Dynamic bedrock channel width during knickpoint retreat enhances undercutting of coupled hillslopes

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Abstract

Mountain landscapes respond to transient tectonic and climate forcing through a bottom-up response of enhanced bedrock river incision that undermines adjoining hillslopes, thus propagating the signal from the valley bottom to the valley ridges. As a result, understanding the mechanisms that set the pace and pattern of bedrock river incision is a critical first step for predicting the wider mechanisms of landscape evolution. Typically, the focus has been on the impact of channel bed lowering by the upstream migration of knickpoints on the angle, length and relief of adjoining hillslopes, with limited attention on the role of dynamic channel width. Here, we present a suite of physical model experiments that show the direct impact of knickpoint retreat on the reach-scale channel width, across a range of flow discharges (8.3 to 50 cm³ s⁻¹) and two sediment discharges (0 and 0.00666 g cm⁻³). During knickpoint retreat, the channel width narrows to as little as 10% of the equilibrium channel width, while the bed shear stress is >100% higher immediately upstream of a knickpoint compared to equilibrium conditions. We show that only a fraction of the channel narrowing can be explained by existing hydraulic theory. Following the passage of a knickpoint, the channel width returns to equilibrium through lateral erosion and widening. For the tested knickpoint height, we demonstrate that the lateral adjustment process can be more significant for hillslope stability than the bed elevation change, highlighting the importance of considering both vertical and lateral incision in landscape evolution models. It is therefore important to understand the key processes that drive the migration of knickpoints, as the localized channel geometry response has ongoing implications for the stability of adjoining hillslopes and the supply of sediment to the channel network and export from landscapes onto neighbouring depositional plains.

KEYWORDS
analogue experiments, bedrock river, channel width, cohesive substrate, hillslope, knickpoint, lateral erosion

1 | INTRODUCTION

The dynamic adjustment of bedrock river channels to transient forcing controls the mechanism and pace of wider landscape evolution (e.g. Burbank et al., 1996; DiBiase et al., 2015; Duvall et al., 2004; Lague, 2014; Whittaker et al., 2007; Yanites, 2018), with increasing recognition that landscape-scale studies require an understanding of the coupling of in-channel and hillslope processes (e.g. Hurst et al., 2019). A common manifestation of this phenomenon is the bottom-up landscape adjustment to changes in external forcing (e.g. tectonic uplift rate or base-level fall) through the upstream migration of knickpoints often in the form of waterfalls or channel reaches with a heightened bed slope. At a knickpoint, the channel bed elevation drops relatively suddenly so as it migrates upstream, the signal of
base-level fall (e.g. increased uplift rate) is transferred to the adjoining hillslopes, leading to their steepening, lengthening, increased relief (Gallen et al., 2011; Grieve et al., 2016; Hurst et al., 2013) and a shift in the pattern of basin hypsometry (Gallen et al., 2011). As a result, hillslopes can become destabilized and contribute more sediment to the fluvial system (Attal et al., 2015) due to increased hillslope potential energy leading to enhanced mass-wasting events such as landsliding, rockfalls or debris flows (Gallen et al., 2011; Golly et al., 2017; Korup & Schlunegger, 2007; Mackey et al., 2014; Reinhardt et al., 2007). Therefore, the physical processes that control the dynamic adjustment of bedrock channel morphology during knickpoint retreat have important implications for adjoining hillslopes and wider landscape evolution over short and long timescales.

The vertical adjustment of channel bed elevation during knickpoint retreat and its role in controlling downstream hillslope morphology, including hillslope destabilization, is well known and has been identified extensively in multiple field settings (e.g. Swiss Alps—Korup & Schlunegger, 2007; Southern Spain—Reinhardt et al., 2007; Southern Appalachians—Gallen et al., 2011; Kaua’i, Hawai’i—Mackey et al., 2014; California—Hurst et al., 2019), as well as in laboratory experiments (e.g. Bigi et al., 2006; de Lavaissiere et al., 2022; Hasbergen & Paola, 2000). In contrast, the importance of processes that govern lateral adjustment of bedrock channel geometry has received relatively little attention compared to vertical incision processes (e.g. Baynes et al., 2020; Cook et al., 2013; Finnegam et al., 2007; Li et al., 2020; Turowski, 2018; Turowski et al., 2009; Whitbread et al., 2015; Wobus et al., 2006; Yanites & Tucker, 2010), and has primarily focused on the role of sediment availability and transport (e.g. the tools and cover effects).

Channel morphology is expected to change at, and upstream of, waterfalls/knickpoints due to variability associated with the flow hydraulics (e.g. Haviv et al., 2006). Rouse (1936) performed a series of experiments to demonstrate the presence of a flow-acceleration zone upstream of a freefall lip (i.e. the brink of a waterfall), as a consequence of a pressure gradient induced by the shift from hydrostatic to atmospheric pressure dominating (Flores-Cervantes et al., 2006; Haviv et al., 2006; Lapotre & Lamb, 2015). The magnitude of flow acceleration is a function of the Froude number upstream of the waterfall (Rouse, 1936) and impacts the flow velocity, water depth and shear stress acting on the bed over a distance of two to four times the normal flow depth (Stein & Julien, 1993), under the assumption of a fixed channel width (Haviv et al., 2006):

$$\frac{\tau_{lip}}{\tau_{upstream}} = \left(1 + \frac{\epsilon}{Fr_{upstream}}\right)^2$$

(1)

where $\tau_{lip}$ is the shear stress at the waterfall lip, $\tau_{upstream}$ is the shear stress upstream of the flow acceleration zone (i.e. at ‘normal’ conditions), $Fr_{upstream}$ is the Froude number upstream of the flow acceleration zone and $\epsilon$ is an empirical constant determined experimentally by Rouse (1936), with a value of 0.4. Haviv et al. (2006) also demonstrated the impact of the flow acceleration zone on the upstream channel slope, with the formation of an oversteepened reach possible when the rate of erosion at the waterfall face is lower than the rate of erosion at the waterfall lip. While the hydraulic theory above predicts that a zone of higher shear stress and flow velocity acceleration is primarily a phenomenon of vertical waterfalls, it was also documented experimentally by Gardner (1983) and Baynes, Lague, et al. (2018) for break-in-slope knickpoints. It is logical, if the flow acceleration upstream of a waterfall is sufficient to enhance erosion to the point of producing a long oversteepened convex reach upstream (e.g. Haviv et al., 2006), that the channel morphology and typical scaling of the channel width and depth would also be affected. For example, due to the principle of conservation of mass and the relationship between hydraulic radius, slope and flow velocity in Manning’s equation, it is possible that channels can narrow with increasing channel slope (Finnegam et al., 2005). Such observations have been made for natural channels in convex knickzones, with channel widths reported to be narrower than would be expected under typical bedrock river hydraulic scaling (Lague, 2014) in the French Alps (Valla et al., 2010), Turkey (Whittaker & Boulton, 2012), the Italian Apennines (Whittaker et al., 2007) and Taiwan, where the Da’an river channel narrowed substantially during a period of rapid knickpoint retreat after the Chi-Chi earthquake (Cook et al., 2013). Despite these observations, and the hydraulic theory that predicts flow acceleration zones upstream of knickpoints, there remains an incomplete understanding of channel width variation in transiently adjusting reaches of bedrock channels (i.e. knickpoints and knickzones) and the possible implications for the stability of adjoining hillslopes.

In this paper, we investigate the role of lateral adjustment of channel geometry during transient knickpoint migration for the first time and present a set of systematic analogue flume experiments to document the extent to which channel width adjustment is a significant process within the transient response of channels to changes in external forcing.

2 | PHYSICAL MODELLING OF TRANSIENT CHANNELS

2.1 | Flume setup and experimental conditions

Due to the slow rates of knickpoint migration and bedrock channel adjustment in the natural environment, field observations often provide important insights into the response of the bedrock channel geometry to external forcing (e.g. Whittaker et al., 2007) and knickpoint formation processes (e.g. Groh & Scheingross, 2021) but lack insights into the temporal dynamics of these processes. We therefore performed a suite of analogue physical modelling experiments where the spatial and temporal scales of bedrock erosion processes are reduced (Paola et al., 2009). The laboratory modelling approach allows a systematic investigation of channel width evolution during knickpoint retreat, and whether input parameters (water and sediment discharge; $Q_w$ and $Q_s$, respectively) have an impact on the magnitude and rate of any channel width adjustment.

Experiments were performed using the 80 $\times$ 30 cm Bedrock River Experimental Incision Tank at the Université de Rennes. The flume setup has been described in detail previously (Baynes, Lague, et al., 2018, Baynes, Lague, & Kermarrec, 2018, Baynes et al., 2020) and implements a ‘similarity of process’ analogue modelling approach whereby no formal scaling of the experiments with a particular natural location is sought. The experiments presented here do not therefore represent scaled experimental versions of any particular natural river,
but the appropriate process representation within the flume allows the relative impact of the initial boundary conditions on the channel morphodynamics to be explored (Baynes, van de Lageweg, et al., 2018; Hooke, 1968; Paola et al., 2009). The scaling of the width and slope of the experimental channels with discharge follows the patterns observed in natural channels (Baynes, Lague, et al., 2018), ensuring that the findings from the experimental channels are transferrable to the natural environment despite erosion being driven primarily by hydraulic shear rather than sediment impacts.

We used a cohesive mix of granular silica cement, spherical beads (ratio 3:1 granular silica to spherical beads, both 45 μm grain size) and water (18% of total mix volume) to represent a cohesive bedrock substrate in the experimental channels (Figure 1). At the beginning of the experiments, we flowed water over the silica surface with a 2 cm initial base-level fall to allow the channel to self-form an equilibrium geometry (width and slope) constrained within silica ‘bedrock’ banks (Figures 1a and c). We performed 11 experiments (Table 1) at water discharges ranging from 8.33 to 50 cm$^3$ s$^{-1}$ (0.5 to 3 L min$^{-1}$), with two scenarios inputting coarse sand sediment of 250 μm grain size: (i) $Q_s = 0$ g of sediment per cm$^3$ of water (g cm$^{-3}$); (ii) $Q_s = 0.00666$ g of sediment per cm$^3$ of water (g cm$^{-3}$). For each experiment, we triggered an upstream migrating knickpoint within the equilibrium channel by dropping the flume outlet plate by 3 cm instantaneously to replicate a sudden base-level fall. As the knickpoint migrated upstream during the experiment, a green-laser terrestrial laser scanner (Leica ScanStation 2) collected high-resolution point clouds of the channel morphology at 2 min intervals. The point clouds were converted into digital elevation models with 2 mm horizontal resolution, and used as input data for the Floodos hydrodynamic numerical model (Davy et al., 2017) to generate water depth masks at each time step. The Floodos-generated water depth masks were used to automatically extract the channel widths as well as calculate the bed shear stress during each time step of each experiment (see Baynes, Lague, et al., 2018, Baynes, Lague, & Kermarrec, 2018, Baynes et al., 2020 for more details of the experimental procedure and coupling with the Floodos model).

To avoid any potential influence of the water inlet and outlet on the channel width, we removed the channel width data from the upper and lower 10 cm of the flume from any further analysis (Baynes et al., 2020). Observations of knickpoint location during the experiments were made through a combination of manual observations of the break in slope in the channel long profile and the location of an area of deeper water in a pool downstream (Figures 1b and d). We used the width at the channel mid-point (i.e. 50% distance from the inlet to the outlet) as the reference location to extract the channel geometry characteristics for the knickpoints for the time period when the channel mid-point first experienced the knickpoint (i.e. when the

FIGURE 1 Photos from mounted camera above the Bedrock River Experimental Incision Tank, showing the experimental setup. Photos on the top row show the equilibrium channel conditions at the start of an experiment, where $Q_s = 0$ g cm$^{-3}$ (a) and $Q_s = 0.00666$ g cm$^{-3}$ (c). Photos on the bottom row (b and d) show the same channels containing knickpoints generated by an instantaneous dropping of the channel outlet. Black dashed lines show the limits of the channel at equilibrium conditions (a and c) and green solid lines show the channel limits in photos b and d for comparison. [Color figure can be viewed at wileyonlinelibrary.com]

| Experiment number | Water discharge (cm$^3$ s$^{-1}$) | Input sediment flux (g cm$^{-3}$) |
|-------------------|---------------------------------|----------------------------------|
| 1                 | 8.33                            | 0                                |
| 2                 | 12.5                            | 0                                |
| 3                 | 16.67                           | 0                                |
| 4                 | 25                              | 0                                |
| 5                 | 33.33                           | 0                                |
| 6                 | 50                              | 0                                |
| 7                 | 8.33                            | 0.00666                          |
| 8                 | 16.67                           | 0.00666                          |
| 9                 | 25                              | 0.00666                          |
| 10                | 33.33                           | 0.00666                          |
| 11                | 50                              | 0.00666                          |
oversteepened channel reaches the mid-point) through to the time when the knickpoint has fully migrated upstream (i.e. when the downstream limit of the pool is upstream of the mid-point). Therefore, the mean knickpoint width value in Figure 2 encompasses all phases of a knickpoint, from lip to pool, as it migrates past the channel mid-point.

We selected this approach for knickpoint channel width extraction to facilitate appropriate data extraction for knickpoints where the reach of active incision was relatively long (i.e. a steepened reach) or for a single vertical step undergoing parallel retreat.

FIGURE 2 (a) Channel width during equilibrium conditions (white) and at the knickpoints (black) plotted against discharge. Mean values are plotted with error bars indicating two standard deviations. Circles are experiments with $Q_s = 0 \text{ g cm}^{-3}$ and triangles are experiments with $Q_s = 0.00666 \text{ g cm}^{-3}$. (b) The ratio of the knickpoint width to equilibrium channel width. (c) Mean bed shear stress against discharge for both equilibrium conditions (white) and at the upstream lip of the knickpoints (black). Error bars indicate two standard deviations. (d) The width-to-depth ratio for both equilibrium conditions (white) and at the knickpoints (black) plotted against discharge. Mean bed shear stress in experiments where $Q_s = 4.74Q^{0.50}; R^2 = 0.69$, $Q_s = 0.00666 \text{ g cm}^{-3}$ experiments: $W_{KP} = 3.7Q^{0.67}; R^2 = 0.71$, $Q_s = 0.00666 \text{ g cm}^{-3}$ experiments: $W_{KP} = 5.9Q^{0.51}; R^2 = 0.96$ than the channel width at equilibrium conditions (Figures 1 and 2a). The amount of narrowing of the channel at the knickpoint compared to equilibrium conditions increases for higher $Q$, with the knickpoint at $50 \text{ cm}^2 \text{s}^{-1}$, with $Q_s = 0.00666 \text{ g cm}^{-3}$ up to $100 \text{ mm}$ narrower than the equilibrium channel (Figure 2a). Importantly, however, the magnitude of channel narrowing at the knickpoints when normalized by the equilibrium channel width shows no relationship with $Q$ (Figure 2b). Knickpoints with $Q_s = 0.00666 \text{ g cm}^{-3}$ are proportionally narrower than their equilibrium conditions compared to the experiments with $Q_s = 0 \text{ g cm}^{-3}$ across the full range of $Q$ (Figure 2b). The value of bed shear stress follows the pattern observed in Baynes, Lague, et al. (2018) for a similar suite of experiments, with the shear stress at the lip of the knickpoints ~2 Pa, greater than the equilibrium value ~1 Pa, and showing no clear relationship with increasing $Q$ (Figure 2c). The bed shear stress in experiments where $Q_s = 0.00666 \text{ g cm}^{-3}$ is higher than the clear-water flow experiments, following a similar pattern to the channel width where increased narrowing of the width leads to higher water depths for a given $Q$ (Figure 2d), and therefore a higher bed shear stress. The channel bed slope also varies between equilibrium conditions and reaches upstream of the knickpoints, with channels steepening locally during the phase of transient adjustment (i.e. at the knickpoints; Figure 2e).

2.2.2 | Experimental results

2.2.1 | Impact of transient incision on channel geometry

At equilibrium conditions before the base level was dropped by $3 \text{ cm}$, the width of the experimental channel increases with $Q$ (Figure 2a) following a power law (all experiments: $W_{EQ} = 11.9Q^{0.52}; R^2 = 0.53$) consistent with typical natural bedrock channels (Lague, 2014). The experiments that had an additional input $Q_s$ were wider ($W_{EQ} = 13.5Q^{0.54}$) than those without an input $Q_s$ ($W_{EQ} = 11.9Q^{0.48}$), matching previous experimental results (Baynes et al., 2020). The channel widths at the knickpoints at the channel mid-point are systematically narrower (all experiments: $W_{KP} = 4.74Q^{0.50}; R^2 = 0.69$, $Q_s = 0.00666 \text{ g cm}^{-3}$ experiments: $W_{KP} = 3.7Q^{0.67}; R^2 = 0.71$, $Q_s = 0 \text{ g cm}^{-3}$ experiments: $W_{KP} = 5.9Q^{0.51}; R^2 = 0.96$) than the channel width at equilibrium conditions (Figures 1 and 2a). The amount of narrowing of the channel at the knickpoint compared to equilibrium conditions increases for higher $Q$, with the knickpoint at $50 \text{ cm}^2 \text{s}^{-1}$ with $Q_s = 0.00666 \text{ g cm}^{-3}$ up to $100 \text{ mm}$ narrower than the equilibrium channel (Figure 2a). Importantly, however, the magnitude of channel narrowing at the knickpoints when normalized by the equilibrium channel width shows no relationship with $Q$ (Figure 2b). Knickpoints with $Q_s = 0.00666 \text{ g cm}^{-3}$ are proportionally narrower than their equilibrium conditions compared to the experiments with $Q_s = 0 \text{ g cm}^{-3}$ across the full range of $Q$ (Figure 2b). The value of bed shear stress follows the pattern observed in Baynes, Lague, et al. (2018) for a similar suite of experiments, with the shear stress at the lip of the knickpoints ~2 Pa, greater than the equilibrium value ~1 Pa, and showing no clear relationship with increasing $Q$ (Figure 2c). The bed shear stress in experiments where $Q_s = 0.00666 \text{ g cm}^{-3}$ is higher than the clear-water flow experiments, following a similar pattern to the channel width where increased narrowing of the width leads to higher water depths for a given $Q$ (Figure 2d), and therefore a higher bed shear stress. The channel bed slope also varies between equilibrium conditions and reaches upstream of the knickpoints, with channels steepening locally during the phase of transient adjustment (i.e. at the knickpoints; Figure 2e).

2.2.2 | Temporal evolution of channel width during transient adjustment

Reach-scale adjustment

Due to the reduced spatial scale and analogue processes at work in the flume experiments, the temporal evolution of the channel geometry is accelerated compared to natural bedrock systems. As a result, we are able to observe the coincident channel geometry adjustment as the knickpoints retreat over the course of the experiments (up to $150 \text{ min}$) rather than interpreting such change in the natural environment. Here, we exploit this experimental capability to explore the processes that drive the difference in channel geometry at and around knickpoints compared to equilibrium conditions.

Figure 3 shows the temporal evolution of the distribution of width ratios (WR), defined as the channel width divided by the equilibrium width, for all channel cross-sections (excluding the upper and lower $10 \text{ cm}$ of the channel). WR = 1 implies that the channel is at
equilibrium conditions, whereas $WR < 1$ is a channel that is narrower than equilibrium. All experiments experience the same overall pattern of channel narrowing, and then widening, as the geometry experiences the transient adjustment of the knickpoint propagating upstream from the outlet to the inlet (Figure 3). Importantly, the narrowing of the channel caused by the knickpoint is not limited to the specific location of the knickpoint, with the dynamic width adjustment experienced along the full channel reach, although the focus of the greatest narrowing (smallest value of $WR$) typically follows the location of the knickpoint for all $Q$ and $Qs$ combinations (see the relative position of the blue knickpoint line and the shaded pdf in Figure 3). After the knickpoint has reached the channel inlet (vertical dashed blue line in Figure 3), $WR$ typically continues to increase as the channel continues to readjust back towards equilibrium conditions and there is a shift from transport-limited to supply-limited conditions during knickpoint retreat.

**Dynamic channel geometry evolution at a point location**

By focusing on the evolution of the channel width and the vertical incision at a single location through time (Figure 4), we can consider the complete response to the transient phase of incision driven by the propagation of the knickpoint. The substitution of space for time allows the rate of width adjustment before, during and after knickpoint propagation to be extracted for the different experimental input conditions ($Q$ and $Qs$). The presence of the knickpoint at the channel mid-point coincides with the highest rates of vertical bed incision as well as the narrowest channel widths (Figure 4). For a given $Q$, $WR$ at the knickpoint is smaller for the experiments with $Qs = 0.00666 \text{ g cm}^{-3}$ than with $Qs = 0 \text{ g cm}^{-3}$ (Figure 4), implying a greater narrowing effect for channels that contain additional input sediment (also seen in Figure 2).

The sharpest change in the vertical bed incision is associated with knickpoints that are present at the channel mid-point for a short duration (i.e. vertical steps undergoing parallel retreat; Figures 4b, d, g and h) compared to more sustained, slower, periods of bed elevation change for longer-duration knickpoints (typically steepened reaches; Figures 4e and i). For the majority of the time during the experiments, the channels experience little bed elevation or channel width adjustment, shown by the cluster of points near the origin of Figure 5. Importantly, where the rates of change of width ($dW/dt$) and bed elevation ($dZ/dt$) are furthest from zero, there is a trend in the overall vector direction of two-dimensional channel geometry change.
apparent in the kernel density plots (Figures 5b and d). The pattern of channel narrowing occurring when the bed is incising and channel widening occurring when the bed is aggrading is particularly evident when \( Q_s = 0.00666 \) g cm \(^{-3}\) (Figures 5c and d). We can identify three phases of channel response at a point location during the passage of the transient knickpoint (Figure 4): (1) the channel narrows as the knickpoint approaches, coincident with the beginning of an increase in vertical incision rate and local steepening of the channel; (2) the knickpoint propagates past the point location, with heightened vertical incision and the narrowest widths; followed by (3) channel widening immediately after the knickpoint has propagated past, with limited incision or sediment aggradation on the bed during the widening phase (Figure 4). The mean duration of channel narrowing until the narrowest recorded width at the channel mid-point (40 cm from the outlet) was 48 min after the start of the experiment. Channel widening at the channel mid-point following the passage of the knickpoint continued until the end of the experiment (average from time of recorded width until end of experiment = 68 min), including during the period after the knickpoint had retreated the full reach length to the channel inlet (e.g. Figures 4a and h).

3 | DISCUSSION

The experimental results presented here demonstrate a clear link between channel width variability and the retreat of knickpoints within bedrock channels. Here, we discuss the drivers of channel change at knickpoints (Section 3.1), the implications for adjoining hillslopes (Section 3.2), insights into the response time of landscapes (Section 3.3) and finally the role of sediment (Section 3.4).

3.1 | Drivers of channel change at knickpoints

The systematic narrowing of bedrock channels associated with high tectonic uplift rate, active faulting or landslide dams has been observed in the natural environment (e.g. Burbank et al., 1996; Cook et al., 2013; Duvall et al., 2004; Ouimet et al., 2008; Whittaker et al., 2007), or within numerical model outputs (e.g. Yanites, 2018) and is thought to be associated with an intrinsic mechanism induced by high local slope that leads to focused flow, high shear stresses and stream power, bedrock scour and a narrower channel with a smaller.
width-to-depth ratio (Finnegan et al., 2005; Whittaker et al., 2007). The rapid headward retreat of a knickpoint in the Da'an River, Taiwan (Cook et al., 2013, 2014, 2020) is the most relevant natural analogue for the experimental results presented here due to the discrete generation of a single knickpoint following the uplift of an anticline feature during the 1999 Chi-Chi earthquake. Cook et al. (2013) documented the controls on the rapid retreat knickpoint rate and subsequent channel geometry adjustment at the reach scale, although the magnitude and pattern of channel narrowing and widening was not the main focus of their work. Before the Chi-Chi earthquake, the Da'an River flowed across an ~450 m-wide braidplain ($W_{KP}$) over the anticline and the initial knickpoint retreat cut an incised gorge 14 m deep ($K_{P}$) and 31 m wide ($W_{eq}$), 7% of the pre-disturbance width (Cook et al., 2013). Following the rapid passage of the knickpoint past a point (>100 m per year between 2004 and 2008), the channel width widened initially at 5 m per year (2005–2008) before slowing to 1.5 m per year (2008–2013).

In these experiments, we demonstrate the same phenomenon of channel narrowing and widening as observed in the Da’an River by Cook et al. (2013), demonstrating the relevance of our results for natural channels. Significant channel narrowing (up to 10% of equilibrium width; a similar order of magnitude to the Da'an River) occurs as part of the migration process of a specific knickpoint in the experiments, triggered by an instantaneous base-level fall and generation of a vertical step at the channel outlet. The vertical step commonly diffuses into an oversteepened reach knickpoint with a downstream scour/plunge pool over a distance of up to five channel widths as it migrates upstream (Figure 1), with an associated pulse of narrowing where channels can be as little as 10% of the width at equilibrium conditions (Figure 2). The narrower, and steeper, channels lead to bed shear stress values >100% higher immediately upstream of the knickpoint compared to equilibrium conditions. The power law exponent $b (W = KQ^b)$ between channel width and discharge (or drainage area) is similar for equilibrium channels as well as knickpoints ($b \sim 0.5$), matching the findings of Duvall et al. (2004). However, the value of $K$ is approximately three times smaller for the knickpoints (Figure 2), showing the importance of reach-scale variability in response to transient forcing (instantaneous base-level fall) on the channel width. Similar to the observations in the Da'an River, the rate of channel widening following knickpoint retreat is prolonged compared to the shorter duration of narrowing as the knickpoint approaches the point location (Figure 4).

At a single location during a transient response of a bedrock reach to base-level fall, channel geometry adjustment is characterized by long periods of slow and gradual adjustment punctuated by a short pulse of vertical incision, demonstrated by the cluster of data where both $dW/dt$ and $dZ/dt$ are near zero, with fewer points where $dZ/dt < 0$ in Figure 5. Furthermore, the vector direction of channel geometry adjustment matches observations in the field of channel widening occurring during phases of aggradation (e.g. East et al., 2015) and channel narrowing during incision (e.g. Finnegan et al., 2007; Johnson et al., 2010), highlighting the importance of understanding the role of dynamic river width when considering bedrock river adjustment to external forcing.

According to hydraulic theory associated with the acceleration zone upstream of a knickpoint lip (e.g. Rouse, 1936), some of the increase in bed shear stress may be induced by the change from hydrostatic pressure to atmospheric pressure [Equation 1]. We find that this hydraulic theory can only account for a small fraction of the total increase in bed shear stress observed in the experiments (Figure 6a), and the residual bed shear stress appears to be related to the magnitude of channel width narrowing (Figure 6b; correlation

**FIGURE 5** Combined data for the rate of change of channel width ($dW/dt$) as a function of rate of bed elevation change ($dZ/dt$) for all experiments where $Q_s = 0$ g cm$^{-3}$ (a and b) and where $Q_s = 0.00666$ g cm$^{-3}$ (c and d). b and d are kernel density plots of the raw data (a and c). The quadrants of each plot indicate where the channels are widening ($dW/dt > 0$), narrowing ($dW/dt < 0$), aggrading ($dZ/dt > 0$) and narrowing ($dZ/dt < 0$). [Color figure can be viewed at wileyonlinelibrary.com]
The hydraulic theory associated with the zone of flow acceleration upstream of the knickpoint lip suggests that any impact is experienced over an along-stream distance of a few water depths (Haviv et al., 2006). The experimental results here (e.g. Figure 3) show that the whole mechanism of transient width variation can impact a reach of distance > five channel widths and any purely hydraulic induced width variability component is relatively minimal overall.

Following the instantaneous base-level fall, the transient response of the channel acts to return the channel back to the smooth profile representative of equilibrium conditions. In the experiments, where the substrate can be eroded through clear water flow, the channel width self-forms in order to optimize the bed shear stress for producing the most efficient upstream propagation of the knickpoint by eroding and transporting the bed material until the downstream reach, which is graded to the new outlet elevation. The width-adjustment process to optimize the bed shear stress follows the width-adjustment model proposed by Yanites (2018), where a channel will tend towards a condition that leads to the greatest vertical incision.

We can speculate that the excess higher shear stress observed beyond what is predicted by the hydraulic theory of the acceleration zone is due to the requirement for the channel to increase its transport capacity and bed shear stress in order to transport the optimum material eroded from the knickpoint in addition to the sediment supplied from upstream in the most efficient way possible. Narrowing of channels in order to increase the transport capacity has been numerically modelled, as suggested for the mobilization of landslide material following a sudden input of sediment (Croissant et al., 2017), and we suggest a similar mechanism is occurring during knickpoint retreat. The hydraulic theory of Rouse (1936) does not take into account knickpoint generation and longer-term shift of a channel from equilibrium conditions. Rather, it predicts the hydraulics at knickpoints themselves, so it could be expected that any hydraulic-induced width variability is superimposed on the more significant transport capacity-induced width variability.

The set of experiments that included an additional input of coarse sediment had a higher bed shear stress both at equilibrium and knickpoint conditions (Figure 2c), driven by the requirement to transport both the eroded material from the knickpoint as well as the sediment load from upstream. There is a larger difference between $\tau_{eq}$ and $\tau_{KP}$ than between the $Q_s = 0 \text{ g cm}^{-3}$ and $Q_s = 0.00666 \text{ g cm}^{-3}$ experiments, highlighting that in the cases tested here, the transient nature of channels is more significant for their geometry than variability in upstream sediment supply.

3.2 | Hillslope–channel coupling

The impact of headward knickpoint migration on adjoining hillslopes through the vertical reduction of the hillslope ‘base-level’ elevation can be significant in triggering the onset of active hillslope processes downstream of the knickpoints (e.g. Gallen et al., 2011; Reinhardt et al., 2007). The phases of lateral channel adjustment associated with knickpoint retreat highlighted in the experiments presented here (narrowing then widening) indicates an additional mechanism for the destabilization of the adjoining hillslopes. As the channel geometry relaxes back to equilibrium conditions following the knickpoint migration, the width can increase by >50% (and up to 80%) where channels have a high sediment load; Figure 2). Channel widening through bank erosion or gorge wall retreat has been shown to destabilize hillslopes through undermining of the hillslope toe (Golly et al., 2017; Harvey, 2001; Kondolf et al., 2002), and steepening of the hillslope beyond the threshold angle for failure (Larsen & Montgomery, 2012), so it would be anticipated that knickpoint retreat can drive hillslope destabilization by both the rapid vertical incision as well as the lateral adjustment component. To assess the relative importance of vertical channel incision (defined as the knickpoint height, $KPH$) and lateral adjustment component (defined as $W_{KP}$) on hillslope destabilization, we calculated the ratio $\frac{KPH}{(W_{KP} - W_{KL}) \tan \theta}$, where $\theta$ is the hillslope angle. In Figure 7, we used a hillslope angle of 30°; a value appropriate for representing hillslopes at a typical angle of repose (e.g. Whittaker et al., 2007) and identified the experiments where $\frac{KPH}{(W_{KP} - W_{KL}) \tan \theta} < 1$ to indicate when the lateral widening component is more important for hillslope destabilization than the magnitude of the channel incision (i.e. the knickpoint height). The lateral adjustment process is relatively more important than vertical incision for hillslope destabilization in the experiments with higher $Q$ (Figure 7a). We suggest that this is due to the lower values of $\frac{KPH}{W_{KL}}$ at higher $Q$, when $KPH$ is fixed across all experiments (Figure 7b). This equation could also be applied in natural field settings where knickpoint width, knickpoint height, hillslope angle and equilibrium channel width can be estimated, and we can suggest that hillslope destabilization driven by lateral channel undercutting can be particularly prevalent in circumstances where the channel width is relatively large compared to the knickpoint height (when $\frac{KPH}{W_{KL}} < \sim 0.7$).

The hillslope response to knickpoint migration can be mapped to the same three phases described above and shown conceptually in Figure 8. (1) Hillslopes become decoupled from the channel as the width narrows and there is an increase in the incision rate as the
knickpoint approaches. (2) As the knickpoint propagates past the point location, rapid vertical bed incision leads to rapid reduction in the hillslope base level that triggers hillslope destabilization (Gallen et al., 2011; Mackey et al., 2014). (3) Channel widening after the knickpoint has propagated past, leading to continued hillslope destabilization. The wave of knickpoint-induced lateral adjustment can be an integral feature of the coupling of hillslopes and channels in transient landscapes, depending on the relative magnitudes of $K_{ph}$ and $W_{eq}$.

3.3 | Landscape response time

Figures 3 and 4 provide insight into the timescale of the wave of knickpoint-induced lateral adjustment of the channel geometry, with the channel widening continuing for a prolonged period of time after the passage of the knickpoint. For example, the channel width at the channel mid-point is still increasing at the time that the knickpoint has reached the channel inlet, 40 cm upstream for most of the experiments (Figure 4). The range of $W_{eq}$ is from 4 to 10 cm (Figure 3), suggesting that the lateral adjustment phase is at least the time taken for the knickpoint to retreat 4–10 channel widths. In all experiments, the rate of lateral adjustment is slower than the rate of upstream knickpoint retreat (Figure 4), such that the duration of the lateral adjustment phase is sustained over a significantly longer period than the relatively rapid pulse of vertical incision associated with the passage of a knickpoint. Lateral erosion associated with channel widening downstream of a migrating knickpoint is therefore an important bottom-up control on hillslope stability, leaving an ongoing legacy of knickpoint retreat within the landscape, and may erode evidence of past environmental conditions through the removal of preserved strath terraces downstream of knickpoints (Baynes, Lague, & Kermarrec, 2018). The longer-term legacy of knickpoint retreat on hillslopes has important implications for setting the wider timescale of landscape response to transient forcing (Hurst et al., 2019), and variable channel width should be an important component of landscape evolution models where possible. The quantification of rates of channel widening relative to knickpoint retreat in natural settings would further demonstrate the importance of in-channel processes for hillslope destabilization.

3.4 | Role of in-channel sediment supply in setting the degree of hillslope destabilization

Previous field and experimental observations (e.g. Baynes et al., 2020) and modelling studies (Li et al., 2020; Turowski, 2018, 2020) have
shown that channels with higher sediment supplies are typically wider for a given discharge, thought to be due to the ‘cover effect’ that protects the bed from vertical incision and encourages lateral erosion of the banks by particle impacts (the ‘tools effect’); Sklar & Dietrich, 2004). Here, we show that sediment-rich channels under transport-limited conditions are not only wider under equilibrium conditions (Baynes et al., 2020), they also undergo a more dynamic response to transient forcing (i.e. knickpoint retreat), as they narrow proportionally more from their equilibrium state compared to low Qs channels (Figures 2 and 4). Absolute KPw values are similar for both Qs = 0 and 0.00666 g cm⁻³ experiments at a given discharge (Figure 2a), which is expected as the higher slope at the knickpoint increases the sediment transport capacity significantly (Croissant et al., 2017), such that the higher sediment supply has a negligible impact on the channel width under knickpoint conditions compared to equilibrium (Baynes et al., 2020). As the channels return to WEQ following the passage of the knickpoint and the slope of the channel is reduced (during phase 3 in Figure 8), channels with a high Qs and therefore the bed are protected by the ‘cover effect’ widened to a larger extent, and therefore potentially have a stronger role in undermining the adjoining hillslopes through bank erosion (Kondolf et al., 2002). There exists a potential positive feedback, whereby channels with a higher Qs experience a more pronounced wave of lateral adjustment during knickpoint retreat, leading to an increased likelihood of hillslope destabilization following the passage of a knickpoint. In turn, the heightened hillslope instability supplies more sediment to the channel through mass wasting (Attal et al., 2015; Gallen et al., 2011), completing the positive feedback loop with a wider equilibrium channel state before the migration of subsequent knickpoints in response to further base-level falls. Such an observation from the experiments presented here highlights an additional complexity resulting from the presence of sediment in bedrock channels and highlights its importance for both erosion processes and wider landscape response.

4 CONCLUSION

Headward-migrating knickpoints are key features of transiently adjusting landscapes through the translation of bottom-up signals of base-level fall or changes in tectonic uplift through the river network and the adjoining hillslopes. In addition to the rapid vertical incision associated with knickpoint passage, we show here—using a suite of analogue flume experiments—that a wave of lateral adjustment of channel geometry (narrowing by up to 80% compared to equilibrium conditions, followed by a widening after the passage of a knickpoint) can have a long-lasting impact on the stabilization of hillslopes. The relative degree of channel narrowing/widening is independent of the water discharge, but channels with a high sediment load experience a greater extent of narrowing/widening compared to channels with a lower sediment load, and the lateral adjustment can be more important for the destabilization of hillslopes than the magnitude of vertical incision. Rates of lateral adjustment are typically slower than rates of upstream knickpoint migration, therefore having a longer-term impact on the stability of hillslopes than rapid bed-elevation change. These observations enhance the importance of understanding the key processes that drive the migration of knickpoints, as the localized channel geometry response has ongoing implications for the stability of adjoining hillslopes and, therefore, the supply of sediment to the channel network and export from landscapes.

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AUTHOR CONTRIBUTIONS

EB, DL and PS designed the study. PD developed the numerical hydrodynamic model. EB performed the laboratory experiments and numerical simulations. All authors contributed to the data analysis and interpretation of the results. EB wrote the paper with input from all the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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