meandering (Fig. 2D) and had several minor lips around the pre-earthquake shoreline and an additional knickpoint (KP-2') at around 250 m upstream of the post-earthquake mouth (Figs. 2D, 2E and 4A).

The positions of KP-1 and KP-2 remained largely unchanged from February to 29 April (Figs. 2D, 2E and 3A). The riverbed upstream of KP-1 maintained a gentle longitudinal profile, while the downstream segment had a slope of ~4% (Fig. 4A). The river channel position downstream of KP-2 also remained stable during this two-month period; however, the uniform lowering of the riverbed elevation in this segment from February to April is inferred to be due to just a water-discharge decrease.

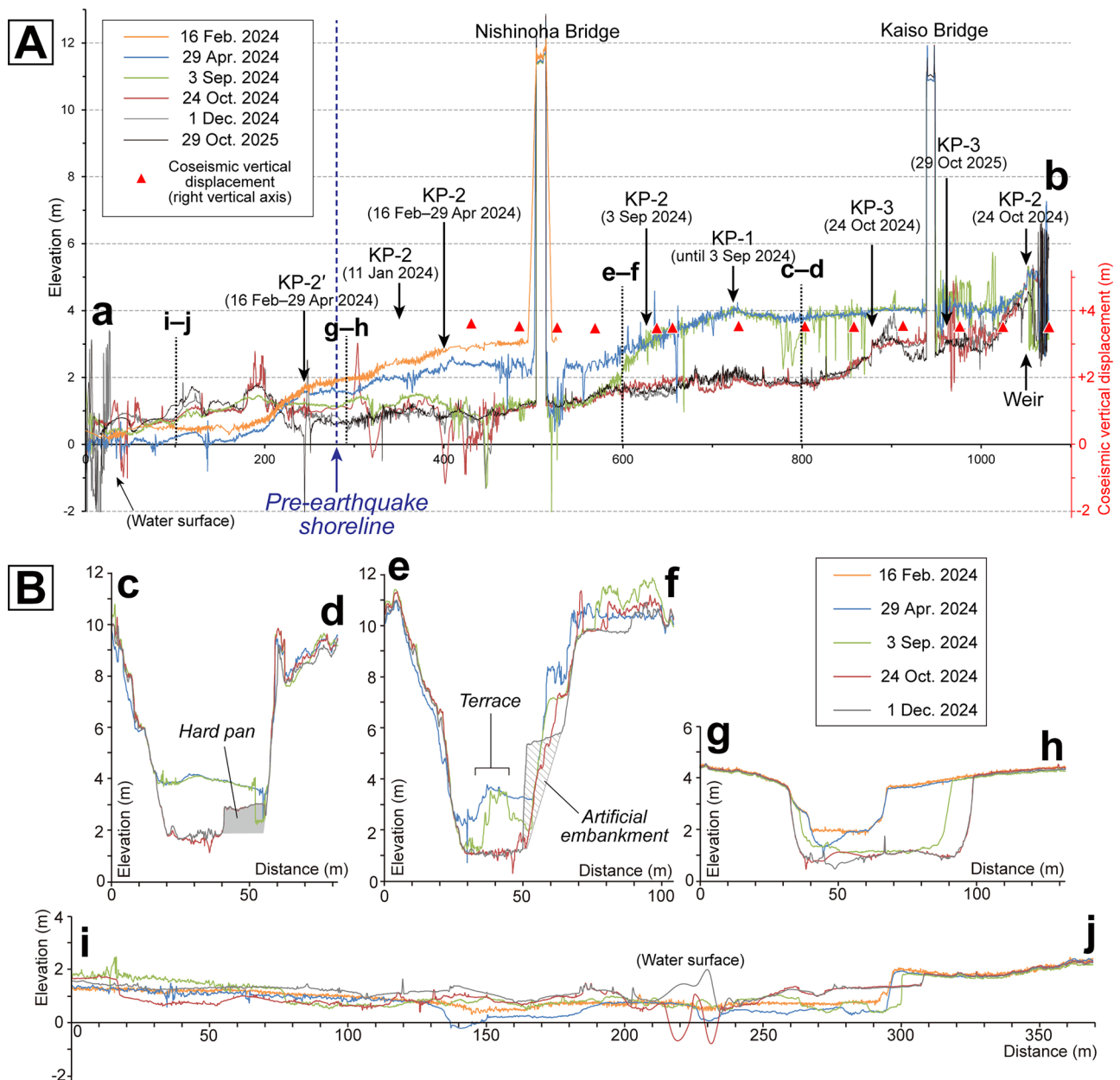
While KP-1's position remained stable until 3 September, KP-2 continued its upstream migration, approaching KP-1 (Fig. 4A). Subsequently, the riverbed downstream of KP-2 was incised to form a terrace tread (Figs. 2F, 3B, 4, Supplementary Fig. 1 and Supplementary Fig. 5D). Water discharge increased multiple times between April and September, peaking at over 60 m<sup>3</sup>/s during the 24 July rainfall event (Supplementary Fig. 2). These summer rainfall events drove upstream migration of KP-2 and KP-2' by several hundred meters and leading to their convergence but did not trigger the migration of KP-1.

As KP-2 migrated upstream, the lower meandering channel transformed into a broad, linear gravel-bed channel (Fig. 2). The river-mouth deviation observed on 29 April was reduced, and fan-shaped distributary channel networks subsequently appeared (Fig. 2F). Furthermore, aggradation of ~1 m occurred around the mouth between 29 April and 3 September, probably resulting from sediment generated by the incision associated with the upstream migration of KP-2 and KP-2' (Fig. 4A). This aggradation and knickpoints migration caused a smoother longitudinal profile in the

segment downstream of Nishinoha Bridge (Fig. 4A). The longitudinal profile of 3 September intersects with that of 29 April a few tens of meters downstream of the pre-earthquake shoreline. Downstream of KP-2, the September profile exhibits a gentler gradient compared to the April profile (Fig. 4A).

The Okunoto heavy rain on 20–22 September 2024 increased the Hakka River's maximum water discharge to around 100 m<sup>3</sup>/s on 21 September (Supplementary Fig. 2). This flood event accelerated the upstream expansion of incision and removed the riverbed sediments including the terrace adjacent to the Nishinoha Bridge (Fig. 2G and Supplementary Fig. 1). A maximum incision of 2 m occurred downstream of the artificial weir located 1 km upstream from the post-earthquake mouth, implying that the slope-break knickpoints migrated >300 m upstream and were halted by this weir during the flood (Figs. 2, 3 and 4A). A new small knickpoint (KP-3) appeared at the Kaiso Bridge following the heavy rain (Fig. 4A). The channel cross-section widened due to further lateral erosion, reaching a width of >60 m at cross-section g–h (Fig. 4A). Even in the segment between the Kaiso and Nishinoha bridges, which is artificially constrained, part of the left bank was scoured (Fig. 2H and Supplementary Fig. 1E). Although driftwood accumulated around the mouth, the aggradation caused by the Okunoto heavy rain was less significant than that observed between April and September. Despite the Okunoto heavy rain in September 2024 being the largest flood event of one year after the earthquake (Supplementary Fig. 2) and triggering remarkable incision even in this reach (Fig. 3), the sediment supplied to the mouth did not significantly contribute to aggradation, appearing to have been thinly deposited or discharged directly into the sea. Although numerous landslides were triggered by the earthquake and this heavy rain, additional coarse sediment supply to this segment seems to be limited due to the gentle slope and artificial structures across the channel in the middle reaches of Hakka River.

Subsequently, the channel and riverbed morphology remained almost unchanged except for artificial deformation at the banks related to repairs before early August 2025 (Figs. 2G, 3, 4A and Supplementary Fig. 1). The shoreline slightly retreated due to the wave erosion by 1 December (Fig. 2G).



**Fig. 4 | Longitudinal and cross-sectional profiles and their changes.** **A** Longitudinal profile (a–b); **B** Cross-sectional profiles (c–d, e–f, g–h, i–j). The positions of section lines were indicated in Fig. 3. Note that the model partly captured the water surface with incorrect elevation.

Furthermore, a heavy rain in mid-August 2025 triggered the scouring beside the artificial weir and the riverbed lowering in the segment upstream of KP-3 (Figs. 2J, 3E, 3F and Supplementary Fig. 2). The river mouth shifted northward, then lateral erosion occurred at the right bank around the mouth (Figs. 2J and 3E). The water-level data at the observatory of Kaiso Bridge apparently reflects this riverbed lowering due to the passage of KP-3 (Supplementary Fig. 2B).

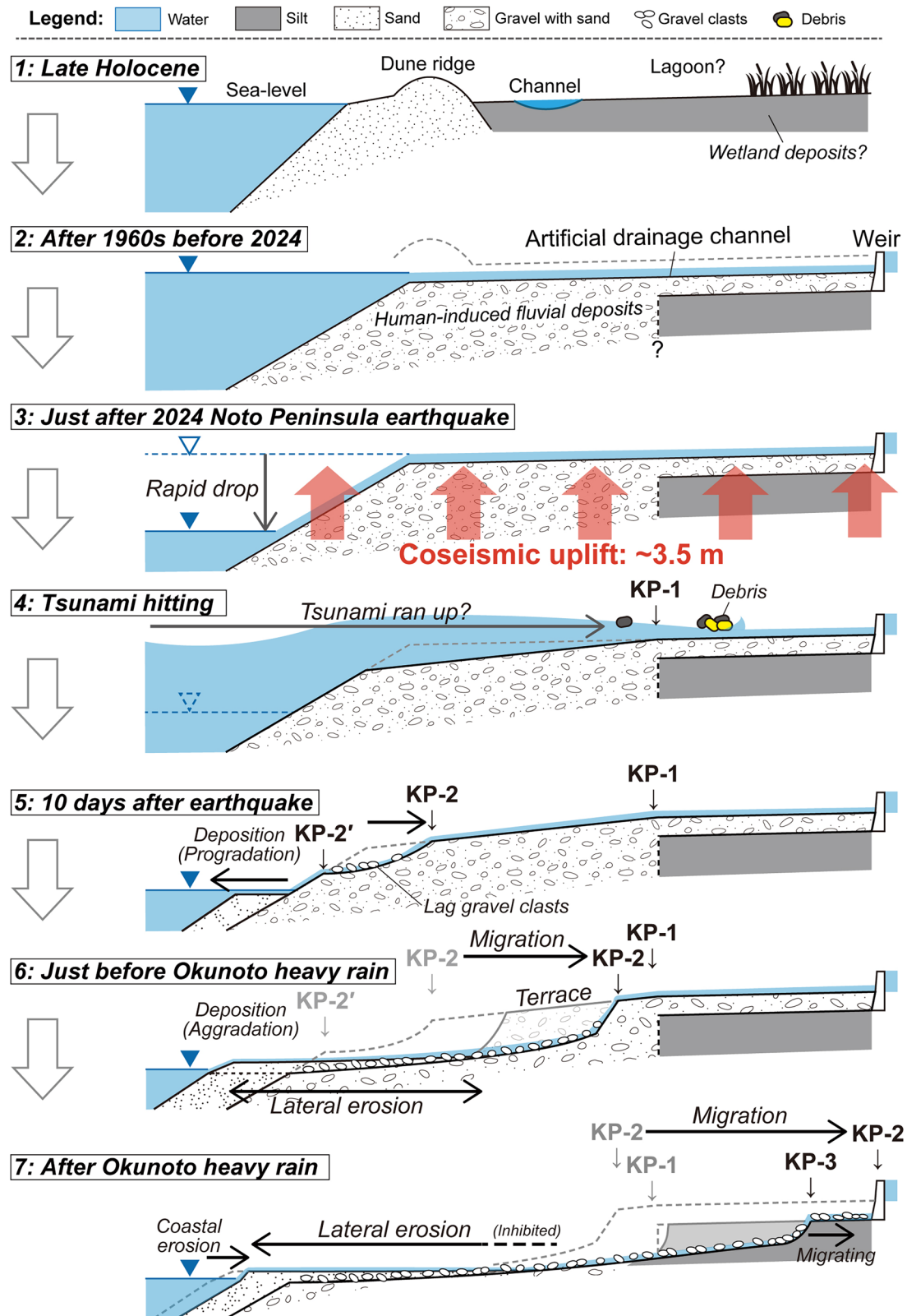
As incision progressed after the earthquake, deposits underlying the pre-earthquake riverbed were exposed. Semi-consolidated organic mud and sand were exposed as a hardpan at Loc. 1 near the former position of KP-1 following the Okunoto heavy rain (Fig. 4B, Supplementary Fig. 3B and Supplementary Fig. 3C). This deposit yielded a wood fragment with a  $^{14}\text{C}$  age of 7428–7317 cal BP (Supplementary Fig. 3C, Supplementary Table 1) and is inferred to be deposited during the Holocene marine transgression.

Following the upstream migration of KP-2, unconsolidated sand and cobble deposits were exposed at Loc. 2 (Fig. 2 and Supplementary Fig. 3D).

The lower part of this deposit was interbedded with a piece of plastic packaging for sugar on which the names of the manufacturer (Nagoya Seito Co., Inc.; currently bankrupt) and plant (Kobe Plants) were visible (Fig. 2, Supplementary Fig. 3D and Supplementary Fig. 3E). As this plant was established in 1954<sup>49</sup>, this deposit is identified as fluvial sediment deposited on the channel bottom after 1954. At the lower right bank of the channel (Loc. 3), the unconsolidated sand with cobbles composing the dried-up beach was exposed, revealing herringbone cross-stratification formed by the bidirectional currents offshore as Yuhi et al.<sup>33</sup> reported (Fig. 2H, Supplementary Fig. 3G and Supplementary Fig. 5F).

#### Upstream migration of knickpoints in the alluvial plain

In summary, we documented knickpoint migration of nearly 1 km upstream from the post-earthquake river mouth within one year of the Noto Peninsula earthquake (Figs. 2–6). Specifically, KP-1 was located 730 m upstream of the mouth 7 hours post-earthquake and remained stationary until the Okunoto heavy rain (Figs. 2B, 2C, 2E, 2F, 5 and 6). Given the

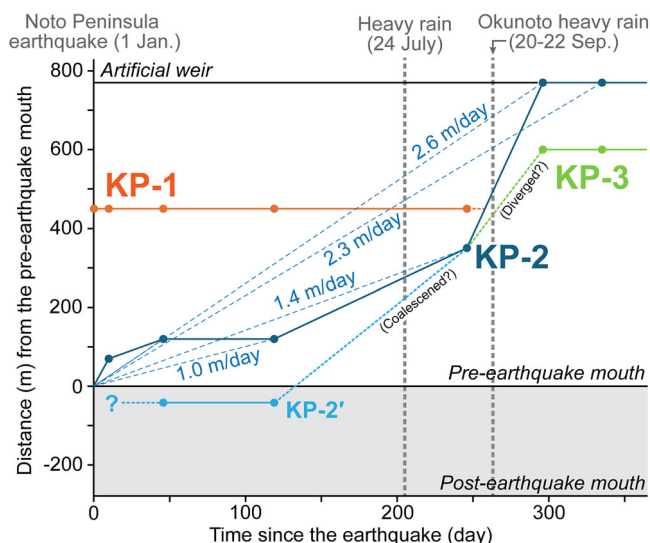


**Fig. 5 | Schematic longitudinal profiles indicating landform changes around the mouth of the Hakka River.** Note that the aspect ratio and scale of this figure do not reflect the actual dimensions.

absence of artificial structures across the channel near KP-1, why did KP-1 halt its migration for over eight months?

The tsunami generated by the 2024 Noto Peninsula earthquake reached the western coast with a run-up height of 7–8 m around the Hakka River mouth<sup>50</sup> (Fig. 1E). Such a tsunami wave run-up can cause formation of

a knickpoint inland<sup>51</sup>. The tsunami run-up height is recorded by UAV orthophotos that document discarded fishing equipment washed ashore along the Hakka River channel at an elevation of approximately 5 m above sea level (Supplementary Fig. 4). The upstream edge of the KP-1 knickzone corresponds to that elevation (Figs. 4A and 5).



**Fig. 6 | Schematic time-distance diagram for migration of knickpoints on the Hakka River during the one year after the earthquake.** The slopes of blue-colored broken lines between the points of KP-2 indicate the mean rates of upstream migration.

Furthermore, KP-1 had a gentler slope than KP-2 and resisted upstream recession, even during the increased discharge of 24 July (Fig. 4A). It is possible that the semi-consolidated alluvial hardpan underlying the riverbed inhibited KP-1's upstream migration after its formation (Fig. 2G, H and Supplementary Fig. 4).

KP-2, the upstream edge of the steeper rapid, migrated 350 m upstream from the pre-earthquake mouth over eight months post-earthquake, eroding and reworking unconsolidated riverbed deposits via fluvial flow (Figs. 2–6). It then migrated an additional 420 m upstream, coalescing with KP-1 and eroding the alluvial hardpan during the floods of the 20–22 September Okunoto heavy rain. Thus, the continued upstream migration of KP-2 from river mouth supports a coseismic uplift.

KP-2' is a knickpoint identified in the longitudinal profiles of 16 February and 29 April 2024 but could not be found from the orthophoto on 11 January 2024 (Fig. 4A). In these two profiles, KP-2' represents a part of the steep segment 200 m downstream from KP-2, initially located upstream of the pre-earthquake shoreline (Fig. 4A). As KP-2' was located downstream of the pre-earthquake shoreline, it was likely inherited from the relief of pre-earthquake submarine landforms. KP-2' disappeared by September 2024 due to aggradation at its downstream end and its merger with KP-2.

KP-3 appeared following the Okunoto heavy rain, located 250 m upstream of KP-2's September 3 position (Figs. 2–4A and 5). It maintained its form and position through at least December 2024 (Figs. 3 and 4A). One-meter vertical incision occurred even upstream of KP-3 during the heavy rain (Fig. 4A), implying that KP-3 diverged from KP-2 according to localized inhibition of underlying hardpan or artificial debris on riverbed. While the exact causes of KP-3 remain unclear, ongoing monitoring of its migration dynamics will clarify it.

Assuming that KP-2 initiated migration from the pre-earthquake mouth position, the migration rate ranged from ~1–8.4 m/day, increasing during periods of water-level rise (Fig. 6, Supplementary Table 2). The mean rate of horizontal migration since the earthquake occurrence ranged from 1–3 m/day. During the peak discharge of the Okunoto heavy rain, knickpoint KP-2 was arrested by the artificial weir, preventing further upstream migration (Figs. 4–6, Supplementary Table 2). Without the weir, it would likely have been located further upstream post-flood.

Investigating knickpoint migration rates in unconsolidated alluvial rivers over very short periods necessitates a different modeling approach than that used for bedrock rivers over longer time scales<sup>5</sup>. The 2007 Marmot Dam removal case in the US showed migration rates peaking at

480–4800 m/day in the first three days, then decelerating to the order of  $10^0$ – $10^1$  m/day<sup>27,28</sup>. The Hakka River case indicates rates of a similar order to the Marmot case, but the knickpoint exhibited repeated intermittent recession synchronized with high discharge events. This pattern reflects the heterogeneity of the riverbed material and the irregular nature of the 2024 Okunoto heavy rain. We suggest that knickpoints formed on alluvial plains migrate in a complex and intermittent fashion due to riverbed slope, steepness of initial knickpoint, and the strength of material composing the riverbed<sup>32</sup>.

The mean recession rate of KP-2 over the one-year period is calculated as  $>0.8 \times 10^3$  m/yr, even though the artificial weir has inhibited upstream migration of knickpoints. This rate is more than two orders of magnitude larger than the mean recession rate of 0.1–10 km/kyr ( $10^{-1}$ – $10^0$  m/yr) typically obtained from Late Pleistocene fluvial terrace ages in Japan over  $10^4$  years timescale<sup>53</sup>. We attributed this significant difference to the scale difference in observation timescales. Although the bedrock hardness and the discharges of water and sediment in river varies, our observation indicates that knickpoints can migrate upstream remarkably fast during flood stages following a base-level fall event.

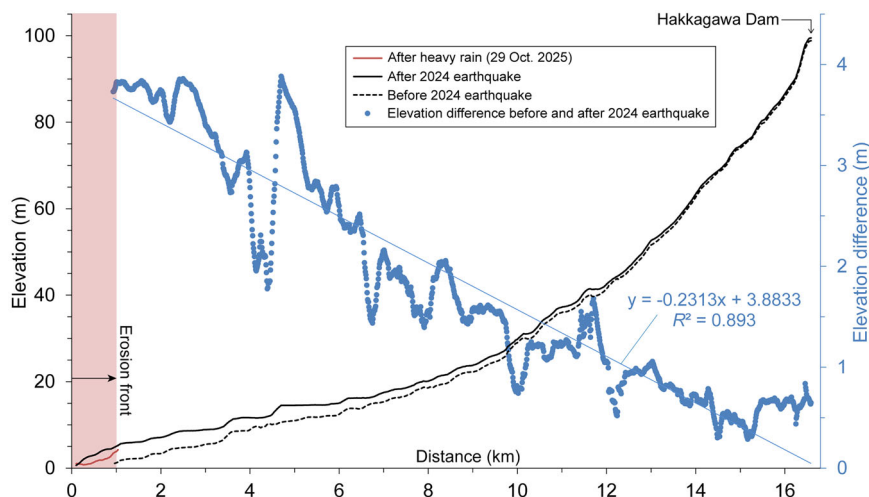
The fact that knickpoint retreat exposed Holocene and anthropogenic deposits implies that the alluvial plain was abandoned and transferred to a terrace by this incision. In areas with coseismic uplift, fluvial terrace profiles in the lower reaches of rivers occasionally match marine terrace levels<sup>54</sup>. Our results, showing the fluvial knickpoint migrating 770 m upstream within one year, imply that fluvial terraces can be formed within one year if a wide enough floodplain had been developed, and that any age difference between a marine terrace and its corresponding seafront fluvial terrace is likely insignificant on a geological timescale. Gentle rivers can respond immediately to a rapid drop in relative sea level and form fluvial terraces abandoning lower unconsolidated alluvial plains.

Then, how far upstream will the incision at the Hakka River mouth, caused by the 2024 Noto Peninsula earthquake, eventually migrate? Even though the knickpoint KP-2 has only reached 1 km upstream from the post-earthquake mouth, the elevation difference between the pre- and post-earthquake longitudinal profiles suggests the lower 12 km segment was uplifted by  $>1$  m (Fig. 7). Assuming the uplifted longitudinal profile will eventually return to its pre-event graded state, it is inferred that downcutting will migrate  $>10$  km further upstream, potentially causing meter-scale incision across most of the middle and lower Hakka River alluvial plain (Figs. 1B and 7). In 2025, KP-2 stopped below the artificial weir at 1-km upstream of the post-earthquake mouth since the Okunoto heavy rain, but heavy rain on August 2025 led to scouring beside the weir and further upstream migration of KP-3 (Fig. 4A, Supplementary Fig. 1H and Supplementary Fig. 1I). Once the weir is scoured and broken (Supplementary Fig. 1I), knickpoints will continue their upstream migration.

Ongoing monitoring of knickpoint migration is essential to determine the speed and extent of incision until the river profile fully adjusts. If migration sustains the rate observed in the first year post-earthquake (Fig. 6 and Supplementary Table 2), we estimate it would take over 10 years for the profile to transform to its final graded shape. However, the actual time taken is likely longer due to the expected decrease in recession rate with upstream migration<sup>10,14,28,53</sup> and the presence of multiple artificial structures across the channel.

Considering that the knickpoint migrations one year after the earthquake mainly proceeded during heavy rain events (Fig. 6 and Supplementary Fig. 2), we infer that the time required for the longitudinal profile to reach an equilibrium state depends on the recurrence interval of heavy rainfall events. Although the Holocene frequency of similar high-intensity rainfall events in this region remains uncertain, remarkable heavy rainfall events have occurred in the Noto Peninsula once in decades or a few years<sup>55</sup>. It has been also reported that the Okunoto heavy rain was linked to an irregular high sea surface temperature anomaly of the Sea of Japan<sup>56</sup>. The migration rate of current knickpoints probably depends on also the frequency and intensity of heavy rain events hereafter.

**Fig. 7 | Changes in longitudinal profiles of the Hakka River in 2024.** Profiles are 21-periods centered moving averages of 10-m interval points along the Hakka River using 1-m mesh DEMs before<sup>69</sup> and after<sup>68</sup> the 2024 earthquake. The profile after heavy rain is from DEM taken on 29 October 2025. Elevation difference between before and after the earthquake along the Hakka River was made from the smoothed profiles.



### Changes in channel morphology during the incision phase

Since the Okunoto heavy rain, the riverbed elevation and longitudinal profile downstream of KP-2 have remained largely stable, excluding the lowermost ~200 m segment, where deposition occurred between April and September (Figs. 3 and 4). Does the incised riverbed downstream of KP-2 have any more incision potential?

The total downcutting observed immediately after the Okunoto heavy rain is ~2 m at the cross section of c–d, less than the amount of coseismic uplift along the Hakka River, even considering a 1 m water depth (Fig. 4). Therefore, the riverbed has not been fully lowered and retains erosional potential. The pre-earthquake riverbed sediment consisted mainly of unconsolidated sand and gravel (Fig. 2, Supplementary Fig. 3D, Supplementary Fig. 3G and Supplementary Fig. 5), but it transformed into a gravel-bed river composed of cobble and boulder clasts and broken artificial concrete blocks post-incision (Supplementary Fig. 3 and Supplementary Fig. 5). This implies that selective transportation of finer deposits promoted riverbed armoring during incision, thereby inhibiting further incision<sup>57</sup>.

Vertical incision on the Hakka River channel near its mouth was actively driven by the upstream migration of KP-2, which was generated by the rapid uplift caused by the 2024 Noto Peninsula earthquake (Figs. 4 and 5). Although the erosion was influenced by the pre-earthquake submarine landforms and artificial structures, the channel became narrow and steep in the segment just downstream of KP-2 (Fig. 2D–2F). Later it evolved into a shallow, wide, and linear gravel-bed channel upon the subsequent flood events (Fig. 2). Even within the artificially constrained segment upstream of the Nishinoha Bridge, the channel transformed into shallow and gravelly one after passage of KP-2 (Fig. 2, Supplementary Fig. 5A and Supplementary Fig. 5B).

Channel width increased in the lower reaches without artificial structures as revealed by changes in cross sections of g–h and i–j (Figs. 3, 4B and 5). Although the vertical incision seems more remarkable rather than the lateral erosion in the segment between the Kaiso and Nishinoha bridges during this event (Figs. 2, 3 and 4B), the bank erosion during the heavy rains in September 2024 and August 2025 implies a lateral erosion potential even in the artificial concreted channel (Figs. 2G, H, J, 3C, E, F and Supplementary Fig. 1). These changes might have been simply caused by channel widening during high discharge events. They reveal that lateral erosion became active, superseding vertical incision, which became inactive as the knickpoint migrated and the riverbed became armored.

Our observation implies that lateral erosion started after the knickpoint passed through a reach (Figs. 2–5). Similar transitions from vertical incision to lateral erosion according to the knickpoint recession have been observed in the flume experiments<sup>12,13</sup> and in the field of 1964 Alaska earthquake<sup>25</sup> as well. This pattern suggests that the rivers on unconsolidated deposits can rapidly enter a phase of lateral adjustment after knickpoint passage, but in

the Hakka River the relative roles of flood discharge, local sediment sorting, and artificial confinement remain uncertain. In the case that the suitable amount of coarse sediments generated by earthquake-induced landslides were supplied from the upper reaches as in the Chi-Chi earthquake, further vertical incision and knickpoint migration can be activated due to ‘tools effect’<sup>19</sup>. However, in our case with the limited supply of coarse sediments from the upper reaches and the low riverbed slope, in-situ sorting of riverbed sediments is inhibiting further incision due to riverbed armoring and stimulates lateral erosion.

Other rivers in the northern Noto Peninsula have diverse geological and geomorphological settings and were also affected by the earthquake and heavy rain (Fig. 1). Knickzones presumably have formed in these rivers due to these events and are migrating upstream under the various conditions of bedrock lithology and hydrology. Failures in riverbank construction and scouring around bridge piers, caused by downcutting or lateral erosion, have already been observed in the Hakka River (Figs. 2J, 3E, 3F and Supplementary Fig. 1) and are likely to emerge simultaneously in multiple rivers across the peninsula. The necessity of long-term hazard risks and mitigation for riverbed lowering in areas prone to coseismic uplift must be recognized as a key lesson from the 2024 Noto Peninsula earthquake.

### Methods

After the 2024 Noto Peninsula earthquake, digital elevation models (DEMs) were generated using UAV–LiDAR surveys conducted on 16 February, 29 April, and 3 September 2024 (Supplementary Table 3). The DJI Matrice 300 RTK UAV (DJI, Shenzhen, China) equipped with a Zenmuse L1 laser scanner (DJI, Shenzhen, China) conducted LiDAR measurements. Point cloud data were acquired in terrain-following mode at a constant altitude of 80 m above ground, with both front and side overlap rates set to 80%. A D-RTK2 GNSS receiver (DJI, Shenzhen, China) was used as the base station for real-time kinematic (RTK) positioning. The onboard camera was mounted at nadir, and flight paths were planned and executed automatically using the DJI GS RTK app. The raw data were processed in DJI Terra (ver. 4.4.0) to generate point cloud data, and further filtering was conducted in ScanX ver. 2.0 (Locus Blue), where machine-learning algorithms removed non-ground points. Finally, DEMs were generated from the extracted ground-surface point cloud data using Natural Neighbor of CloudCompare (ver. 2.12).

Following the Okunoto heavy rain flooding (20–22 September 2024), additional UAV photogrammetry surveys were conducted on 24 October and 1 December in 2024, 29 October in 2025 using a Mavic 3 Enterprise UAV (DJI GS RTK) (Supplementary Table 3). The UAV operated autonomously at an altitude of approximately 140 m above ground, with 80% overlap and sidelap, and the camera was set to an oblique angle (70°) to minimize doming/bowling effects<sup>58</sup>. Images were processed in Agisoft

Metashape Professional ver. 2.2.0 (Agisoft, St. Petersburg, Russia) to generate Digital Surface Models (DSM) from detected feature points. Flight path planning and autonomous operations were also performed using DJI GS RTK. During image acquisition, live GNSS positioning and camera feeds were monitored. Additional details of the data acquisition procedures are provided in Ogura et al.<sup>59</sup>

Additionally, an orthophoto was obtained on 3 August 2025 by the below method (Supplementary Table 3). UAV images were acquired using a DJI Mavic 3 T with RTK positioning at a constant altitude of 70 m above ground. The base station coordinates and the other settings of flight and camera are similar to above surveys. SfM-MVS processing was performed in Agisoft Metashape Professional ver. 2.2.1.

Longitudinal and cross-sectional profiles were generated from the above DEMs and DSMs using the Stack Profile tool in ArcGIS Pro ver. 3.1 (ESRI Inc.). Lips of rapid riffles recognized by the field observation and major slope breaks displayed in the longitudinal profiles generated by the above method were identified as the knickpoints. The mean rates in upstream migration of knickpoints were calculated by the longitudinal migration distance and the number of days (Supplementary Table 2).

Water level data have been obtained at the observatory of the right bank of Kaiso Bridge (Figs. 1E and 2) at 1-hour intervals. Water discharge was estimated by the below  $H$ - $Q$  relationships for post-earthquake conditions,

$$Q = 60.732(H - 0.465)^2 \quad (1)$$

$$Q = 42.623(H - 0.364)^2 \quad (2)$$

$$Q = 68.545(H - 0.668)^2 \quad (3)$$

$H$  is water level (m) and  $Q$  is water discharge ( $\text{m}^3/\text{s}$ ). Equation (1) were applied for the water levels in pre-earthquake (prior to 17:00 1 January 2024). Equations (2) and (3) were applied for water levels (from 17:00 1 January 2024) of 0.37–1.79 m and 1.80–2.22 m, respectively. The water level data and  $H$ - $Q$  curves were provided by the Ishikawa Prefectural Office.

Field observations confirmed outcropped deposits forming the pre-earthquake riverbed. A wood sample from these deposits (Supplementary Fig. 3C) was dated using the Accelerator Mass Spectrometry ( $^{14}\text{C}$ -AMS) method at the Institute of Accelerator Analysis Ltd. The sample was chemically pretreated via an Acid-Alkali-Acid wash. The  $^{14}\text{C}$  age was measured based on the Libby age using  $\delta^{13}\text{C}$  for isotopic fractionation correction<sup>60</sup> and calibrated by IntCal20<sup>61</sup> and OxCal ver. 4.4 program<sup>62</sup>.

## Data availability

Data of orthophotos and DEMs obtained by this research are available on the Zenodo repository (<https://doi.org/10.5281/zenodo.21257512>)<sup>63</sup>.

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### Author contributions

T.T.: conceptualization, methodology, project administration, funding acquisition, investigation, formal analysis, data curation, writing—original draft, visualization. T.O.: funding acquisition, investigation, data curation, writing—review and editing. K.I.: investigation, data curation, writing—review and editing. Y.I.: investigation, formal analysis, writing—review and editing. Y.S.H.: supervision, investigation, writing—review and editing. T.A.: project administration, supervision, investigation, writing—review and editing. N.M.: supervision, funding acquisition, investigation, writing—review and editing.

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### Competing interests

The authors declare no competing interests.

### Additional information

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**Correspondence** and requests for materials should be addressed to Takayuki Takahashi.

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