

Technical note

Conceptual basis and operational guidance for inferring drainage divide migration and river capture using topographic data

Bases conceituais e guia operacional para inferir migração de divisores de drenagem e capturas fluviais com dados topográficos

Daniel Peifer¹

¹ Federal University of Minas Gerais, Department of Geography, Belo Horizonte, Brazil. peiferdaniel@gmail.com.
ORCID: <https://orcid.org/0000-0001-9238-5072>

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Abstract: Drainage divide migration and river capture reorganise drainage networks by redistributing drainage area between adjacent basins, thereby altering water and sediment fluxes, patterns of fluvial incision, and ecological connectivity. Computational advances have made it routine to derive landscape-scale topographic metrics that are commonly used to suggest divide instability and drainage reorganisation. This operational ease, however, has not been matched by a detailed conceptual-operational guide that makes explicit the underlying assumptions, limitations, and best practices. Here, I provide a roadmap to infer divide mobility and discrete capture events from topography. I first introduce the χ integral transformation and key practical decisions for its use, including extensions for spatially variable uplift and effective erodibility and the link between χ and fluvial response times. I then outline a workflow to infer likely divide mobility from cross-divide χ contrasts between adjacent basins and complementary hillslope-asymmetry metrics, emphasising internal consistency checks and sensitivity tests. Finally, I develop an evidence-based logic for diagnosing discrete captures centred on topographic archives that record past connectivity, especially windgaps and valley-scale inherited geometry. I show how these archives can be quantified and how to evaluate alternative controls (regional transients driven by changes in tectonics, lithology, and climate) to reduce false positives. I conclude by outlining minimum reporting standards and operational recommendations.

Keywords: drainage divides; chi metric; divide migration; river capture; windgaps.

Resumo: A migração de divisores de drenagem e as capturas fluviais reorganizam redes de drenagem ao redistribuírem área entre bacias adjacentes, modificando os fluxos de água e de sedimento, os padrões de incisão fluvial e a conectividade ecológica. Avanços computacionais tornaram rotineiro o cálculo de métricas topográficas usadas para indicar instabilidade de divisores e reorganização fluvial. Essa facilidade operacional, porém, não foi acompanhada de um guia conceitual-operacional detalhado que explicita hipóteses, limitações e boas práticas. Nesta nota técnica, proponho um roteiro para inferir mobilidade de divisores e capturas discretas a partir da topografia. Primeiro, apresento a transformação integral χ e decisões críticas de uso, com extensões para variações espaciais de soerguimento e erodibilidade, e a ligação de χ ao tempo de resposta fluvial. Em seguida, mostro como inferir a mobilidade provável de divisores a partir de contrastes de χ entre bacias adjacentes e de métricas de assimetria de encosta. Por fim, desenvolvo uma lógica de evidências para capturas discretas centrada em arquivos topográficos que registram conectividade pretérita, sobretudo *windgaps* e geometria herdada em escala de vale. Mostro como os principais arquivos admitem quantificação e como avaliar controles alternativos, reduzindo os falsos positivos. Encerro com boas práticas e critérios mínimos de reporte.

Palavras-chave: divisores de drenagem; métrica χ ; migração de divisores; captura fluvial; *windgaps*.

1. Introduction

Drainage divides organise and delimit the terrestrial surface into drainage basins and, by extension, control the transfer of water, sediment, and biota across landscapes. In topographic maps and digital elevation models (DEMs), a divide can be represented by a line. Although this line appears fixed over human timescales, drainage divides are dynamic geomorphological features: their position results from competition between adjacent drainage networks and from the balance between processes that lower or raise surface elevation through time (Gilbert, 1877; Willett et al., 2014; He et al., 2024).

This competition does not depend only on instantaneous or local cross-divide erosional asymmetries (He et al., 2024). Divide mobility responds to persistent cross-divide contrasts in relative surface lowering between adjacent basins, that is, to the balance between relief-generating processes, such as rock uplift or relative base level fall, and surface-lowering processes, such as denudation or fluvial incision. When one side lowers surface elevation more rapidly than the other, the divide tends to migrate towards the relatively less efficient side, transferring drainage area through time. However, cross-divide erosional asymmetries do not necessarily imply present-day mobility: spatial differences in rock uplift, erodibility, denudation, network geometry, or drainage-area distribution may compensate for one another or become stabilised, maintaining a stable divide even under apparent topographic asymmetry (see, for example, Figure 6 in Shelef; Goren, 2021). Therefore, the central question is not merely whether local erosional asymmetry exists, but whether it expresses a persistent cross-divide contrast in relative surface lowering capable of sustaining horizontal divide displacement (Bishop, 1995; Willett et al., 2014; He et al., 2024).

Two modes of drainage reorganisation are particularly important. The first is gradual divide migration, in which a persistent cross-divide contrast in relative surface lowering sustains the progressive advance of one drainage basin into an adjacent one (Bishop, 1995; He et al., 2024). The second is river capture, a discrete reorganisation in which a topological change diverts part of the flow from one basin to another, annexing headwaters and preserving, as an inherited record, part of the pre-capture geometry (Bishop, 1995; He et al., 2024). Although both processes redistribute drainage area and modify water and sediment fluxes, they differ in the timescale of adjustment, the type of geomorphological evidence expected, and the inferential logic required to diagnose them (He et al., 2024).

Recent interest in divide migration and river capture has been driven by three complementary developments. First, conceptual advances have clarified the link between drainage-network reorganisation, patterns of fluvial incision, and divide geometry, with implications for sediment dynamics and the evolution of longitudinal profiles (Willett et al., 2014; Yang; Willett; Goren, 2015; Whipple et al., 2017). Second, an interdisciplinary research agenda has emerged in which drainage reorganisations are recognised as controls on ecological connectivity, dispersal routes, and isolation, with implications for biogeography (e.g., Burridge; Craw; Waters, 2006; Hoorn et al., 2010; Craw et al., 2016; Albert et al., 2017; Musher et al., 2022; Salles et al., 2023; Stokes et al., 2023a; Liu et al., 2024; Vance et al., 2025). Third, advances in digital elevation models and computational tools have made it routine to calculate landscape-scale topographic metrics used to infer divide instability and drainage reorganisation (e.g., Willett et al., 2014; Schwanghart; Scherler, 2014; Scherler; Schwanghart, 2020), reducing operational barriers and broadening the use of these approaches.

The emphasis on topographic data in this technical note is deliberate. Divide migration and, in particular, river capture are rarely observed directly, and many of their sedimentary, stratigraphic, chronological, or biogeographical records are discontinuous, absent, or preserved only locally (Bishop, 1995; He et al., 2024). By contrast, DEMs allow drainage networks, divides, and morphological archives to be examined at landscape scale, providing a reproducible basis for screening, comparison, and hypothesis formulation. This advantage is important because the identification of captures and divide mobility still tends to be selective: conspicuous features are frequently revisited, whereas many other potentially mobile drainage divides remain poorly tested. An explicit and systematic topographic approach does not eliminate this limitation, but it helps reduce sampling bias and makes the pathway from morphological observation to geomorphological hypothesis and interpretation auditable.

This does not mean that topographic metrics replace field surveys or independent records when these are available. On the contrary, the relationship should be bidirectional. Topographic inferences can be evaluated using preserved alluvial deposits, terraces, gravel deposits, palaeoflow indicators, stratigraphy, sediment provenance, biogeographical records, or field relationships between lithology, structure, and inherited forms (Bishop, 1995; He et al., 2024). However, they can also guide these investigations by indicating where to search for alluvial material

on low-elevation divides, which underfit valleys, that is, valleys oversized relative to the modern drainage, may preserve sedimentary records, and which basin pairs offer more robust tests of past connectivity. The aim, therefore, is to establish criteria so that topographic inferences can be formulated explicitly, auditably, and with less circularity, indicating when they are strong, when they are conditional, and when they require testing against independent evidence. Because these are inferential criteria rather than a regional typology, they are transferable to different landscapes, including Brazilian ones, provided that the tectonic, denudational, lithological, climatic, and structural context is made explicit and the available independent evidence is considered.

Despite this operational gain, interpretative progress has not occurred at the same pace. Products such as χ maps, χ values, and metrics of morphological asymmetry between adjacent basins have sometimes been used as direct evidence of drainage reorganisation, although they depend on strict assumptions, including spatial uniformity in rock uplift and erodibility, consistent boundary conditions, and appropriate parameterisation. Moreover, two inferential targets are frequently conflated: gradual migration is a diagnosis of tendency under divide disequilibrium, whereas discrete river captures require evidence of past connectivity and topological change.

This technical note is organised to reduce these confusions while offering a conceptual and operational guide for inferences based on topographic data. First, I establish what χ represents, which assumptions allow it to be linked to incision potential and disequilibria in drainage networks, and where its limits lie. I then present a workflow for inferring gradual divide migration from χ and hillslope-asymmetry metrics. Finally, I develop an expanded section on discrete river captures, structuring an evidential logic in which windgaps, that is, low-elevation divide segments that may preserve the geometry of a former fluvial passage, and other topographic archives are evaluated sequentially, with explicit attention to plausible alternatives, sampling bias, and the role of topographic inferences as a guide for sedimentary, chronological, biogeographical, and field investigations.

2. Theoretical foundations: the stream-power model and Flint's law

The stream-power model is presented in this technical note because it provides a conceptual bridge between physical processes, the shape of longitudinal profiles, and the metrics commonly used to infer disequilibrium in drainage networks. It should not be read as a complete description of all processes involved in fluvial incision, but as a simple and widely used formulation that makes explicit how slope, drainage area, relative uplift, and fluvial erodibility enter the interpretation of fluvial topography (cf. Peifer et al., 2022). This formulation is also important because it allows one to move from the local slope-area relationship to integral methods, such as the χ transformation, which reduce dependence on local slope estimates extracted directly from DEMs (Perron; Royden, 2013; Mudd et al., 2014).

The morphology of longitudinal profiles in bedrock rivers is commonly interpreted within a framework that balances relief generation relative to base level and fluvial incision. A widely used form of this balance is the stream-power model (Howard; Kerby, 1983):

$$\frac{\partial z(x,t)}{\partial t} = U(x,t) - K(x,t) A(x,t)^m S(x,t)^n, \quad (1)$$

where $z(x,t)$ is bed elevation along the longitudinal coordinate x and through time t , $U(x,t)$ represents an effective rate of relative uplift or relative base level fall with respect to the river, $K(x,t)$ is an effective coefficient of fluvial erodibility, $A(x,t)$ is upstream drainage area, and $S(x,t)$ is local channel slope, equivalent to $|dz/dx|$. The positive exponents m and n control how A and S modulate the incision rate.

The interpretation of Eq. (1) requires caution. The term U should not be read only as absolute tectonic uplift. In this formulation, it represents an effective rate of relative uplift between the river profile and its base level. Positive U may therefore reflect rock uplift or relative base level fall. Conversely, subsidence or base level rise would reduce this relative uplift, or appear as negative U , depending on the sign convention adopted. Likewise, K rarely corresponds to “pure” erodibility. In practice, K synthesises controls that affect the efficiency of fluvial erosion, such as lithology, structure, the degree of rock fracturing, the hydrological regime, and the availability of sediment either as an abrasive tool or as protective bed cover. Finally, A is commonly used as a proxy for discharge, although this approximation has limitations where precipitation, evapotranspiration, infiltration, and hydrological connectivity vary spatially (Whipple; Tucker, 1999).

If a river reach is close to dynamic equilibrium in the sense that $\partial z/\partial t \approx 0$, then Eq. (1) reduces to:

$$K A^m S^n \approx U. \quad (2)$$

Solving for S :

$$S = \left(\frac{U}{K}\right)^{1/n} A^{-m/n}. \quad (3)$$

Defining the concavity index as $\theta = m/n$ and the channel steepness index as $k_s = (U/K)^{1/n}$, one obtains the classical form associated with Flint's law (Flint, 1974):

$$S = k_s A^{-\theta}, \quad (4)$$

where:

$$k_s = \left(\frac{U}{K}\right)^{1/n}. \quad (5)$$

Geomorphologically, this relationship expresses the general tendency for longitudinal profiles to be concave: as drainage area increases downstream, the slope required to maintain a given incision rate tends to decrease. Thus, under comparable conditions of U and K , a larger drainage area allows a river to maintain a given incision rate with a lower channel slope. In this formulation, θ controls concavity in the geometric sense: the larger θ is, the more rapidly slope decreases as drainage area increases (Kirby; Whipple, 2012). In turn, k_s controls the scale of the slope field for a fixed concavity: for the same θ , reaches with higher k_s are systematically steeper across the same range of drainage areas (Kirby; Whipple, 2012). Where U and K are approximately spatially uniform, k_s can be interpreted as an integrated measure of the steepness required to balance rock uplift and fluvial incision (Lague, 2014).

The slope-area relationship underpins classical analyses of longitudinal profiles (Kirby; Whipple, 2012), but it also highlights a practical difficulty: estimating S as a local derivative of a DEM can amplify topographic noise, drainage-routing errors, resolution artefacts, and short-wavelength irregularities. Integral methods, such as χ , are particularly useful because they reduce this dependence on local slope, allowing normalised channel steepness to be estimated from the slope of the elevation- χ relationship rather than relying directly on local slope-area regressions or noisy derivatives of the longitudinal profile (Perron; Royden, 2013; Mudd et al., 2014).

Comparing k_s among rivers requires caution because k_s depends on the concavity adopted (Mudd et al., 2018). In practical applications, a reference concavity θ_{ref} is defined and the drainage-area-normalised channel steepness index (k_{sn}) is calculated:

$$k_{sn} = S A^{\theta_{ref}}. \quad (6)$$

This normalisation is not a technical detail. It changes magnitudes and, in networks with large variations in drainage area, may also change the relative contrasts between reaches (Kirby; Whipple, 2012). For this reason, any analysis that uses k_{sn} as a proxy for erosional potential must report θ_{ref} and justify its choice (Peifer; Cremon; Alves, 2020). Where K and climate are approximately uniform, variations in k_{sn} may be interpreted as relative differences in incision or effective uplift. Where U , K , and climate vary simultaneously, this interpretation is no longer direct: k_{sn} records a combination of these controls, and its interpretation requires independent context.

3. The χ integral transformation: derivation, properties, choices, and extensions

The χ transformation can be understood as a change of coordinates arising from both conceptual and operational motivations. Conceptually, it reorganises the longitudinal profile in order to account for the expected effect of drainage area on channel slope (Perron; Royden, 2013). Operationally, it avoids making the interpretation dependent on direct estimates of local slope from the DEM, a step that is sensitive to topographic noise, data resolution, and smoothing choices (Perron; Royden, 2013; Mudd et al., 2014). Instead of representing the profile only by distance along the river, χ replaces x with an integrated distance weighted by upstream drainage area. As a result, k_{sn} can be estimated from the slope of the elevation- χ relationship, rather than from the direct differentiation of z with respect to x or from local slope-area regressions (Perron; Royden, 2013; Mudd et al., 2014).

This operation preserves connectivity to base level and the accumulated geometry of the drainage network, but reorganises the profile into a coordinate in which equilibrium channels, under comparable U and K , tend to

show approximately linear relationships between elevation and χ (Perron; Royden, 2013). Where profiles that should be comparable do not collapse in this space, the difference may indicate transience, drainage reorganisation, inappropriate choice of θ_{ref} , inconsistent base level, or spatial heterogeneity in U and/or K . Therefore, χ is not merely a number calculated along the drainage network, but a coordinate that organises comparison between profiles under explicit assumptions and with practical advantages over the direct estimation of slope (Perron; Royden, 2013; Mudd et al., 2014).

3.1. Derivation from steady state

Starting from the local steady-state form of the stream-power model, with $\partial z/\partial t \approx 0$, Eq. (1) can be rearranged into slope-area form. Since $S = |dz/dx|$, this relationship can also be read as a differential expression for the variation in elevation along the longitudinal profile:

$$\frac{dz}{dx} = \left(\frac{U}{K}\right)^{1/n} A(x)^{-\frac{m}{n}}. \quad (7)$$

Integrating along the river from a reference base level x_b to an upstream point x (Perron; Royden, 2013):

$$z(x) = z(x_b) + \int_{x_b}^x \left(\frac{U}{K}\right)^{\frac{1}{n}} A(x')^{-\frac{m}{n}} dx'. \quad (8)$$

Introducing a reference area A_0 to make the term involving A dimensionless, this can be rewritten as:

$$z(x) = z(x_b) + \left(\frac{U}{K A_0^m}\right)^{1/n} \chi(x). \quad (9)$$

In this expression, $\chi(x)$ is the transformed distance coordinate defined as:

$$\chi(x) = \int_{x_b}^x \left(\frac{A_0}{A(x')}\right)^{\frac{m}{n}} dx' = \int_{x_b}^x \left(\frac{A_0}{A(x')}\right)^{\theta} dx'. \quad (10)$$

The passage from Eq. (8) to Eq. (9) assumes U and K to be spatially uniform, or sufficiently comparable within the analysed domain, so that the term can be taken outside the integral. This is the central simplification of the classical form of χ . In practice, it means that spatial variation in the elevation- χ profile is attributed mainly to drainage-network geometry, drainage area, and transients, rather than to strong spatial contrasts in uplift or erodibility. Where this assumption is not defensible, the generalised form discussed in Section 3.5 is more appropriate.

The χ coordinate is the distance along the fluvial profile weighted by upstream drainage area: it combines geometry (dx) and topology (A) into a coordinate with dimensions of length, generally metres. Numerically, it is calculated along the connected nodes of the drainage network by discrete integration along flow distance. In practice, the integral is approximated by a sum of the form $\sum_i (A_0/A_i)^\theta \Delta x_i$, using the distance increments and the area A_i associated with each reach.

3.2. Slope in elevation- χ space and its connection with k_s and k_{sn}

The integration above produces a function that relates the elevation of the fluvial profile to the χ coordinate. Under approximately uniform U and K , and for a river close to equilibrium, a linear relationship of the following type is expected (Perron; Royden, 2013; Mudd et al., 2014):

$$z(\chi) = z(x_b) + M\chi. \quad (11)$$

In this expression, $z(x_b)$ is the intercept, that is, the elevation of the adopted base level, and M is the slope of the elevation- χ relationship. Under the assumptions of the stream-power model, M represents the scaling factor imposed by U , K , and the exponents of the incision law (Mudd et al., 2014):

$$M = \left(\frac{U}{K A_0^m}\right)^{1/n}, \quad (12)$$

If $A_0 = 1$, then:

$$M = \left(\frac{U}{K}\right)^{1/n} = k_s. \quad (13)$$

That is, for this choice of A_0 , M coincides with the steepness index k_s (Eq. 5). In practical applications, however, χ is frequently calculated using a reference concavity θ_{ref} . In this case, the slope in elevation- χ space is commonly interpreted as k_{sn} (Mudd et al., 2014, 2018).

3.3. Internal consistency: linearity and tributary collapse

Conventional longitudinal profiles $z(x)$ plotted as a function of x tend to be concave because local channel slope decreases as drainage area increases (Eqs. 3 and 4). The χ transformation replaces x with a coordinate that incorporates this dependence and, by construction, linearises the steady-state solution in elevation- χ space (Perron; Royden, 2013).

Where a river and its tributaries share similar U and K conditions and the chosen concavity (θ_{ref}) is appropriate for the drainage network, the trunk river and its tributaries are expected to collapse around an approximately linear trend in elevation- χ space (Perron; Royden, 2013). The converse is also informative: systematic curvature and lack of collapse should not be treated as noise, because they generally indicate transience and/or spatial heterogeneity in U or K , inappropriate θ_{ref} , or a combination of these factors.

A practical protocol for choosing θ_{ref} may combine: (1) linearity of the trunk river in elevation- χ space, evaluated through linear fits and curvature diagnostics for tested values of θ_{ref} (Mudd et al., 2018); and (2) collapse of tributaries onto the trend of the trunk river, quantified by the dispersion around the trunk-river regression or by an aggregate misfit across different stream orders (Hergarten; Robl; Stüwe, 2016; Mudd et al., 2018). In the open-source software TopoToolbox (Schwanghart; Scherler, 2014), for example, routines such as *mnoptimvar* can automate the second criterion by estimating the best θ_{ref} on the basis of tributary-collapse performance. If the trunk river appears linear but the tributaries do not collapse, this is a warning: trunk linearity may reflect random compensations between heterogeneities, such as lithology or transients, and the adopted parameterisation (Mudd et al., 2018).

Figure 1 summarises these properties of the χ transformation using a real example. Panel B shows the conventional longitudinal profiles of the trunk river and its tributaries, whereas panel C shows the same profiles in elevation- χ space, calculated with $\theta_{ref} = 0.45$. The comparison highlights two central points. First, the χ transformation reorganises the profiles into a coordinate that reduces the influence of drainage-area effects and allows the trunk river and its tributaries to be compared more directly. Second, shared transient perturbations, such as slope breaks (knickpoints) associated with the same base level fall, tend to be expressed at similar χ values, even where they occur at different distances along conventional longitudinal profiles. In this space, the slope of segments in elevation- χ space provides k_{sn} for the adopted θ_{ref} , whereas systematic deviations from approximately linear trends may indicate transience, inappropriate parameter choice, or spatial heterogeneity in the effective controls.

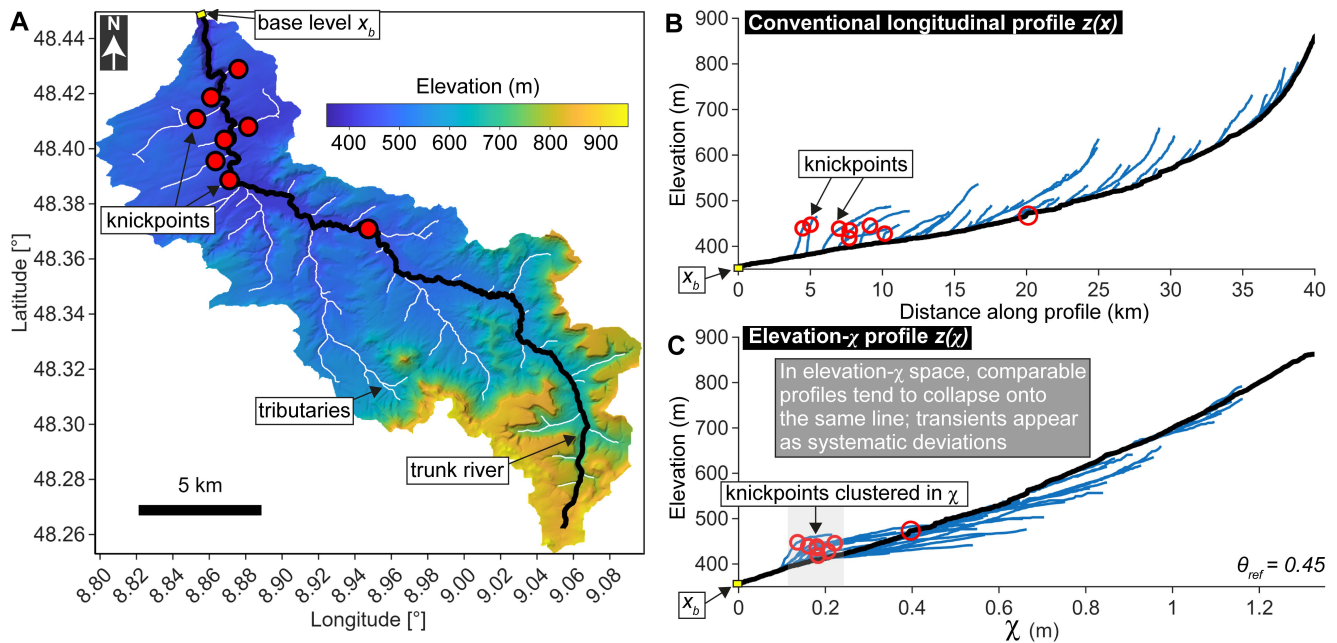


Figure 1. Illustrative example of the χ transformation in a basin affected by a transient perturbation associated with base level fall. (A) DEM of the analysed basin, derived from the LGL-BW ATKIS Digitales Geländemodell DGM 5 m (2005), with the drainage network extracted using a drainage-area threshold of 1 km² in TopoToolbox, the trunk river highlighted in black, and tributaries in white. Red circles indicate knickpoints identified by the TopoToolbox *knickpointfinder* algorithm, with a tolerance of 30 m (e.g., Calegari et al., 2021). The base level adopted for calculating χ , x_b , corresponds to the outlet of the analysed basin, at the confluence with the receiving river. (B) Conventional longitudinal profile, $z(x)$, of the trunk river and its tributaries. Note that the knickpoints align within a narrow range of elevation values. (C) The same profiles represented in elevation- χ space, $z(\chi)$, calculated with $\theta_{ref} = 0.45$. The χ transformation replaces distance along the profile with an integrated distance weighted by upstream drainage area. As a result, comparable profiles tend to organise into approximately linear and collinear relationships, whereas shared transient perturbations appear as systematic deviations. The slope of segments in elevation- χ space provides k_{sn} for the adopted value of θ_{ref} ; in this example, the knickpoints cluster at similar χ values, indicating a common transient response.

3.4. Base level (x_b): common, arbitrary, and sensitive

In the example in Figure 1, the adopted base level, x_b , corresponds to the outlet of the analysed basin, defined by the confluence between the trunk channel of this basin and the receiving river. This example illustrates a simple and geomorphologically defensible choice of reference level for χ integration, but it also anticipates a central issue: comparability between profiles depends on the choice of a common base level and a coherent calculation domain.

The χ integral depends on the lower integration limit x_b . Therefore, χ values are directly comparable only where the rivers analysed are referenced to a common base level and calculated within a domain that preserves complete connectivity to that base level or reference elevation (Willett et al., 2014). In this context, “common” has a strict meaning: the channels being compared must share the reference elevation used as the lower limit of integration. This condition does not require the points used to represent x_b to have the same spatial position, but it does require the drainage networks to be truncated or referenced consistently to the same base level elevation.

The choice of this reference elevation is partly arbitrary, but it should not be casual. There is no universally correct base level for all problems, because the choice depends on the scale of analysis, the organisation of the drainage network, the extent of the available domain, and the inferential objective. A simple practice is to use the same elevation that intersects all networks being compared within the analysed domain, provided that connectivity to this reference is preserved. Another possibility is to use an absolute base level, for example 0 m, when the analysis is conducted down to sea level. However, this choice may be operationally problematic in continental or extensive regional studies, because it requires DEMs covering very large areas and may incorporate low-relief reaches, alluvial plains, or areas with hydrological and elevation uncertainties disproportionate to the problem being analysed.

For this reason, in many cases it is more defensible to choose common base levels associated with recognisable geomorphological or geological boundaries. Examples include the confluence with a trunk river, the transition between a tributary and the regional collector valley, the passage from a predominantly bedrock reach to a continuously alluvial domain, or the transition between geotectonic or morphostructural domains. The central point is that the chosen base level must be made explicit, applied consistently to all networks being compared, and justified in relation to the geomorphological problem. Approaches of this type are consistent with analyses that treat drainage-network geometry in relation to regional domains and to base levels controlled by large basins or geomorphological transitions (e.g., Winterberg; Willett, 2019).

Even when a common x_b is imposed, χ patterns may be sensitive to the position chosen for the base level and to the size of the domain that ensures connectivity to that point. Forte and Whipple (2018) demonstrate this problem in the Greater Caucasus Mountains, where χ maps calculated from different defensible choices of base level – base levels at outlets to the Black Sea and the Caspian Sea, a constant elevation approximating the mountain front, and the bedrock-alluvial transition – produce different interpretations of divide stability and, in some sectors, even of the polarity of the interpreted signal. This shows that different choices of x_b may alter not only the magnitude of χ contrasts, but also which side of the divide appears to have relatively higher or lower χ for a given comparison. Therefore, χ -based inferences may include sensitivity tests to geomorphologically defensible choices of x_b , verifying whether the interpreted signal, for example the predicted direction of divide migration, remains stable. Where the signal changes as a result of a plausible variation in x_b , this instability should not be concealed: it is part of the result and indicates that the directional inference is sensitive to the adopted reference frame.

3.5. Generalised χ where U or K vary spatially

The classical form of χ (Eq. 10) is strictly appropriate where U and K can be treated as approximately uniform within the analysed domain, such that variations in the elevation- χ profile are attributed mainly to drainage-network geometry and transients (Perron; Royden, 2013). In real landscapes, this approximation is not always adequate. Lithological contrasts, structural heterogeneity, spatial variations in effective climate, and tectonic gradients may produce relevant variations in K and/or U , so that part of the observed χ signal may reflect these variations without, in itself, implying divide mobility.

Where known or defensible spatial variation in U and/or K exists, the coordinate that linearises the steady-state solution should incorporate this heterogeneity. To do so, U and K may be decomposed into reference values and relative spatial functions:

$$U(x) = U_0 U^*(x), \quad (14a)$$

$$K(x) = K_0 K^*(x), \quad (14b)$$

where U_0 and K_0 are scalar reference values, whereas $U^*(x)$ and $K^*(x)$ are dimensionless functions that represent relative spatial variations in effective uplift and effective erodibility. Values of U^* or K^* greater than 1 indicate sectors that are higher than the reference value; values lower than 1 indicate sectors that are relatively lower. With this decomposition, a generalised form can be written as (Willett et al., 2014):

$$\chi' = \int_{x_b}^x \left(\frac{U^*(x') A_0^m}{K^*(x') A(x')^m} \right)^{1/n} dx', \quad (15)$$

such that:

$$z(x) = z(x_b) + \left(\frac{U_0}{K_0 A_0^m} \right)^{\frac{1}{n}} \cdot \chi'. \quad (16)$$

The central point of this formulation is not to suggest that U^* and K^* are easily known at sufficient spatial resolution in every application. In practice, this formulation serves three complementary functions. First, it disciplines interpretation: differences in χ may reflect spatial heterogeneity in U and/or K , not only divide instability or transience associated with drainage-network reorganisation. Second, it makes explicit what is being assumed when classical χ is calculated: that spatial variations in U and K are small, irrelevant to the problem being analysed, or cannot be incorporated in an independent and defensible way. Third, where external information

exists on spatial variations in rock uplift or effective erodibility, χ' can be used as an operational test. The question is no longer only “is there a contrast in χ ?”, but rather: does the interpreted pattern, for example the migration direction predicted by cross-divide contrasts in χ , persist when independent and plausible variations in U^* or K^* are incorporated?

A plausible variation in U^* or K^* should not be defined on the basis of the χ pattern that one seeks to explain. For U^* , it may be based on tectonic domains with well-established relative rock uplift rates, on geodetic, thermochronological, geological, and geomorphological data, on incision estimates, or on numerical modelling scenarios constructed to test an explicit tectonic hypothesis. For K^* , it may be anchored in mapped lithological contrasts, structural differences in fracturing and rock strength, empirical calibrations between effective erodibility and erosion rates, or persistent climatic gradients that affect effective discharges and the efficiency of fluvial incision. Studies such as Ferrier et al. (2013), Gallen (2018), Peifer et al. (2021), and Molin et al. (2023) illustrate different pathways for estimating or justifying spatial variations in effective erodibility K associated, for example, with precipitation, lithology, rock strength, denudation rates, and the inversion of river profiles.

The usefulness of χ' is therefore greatest where the landscape contains strong and independent spatial contrasts in U or K . In a landscape that crosses markedly different tectonic, morphostructural, or lithological domains, for example, these contrasts are expected to affect spatial patterns of χ . In such cases, interpreting cross-divide contrasts in χ directly as divide mobility, without considering spatial variations in U and K , may lead to significant errors, including reversal of the polarity of the inferred migration direction. This point is demonstrated by Whipple et al. (2017) and Forte and Whipple (2018), who show that χ anomalies may diverge from metrics more directly linked to local relief and erosional contrast near the divide where there are spatial variations in U , K , climate, or base level.

The generalised formulation proposed by Willett et al. (2014) provides the conceptual basis for this correction. Habousha et al. (2023) demonstrate an explicit operationalisation of this concept in experimental and numerical landscapes subjected to spatial uplift gradients. In that case, the calculation of χ' incorporates a spatial grid of U/K values and allows the expected direction of divide migration to be evaluated under conditions of differential uplift (Habousha et al., 2023). The example is particularly illustrative because the pattern of U is known in advance, avoiding circularity. In natural landscapes, the equivalent application requires independent estimates of U^* or K^* , even if approximate. Where such estimates exist, χ' is preferable to classical χ ; where they do not, interpretation should remain conditional and be accompanied by complementary metrics and consistency checks.

3.6. χ and fluvial response times: connection with transients

Base level perturbations and changes in the effective controls on incision propagate through drainage networks as transient adjustments, expressed as an abrupt increase in local slope, or a knickpoint. In the stream-power model, it is common to interpret the migration of these transients using kinematic-wave formulations. In this class of approximations, the position of a knickpoint along the longitudinal profile follows an upstream migration velocity V_{kp} that depends on K and on the hydraulic geometry represented by A and S (Rosenbloom; Anderson, 1994; Whipple; Tucker, 1999):

$$V_{kp} = \frac{dx}{dt} = K A(x)^m S(x)^{n-1} . \quad (17)$$

This equation should be read as an approximation of knickpoint migration celerity, valid under assumptions that are not always fully met in real landscapes. In particular, it is more defensible where drainage is dominated by fluvial incision into bedrock and connectivity to base level is preserved. In extensive alluvial reaches, in reaches strongly controlled by alluvial sediment, or where abrupt lithological contrasts occur, the interpretation of V_{kp} as an effective celerity should be treated with caution.

Even so, the formulation is useful as a conceptual bridge to the χ coordinate. The integrated time τ required for a transient signal to travel from the base level x_b to an upstream point x can be described as (Whipple; Tucker, 1999; Goren; Fox; Willett, 2014):

$$\tau(x) = \int_{x_b}^x \frac{1}{V_{kp}(x')} dx' = \int_{x_b}^x \frac{1}{K A(x')^m S(x')^{n-1}} dx' . \quad (18)$$

The comparison of Eq. (18) with the definition of χ (Eq. 10) shows that both are integrals along flow distance, in which drainage area imposes a systematic weighting. For this reason, χ can be understood as a coordinate that orders the network according to a geometric component related to the “ease” with which transients propagate towards the headwaters, even though strict equivalence with time depends on additional assumptions about K and, for $n \neq 1$, S .

In the particular case ($n = 1$), the celerity expression simplifies to $V_{kp} = K A^m$, that is, migration depends only on A and K . If, in addition, K is spatially uniform and $A_0 = 1$, then (Goren; Fox; Willett, 2014; Gallen, 2018):

$$\tau(x) = \frac{1}{K} \chi(x). \quad (19)$$

Under this condition, χ is proportional to a kinematic response time with the scalar factor $1/K$. For $n \neq 1$, the presence of S^{n-1} makes τ sensitive to the form of the longitudinal profile during adjustment (Whipple; Tucker, 1999; Goren; Fox; Willett, 2014). Even so, the intuition remains: χ describes a geometric component of how signals associated with changes in base level or erosional efficiency tend to organise within the network.

This connection helps explain why χ is useful for discussing disequilibria and why it arises naturally in capture diagnoses. After a capture, for example, newly annexed reaches begin to respond to a new effective base level and to a new state of connectivity, so that the reorganisation can be interpreted as a transient propagating through the geometry of the drainage network. In this reading, χ does not “date” the event, but offers a convenient coordinate for organising patterns of adjustment and, with caution, comparing reaches that do or do not share the same base level reference and the same effective parameters (Willett et al., 2014).

4. Gradual divide migration: inference from metrics between adjacent basins

4.1. Physical rationale, implicit timescale, and interpretative limits

Gradual divide migration occurs when there is a persistent cross-divide contrast in relative surface lowering (Gilbert, 1877; Willett et al., 2014; He et al., 2024). In operational terms, if one side of the divide lowers surface elevation more rapidly than the other, whether through higher erosion, lower relative uplift, or both, the divide tends to shift towards the side that lowers surface elevation more slowly, transferring drainage area through time. Topographic metrics do not record this movement directly. They diagnose patterns of disequilibrium compatible with a likely direction of mobility, under explicit assumptions.

The use of χ in this context rests on the fact that, within the stream-power framework and under a common base level reference, differences in χ between headwaters competing across the same divide can be interpreted as geometric differences associated with the equilibrium state of the system (Willett et al., 2014). The physical intuition can be presented simply by exploring the symmetry of the comparison problem: when two adjacent basins are paired by the same local divide segment, the divide elevation is the same for both sides and, when the analysis is conducted correctly, the reference base level x_b must also be common. This means that χ integration must start from the same reference elevation for the channels being compared, even though the spatial position of the points used to represent this reference need not be the same.

Figure 2 applies this logic to the comparison between two adjacent channels in the Roan Plateau. Panels *A* and *B* show, in map view and oblique view, two channels that share a common divide and are referenced to the same base level elevation associated with the Colorado River. Panels *C* and *D* show these channels as conventional longitudinal profiles and in elevation- χ space. In *C*, both profiles reach the same divide, at the same elevation, and already show different longitudinal geometries; however, comparison using conventional distance alone does not isolate the drainage-area-weighted contrast that is made explicit in elevation- χ space. In *D*, for the same elevation difference between x_b and the common divide, the two channels show different maximum χ values. The river with the longer pathway to base level has a higher maximum χ , whereas the river with the shorter pathway has a lower maximum χ . This contrast between higher and lower maximum χ expresses the geometric disequilibrium of the drainage network and supports the inference of divide migration towards the side with the higher maximum χ , that is, the side that lies relatively higher with respect to its expected steady-state profile.

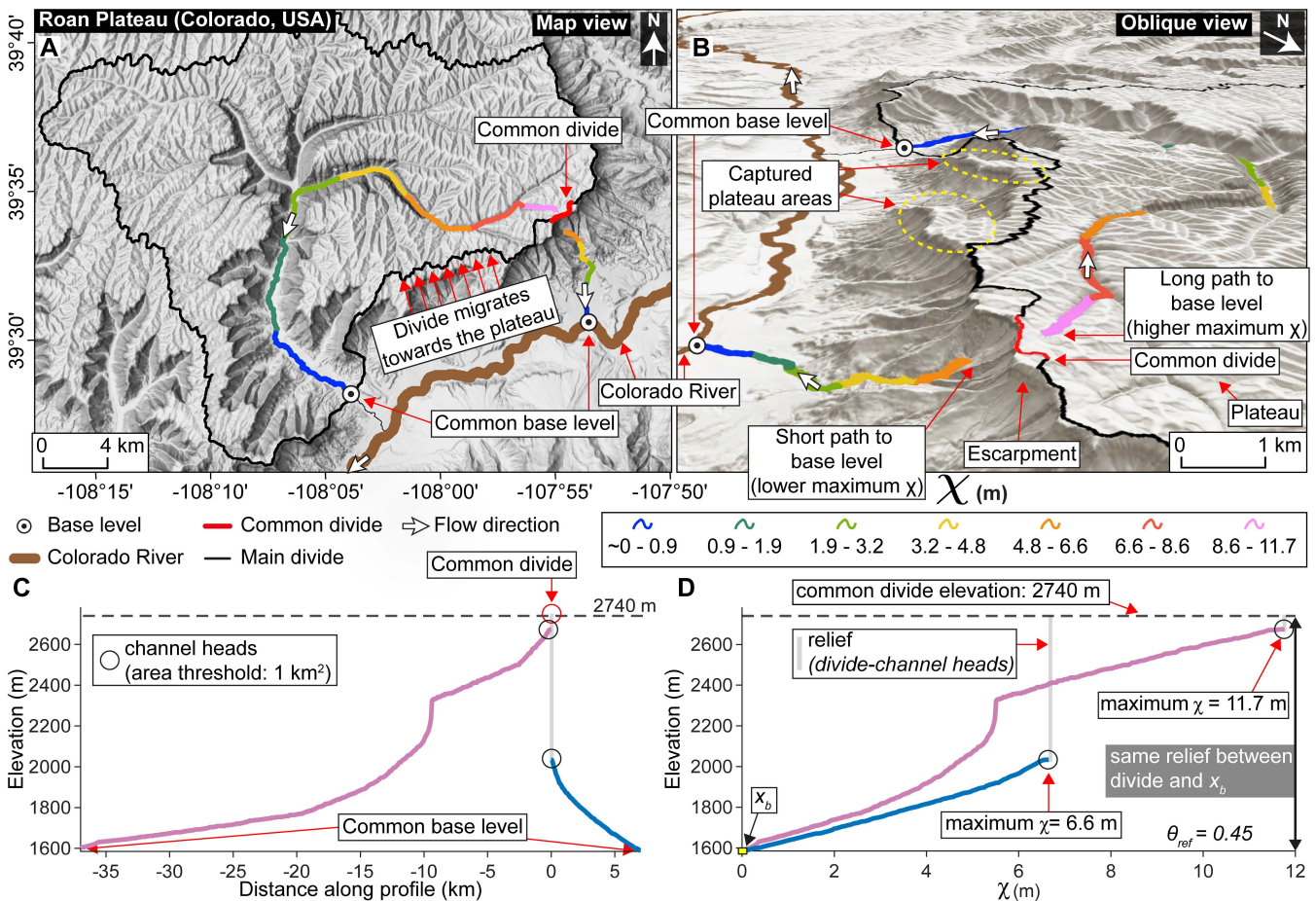


Figure 2. χ and divide instability in adjacent basins, exemplified in the Roan Plateau (Colorado, USA). (A) Map view of the channels compared, the main divide, the common divide, and the Colorado River. The elevation of the confluence of the most upstream tributary with the Colorado River was adopted as the common base level x_b ; the other system, whose confluence lies farther downstream and at lower elevation, is referenced to the same x_b elevation to ensure comparability. Colours along the channels represent χ values, which increase with integrated distance from base level. (B) Oblique view of the same sector, highlighting the contrast between short and long pathways to the common base level, as well as the relationship between the plateau, the escarpment, and the captured areas. (C) Conventional longitudinal profiles of the two channels compared, represented relative to the common divide. The dashed horizontal line indicates the divide elevation and black circles indicate the channel heads defined by the 1 km² drainage-area threshold. (D) Profiles of the same channels in elevation- χ space, referenced to the same x_b . For the same elevation difference between x_b and the common divide, the river with the longer pathway has a higher maximum χ , whereas the river with the shorter pathway has a lower maximum χ . This contrast is consistent with geometric disequilibrium of the network and with divide migration towards the side with higher maximum χ . DEM: Copernicus DEM 30 m.

In this scenario, relatively higher χ values near the channel head indicate that, in order to connect the same downstream reference to the divide neighbourhood, the network has accumulated a longer area-weighted distance. For the same elevation difference between x_b and the common divide, this corresponds to a lower slope in elevation- χ space relative to the opposing side. Under the assumption of spatially uniform U and K , this geometric asymmetry implies that the divide tends to migrate towards the side with higher χ (Willett et al., 2014).

One point worth making explicit is the implicit timescale. Metrics based on χ integrate information along the entire drainage network to base level and therefore carry a longer spatial and temporal “memory” than metrics calculated only in the immediate vicinity of the divide (He et al., 2024). By contrast, metrics based on local relief near the divide tend to reflect more local asymmetries and may respond more rapidly to recent changes precisely because they depend less on the whole domain and on the regional reference frame (He et al., 2024).

4.2. Necessary consistency checks before comparing adjacent basins using $\Delta\chi$

Here, $\Delta\chi$ refers to the contrast between χ values measured at channel heads or equivalent segments located on opposite sides of the same divide. In its simplest form, $\Delta\chi$ can be calculated as $\chi(\text{side 1}) - \chi(\text{side 2})$ for paired channel heads. The sign of $\Delta\chi$ therefore depends on the convention adopted to name the sides being compared. For this reason, any directional interpretation must explicitly state this convention and indicate which side has higher χ relative to the divide.

Before interpreting any map of χ contrasts between adjacent basins paired across the same divide, three consistency checks must be satisfied (Willett et al., 2014; Forte; Whipple, 2018). The first is base level consistency: the profiles and networks being compared must satisfy the conditions discussed in Section 3.4, that is, they must be referenced to the same x_b elevation and calculated within a domain that preserves complete connectivity to this reference. At this stage, the aim is not to redefine the criteria for choosing x_b , but to verify that the comparison using $\Delta\chi$ is not being contaminated by artificial differences in reference elevation, truncation, or spatial clipping.

The second is topological consistency. The channel heads being compared must, in fact, compete across the same local divide and drain, within the calculation domain, to the same base level reference. Comparing basins with different outlet elevations, or pairing channel heads that do not face one another across the same divide segment, mixes signals and may produce patterns that appear coherent only because of the geometry of the spatial subset. The third is geomorphological consistency. Strong lithological, tectonic, or climatic contrasts can generate or modify effective differences in K and/or U , expressed as contrasts in χ and local relief. This does not invalidate the analysis; on the contrary, it may reveal important controls on relative surface lowering and divide mobility. However, it changes the interpretation: in heterogeneous regions, a pattern of χ contrast should be treated as a conditioned hypothesis of disequilibrium, whose plausibility depends on agreement with other evidence, complementary metrics, or, where possible, correction using χ' based on independent information on U^* and/or K^* .

These consistency checks are not merely formal requirements; they define what $\Delta\chi$ can and cannot mean geomorphologically. As discussed in Section 3.4, Forte and Whipple (2018) show that plausible choices of x_b can alter both the magnitude and even the polarity of χ anomalies. Complementarily, Whipple et al. (2017) show that χ anomalies can occur even along stable divides where there is spatial variability in rock uplift, erodibility, or climate. Therefore, a contrast in $\Delta\chi$ should be treated as a conditioned hypothesis of disequilibrium, not as an automatic diagnosis of mobility. The inference is strengthened where the signal remains stable under defensible choices of x_b , θ_{ref} , calculation domain, and, where relevant, U or K , and where it converges with local metrics and independent geomorphological evidence.

4.3. Operational workflow for inferring mobility from χ contrast between adjacent basins

A reproducible workflow begins with DEM preparation and documented decisions on hydrological conditioning. These decisions include, at minimum, the method used to treat spurious depressions (for example, filling or breaching), the resolution of the topographic data, the drainage-area threshold (or other method) used to extract the drainage network, the adopted base level, the calculation domain, the value of θ_{ref} , the channel-head pairing criterion, and the sign convention adopted for $\Delta\chi$. They should be treated as part of the result because they directly condition the calculated values and the directional interpretation.

Next, a drainage-area threshold is defined for extracting the drainage network that represents the fluvial scale of interest. This choice is sensitive because, below a given threshold, the extracted river network may include reaches dominated by diffuse flow and hillslope processes (Kirby; Whipple, 2012). As a conservative rule, thresholds of the order of 1 km² tend to reduce this risk in regional applications, although smaller values are common and may be appropriate depending on DEM resolution, basin scale, and geomorphological context, provided that they are justified. Good practice is to test a range of thresholds and verify the stability of the main divides, consistency with valley morphology, and persistence of the interpreted signal.

Then, based on the criteria in Section 3.4, x_b is recorded and the calculation domain is delimited. The calculation domain is the spatial subset within which the drainage network is extracted, integrated, and compared while preserving complete connectivity of all analysed networks to x_b . This step should verify, rather than merely assume, that the base level is common, that the relevant confluences have been preserved, and that the channel heads being compared belong to the same geomorphological problem.

Once the domain is fixed, one chooses either a best-fit value for θ_{ref} or a reference value justified by the literature and by the analysed data (cf. Mudd et al., 2018). Only then is χ calculated for the entire network and channel heads are paired between adjacent basins that share the same local divide and drain, within the calculation domain, to the same base level reference. This pairing can be performed using different protocols, such as opposite channel-head pairs along a common divide, moving windows along the divide network, or automated procedures based on network topology. In all cases, the adopted criterion must be stated, because different pairing strategies may emphasise different divide segments.

With the channel heads paired, $\Delta\chi$, that is, the contrast in χ between the compared sides, is computed, and its sign and magnitude are mapped along the divide. The convention used to calculate the contrast must be explicit, for example $\Delta\chi = \chi(side\ 1) - \chi(side\ 2)$, so that positive and negative values have reproducible directional meaning. It is also necessary to ensure that the pairing respects divide topology, avoiding comparison of channel heads that do not compete directly across the same local segment (e.g., Beeson; McCoy; Keen-Zebert, 2017; Hu et al., 2021).

Where feasible, the calculation should be repeated using plausible variations in x_b and θ_{ref} to assess the robustness of the pattern (cf. Forte; Whipple, 2018). In landscapes with well-documented lithological, climatic, or tectonic heterogeneity, this test should also include the possibility of recalculating χ' under independent U^* and K^* scenarios. The most important result is not only the magnitude of $\Delta\chi$ under a preferred scenario, but the stability of the interpreted signal: if the predicted direction of migration changes when defensible alternatives for x_b , θ_{ref} , U^* or K^* are used, this sensitivity should be reported as part of the diagnosis rather than treated as a technical detail.

4.4. Local-relief asymmetry and predicted gradual migration direction

The tradition of interpreting divide mobility from topographic asymmetries goes back to Gilbert's (1877) logic, according to which divides tend to migrate where there is a persistent cross-divide contrast in erosion rates between the sides competing across the same divide. In the recent literature, metrics such as local relief, mean hillslope gradient, and channel-head elevation, generally referred to as "Gilbert metrics" (e.g., Forte; Whipple, 2018), have been used as complements to χ -based metrics precisely because they respond more locally to the erosional contrast near the divide (Whipple et al., 2017; Forte; Whipple, 2018). In this technical note, these metrics are treated as complementary indicators rather than substitutes for χ . Their role is to assess whether the tendency inferred from χ is consistent with the local asymmetry of the landscape.

Metrics based on χ integrate information along the entire basin and tend to reflect disequilibria over relatively long timescales and spatial scales. To capture disequilibria concentrated in the immediate vicinity of the divide, it is useful to incorporate metrics based on hillslope relief, with less dependence on the regional domain and the adopted base level (Forte; Whipple, 2018; He et al., 2024).

Divergence between integrated and local metrics can be geomorphologically informative. In Madagascar, for example, Clementucci et al. (2025) show sectors where χ differences relative to the divide indicate a long-term mobility direction, whereas local metrics associated with k_{sn} and relief near divides suggest an opposite tendency at a shorter scale. This disagreement is interpreted in the context of reorganisations related to rifting, volcanism, and localised Cenozoic tectonic activity. Cases of this kind illustrate why χ and local-relief metrics should not be treated as redundant: where they converge, they reinforce the interpretation; where they diverge, they point to differences in timescale, geological controls, or superimposed transients that require discussion.

A practical way to represent this asymmetry is to measure hillslope relief associated with the divide as the elevation difference between the divide and the channel head defined by the extracted drainage network on each side (Scherler; Schwanghart, 2020):

$$HR = z_{div} - z_{channel} , \quad (20)$$

where z_{div} is the divide elevation and $z_{channel}$ is the elevation of the corresponding channel head on each side. In practice, $z_{channel}$ is the elevation of the first node of the extracted network relative to the adopted drainage-area threshold (Scherler; Schwanghart, 2020). Because all channel heads are defined by the same contributing-area threshold, the comparison is made between competing channels whose starting points accumulate approximately the same upstream area. This reduces a common comparability problem in which "headwaters" are chosen at different hydrological positions in each basin.

The magnitude of the asymmetry can be summarised using a dimensionless index (Scherler; Schwanghart, 2020):

$$DAI_{adj} = \left| \frac{HR_1 - HR_2}{HR_1 + HR_2} \right|, \quad (21)$$

where HR_1 and HR_2 are representative values of hillslope relief on the two sides of a divide segment. Values close to zero indicate a locally symmetrical divide, whereas high values indicate strong local asymmetry, compatible with a contrast in erosional potential along the divide (Scherler; Schwanghart, 2020). Because this form uses an absolute value, it describes the magnitude of asymmetry but does not preserve the direction of the contrast.

When the objective is to infer the likely direction of mobility, a signed form must also be retained:

$$DAI_s = \frac{(HR_1 - HR_2)}{(HR_1 + HR_2)}. \quad (22)$$

In this case, the sign convention must be declared. For example, if positive values are defined as $HR_1 > HR_2$, then the sign indicates that side 1 has greater hillslope relief relative to side 2; the directional interpretation will depend on how side 1 and side 2 were assigned in the pairing and on the assumption adopted to relate greater local topography, erosional potential, and divide migration. Without this convention, the metric indicates asymmetry but does not communicate the inferred direction in a reproducible way.

4.5. Inferential limit: diagnosis of instability versus discrete event

In summary, χ contrasts and hillslope-asymmetry metrics provide conditioned diagnoses of instability and of the likely direction of divide mobility under the assumptions of the adopted framework (He et al., 2024). These metrics indicate tendencies to be evaluated and corroborated by independent evidence; they do not constitute direct proof of process. In isolation, they do not unequivocally distinguish gradual divide migration, reorganisation by discrete capture, or the effects of lithological, structural, climatic, or tectonic controls.

The broader geomorphological question remains tied to drainage-network reorganisation, but the inferential target changes. In gradual migration, the aim is to diagnose a tendency towards mobility under disequilibrium, generally expressed by a persistent contrast in relative surface lowering between the two sides of a divide. In discrete captures, the aim is to demonstrate a change in connectivity, that is, evidence that part of the network that currently drains to one basin was formerly connected to another. For this reason, the interpretation of captures requires a distinct evidential logic, based on topographic, sedimentary, stratigraphic, biogeographical, or chronological archives that support the reconstruction of past connectivity. Section 5 addresses this second inferential target.

5. Discrete river captures: post-capture responses, topographic archives, and identification logic

5.1. Capture as a topological change and why the record is asymmetric

River capture is a discrete reorganisation of connectivity within the drainage network. Unlike gradual divide migration, which results from progressive adjustments, capture involves an abrupt topological change: headwaters that previously drained to one basin begin to flow into another adjacent basin (Bishop, 1995). The question “who drains to where?” changes and, with it, so do the partitioning of drainage area, water and sediment fluxes, and, consequently, patterns of incision and relative surface lowering.

The methodological challenge in identifying capture events from topographic data is not simply that evidence may be absent. On the contrary, captures can produce durable records, especially where they preserve inherited valley-scale geometry. The problem is that the record is uneven and ambiguous, and may be overprinted by subsequent adjustments. Capture occurs over a short interval when compared with the time required for longitudinal profiles, hillslopes, and divides to adjust to the new partitioning of area (Whipple et al., 2017). Part of the signal is transient, such as knickpoints and offsets in elevation- χ profiles, and tends to weaken during re-equilibration. Another part may persist for longer, such as windgaps, beheaded valleys, and underfit geometries. Where diagnostic surface materials are preserved, such as fluvial deposits, terraces, gravel deposits, palaeoflow indicators, or biogeographical archives, these independent records may also constrain the timing of reorganisation.

5.2. Divide networks and windgaps as inherited segments of former fluvial pathways

Drainage divides are commonly represented as boundary lines between basins. In the landscape, however, they form connected sets of ridges and interfluves that separate neighbouring basins and sub-basins. These connected divide elements can be treated as a divide network, geometrically analogous to the drainage network they bound (Scherler; Schwanghart, 2020; Figure 3). Treating divides as a network makes their lateral continuity, hierarchy, and topological relations explicit, while also providing a consistent framework for locating, measuring, and comparing specific divide segments within the broader organisation of the landscape.

The hierarchy of this network can be established computationally from the connectivity between channels, ridges, and adjacent basins. In tools such as *DIVIDEobj* in TopoToolbox (Scherler; Schwanghart, 2020), divides are extracted as a connected network between neighbouring channels, allowing each segment to be associated with the basins it separates and enabling attributes such as network position, length, accumulated distance along the ridge network, elevation, local relief, and area of the adjacent basins to be calculated. Figure 3 illustrates this transition by showing that interfluves already visible in the spatial organisation of valleys can be extracted and analysed as segments of a connected divide network. This hierarchy does not mean that all divides have the same geomorphological role. Main divides separate larger basins and integrate longer portions of the network, whereas secondary divides organise local interfluves and adjacent headwaters. This distinction matters because windgaps and captures can occur at different levels of the divide network, with distinct scales, preservation potential, and detectability

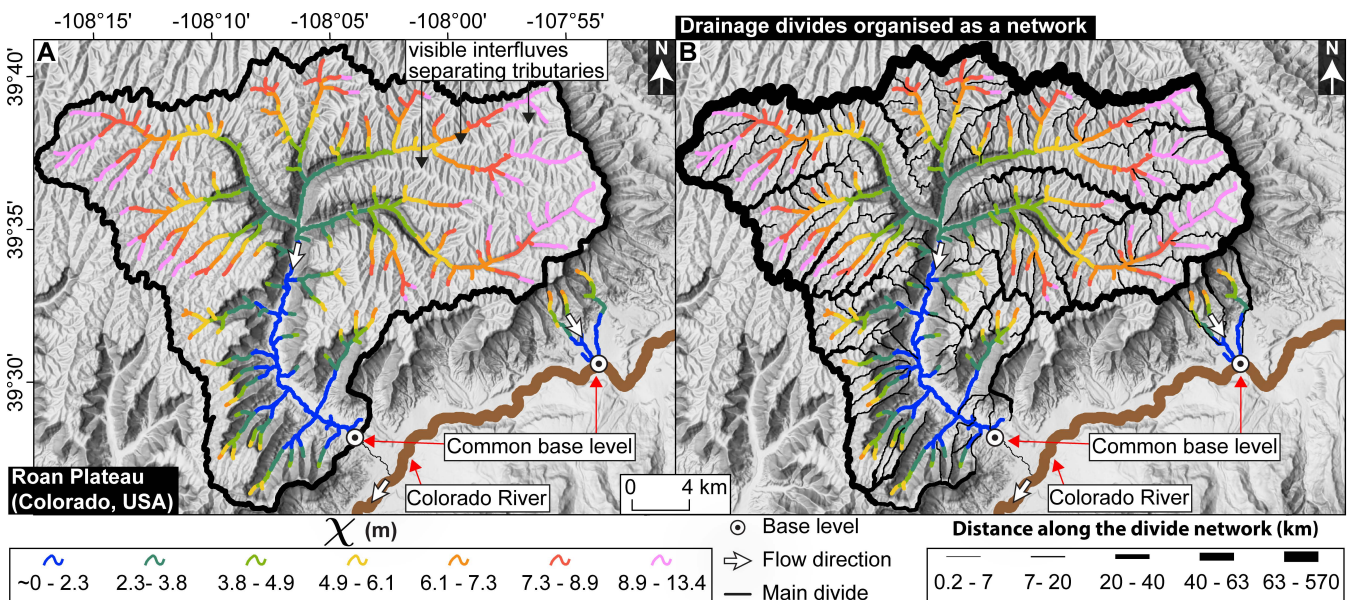


Figure 3. Drainage divides as a connected network and examples of computable attributes along this network, illustrated in the Roan Plateau, Colorado, USA. (A) Map view showing the drainage network and the main divide separating adjacent basins. Colours along the drainage network represent χ , calculated from a common, arbitrary base level applied consistently across the area. Although only the main divide is explicitly traced, the interfluves separating tributaries are already recognisable in the spatial organisation of the valleys and ridges. (B) Divide network extracted with the *DIVIDEobj* algorithm in TopoToolbox (Scherler; Schwanghart, 2020) and represented as a connected network. Segments are ordered and symbolised by classes of accumulated distance along the divide network, shown by line thickness. The divide elements mapped in (B) correspond to interfluves already visible in (A), demonstrating that the divide network is not merely a computational abstraction, but an explicit representation of connected geomorphic elements present in the landscape. Treating these elements as a network allows attributes such as position, distance, hierarchy, length, elevation, relief, and adjacent-basin area to be assigned to individual divide segments. DEM: Copernicus DEM 30 m.

Once divides are represented as a connected network, windgaps can be identified as specific segments within that network. In topographic terms, candidate windgaps correspond to low-elevation divide segments that are flanked by higher divide sections and that preserve morphology compatible with a former valley axis. The most diagnostic cases combine low relative elevation, hillslope convergence towards the divide, and a recognisable valley floor or valley-scale continuity extending to both sides of the divide. Where these conditions occur, the feature can be interpreted as a windgap, that is, a segment of the present divide that retains valley geometry associated with a former fluvial connection but is no longer crossed by an active stream (Bishop, 1995; Shelef; Goren, 2021).

This network-based view is important because windgaps are not incidental low points along divides. In a discrete capture, the former connection between basins is interrupted, and part of the drainage corridor that previously conveyed flow becomes incorporated into the present divide. At least initially, therefore, capture produces a low-elevation divide segment located along the former fluvial pathway. This segment will be recognisable as a windgap where the inherited valley geometry is preserved. What varies is not the genetic relation between capture and interruption of the former pathway, but the preservation and detectability of the resulting topographic archive. The time elapsed since capture, subsequent erosion, sedimentation, post-capture incision, and geological controls may keep the feature clear, make it subtle, or mask it. Figure 4 summarises this post-capture sequence, from the initial topological diversion to prolonged re-equilibration, and brings together the main topographic archives that may be preserved during this adjustment.

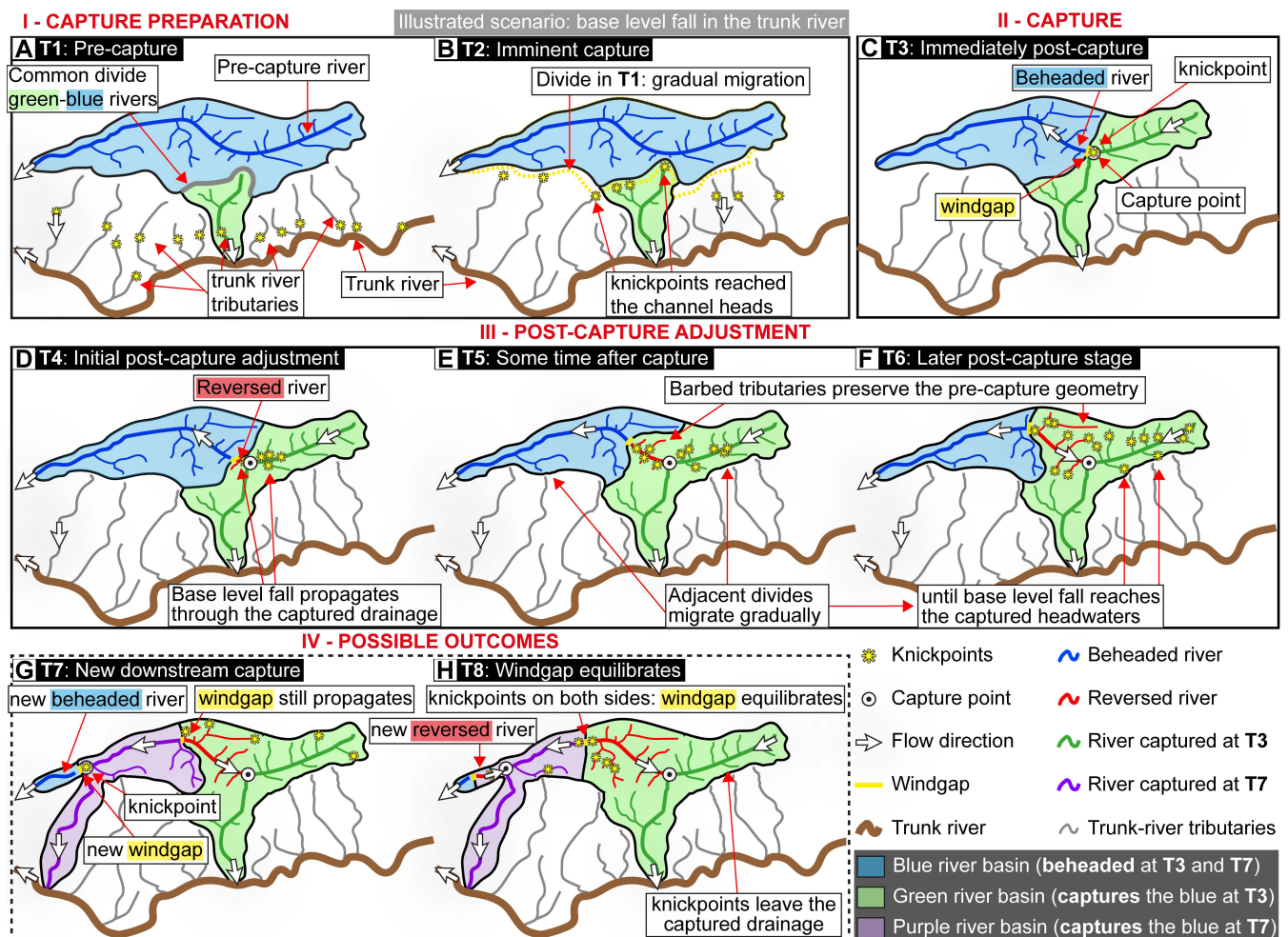


Figure 4. Conceptual sequence of river capture and post-capture landscape adjustments. The figure illustrates a scenario in which base level fall in the trunk river favours the capturing basin, but the sequence synthesises general geomorphological responses that may also be triggered by other mechanisms, such as escarpment retreat, headward erosion, lithological or tectonic contrasts, and downstream reorganisation. (A–B) *Capture preparation*: adjacent basins, separated by a common divide, enter progressive disequilibrium due to base level fall in the trunk river. Knickpoints propagate through the drainage of the green river basin, making it more efficient in erosional terms, and the divide

gradually migrates towards the blue river basin. (C) *Capture*: part of the blue river basin begins to drain into the green river basin; the capture point is established; the blue river is beheaded; and the former connection axis becomes incorporated into the divide as a windgap. (D–F) *Post-capture adjustment*: the annexed drainage responds to the effective base level fall; a reversed river may develop in the inherited valley, and the windgap may migrate through the beheaded valley. The inherited valley downstream of the windgap remains oversized relative to the remaining drainage, forming an underfit condition. As it crosses inherited confluences, the reversed river may capture tributaries sequentially, forming barbed tributaries that preserve the pre-capture geometry. (G–H) *Possible outcomes*: a new downstream capture may reorganise the system, generate a new windgap, and impose a new transient; alternatively, as profiles progressively adjust and the contrast in relative lowering between the two sides is reduced, the windgap may decelerate, become episodic, or equilibrate. Colours distinguish the basins at different moments in the sequence; symbols indicate knickpoints, capture point, flow direction, windgaps, trunk river, beheaded river, reversed river, and trunk-river tributaries.

5.3. Post-capture landscape changes: from initial diversion to prolonged re-equilibration

A capture event abruptly redistributes drainage areas and imposes contrasting post-capture conditions between the side that gains area and the side that loses area (Bishop, 1995; Willett et al., 2014; Whipple et al., 2017). Figure 4 organises this sequence into four blocks: capture preparation (A–B), capture itself (C), post-capture adjustment (D–F), and possible outcomes (G–H). On the side that gains area, the capturing river begins to drain a larger area, increasing its incision capacity near the capture point. This commonly generates a transient adjustment, expressed by a knickpoint that migrates upstream and transmits an effective base level fall through the newly annexed network (Figure 4C–4D).

On the side that loses area, the pre-capture river becomes beheaded: it loses connectivity with an important part of its former drainage area and begins to operate with lower discharge and reduced erosional capacity (Bishop, 1995; Willett; McCoy; Beeson, 2017; He et al., 2024; Figure 4C). Because the valley geometry was carved under the pre-capture condition, the beheaded sector tends to preserve a valley that is too large for the modern drainage, forming an underfit condition (Small, 1978; Bishop, 1995; Figure 4C–4F).

The capture itself transforms part of the former connection axis into a low-elevation divide, the windgap. The windgap does not correspond to the entire palaeovalley, but rather to the segment of the inherited valley that begins to function as the divide between the captor and beheaded drainages. The palaeovalley, in turn, may remain recognisable at valley scale on both sides of this lowered divide. On the captor side, part of the former valley may be incorporated into the new drainage system and begin to flow in the opposite direction to the pre-capture configuration, forming a reversed river (Harel et al., 2019; Shelef; Goren, 2021; Qu et al., 2025; Figure 4D–4E). Here, reversed river designates a segment that flows in the opposite direction to the inherited flow of the pre-capture palaeovalley. The term therefore does not refer merely to an unusual local slope, but to the reversal of flow direction relative to the earlier organisation of the valley.

Although lowered relative to neighbouring ridges, the windgap functions as the topographic high that separates the drainage that gained area from the beheaded drainage (Figure 4C). The redistribution of area tends to increase incision rates on the captor side and reduce them in the beheaded headwaters, producing a contrast in relative surface lowering across the windgap. Where this contrast is large and persistent, the windgap may migrate into the beheaded valley (Shelef; Goren, 2021; Figure 4D–4E). This migration may be favoured because the windgap retreats along the floor of the beheaded valley, which provides a low-gradient inherited corridor; where present, reworkable sedimentary fill may further enhance this mobility (Harel et al., 2019; Shelef; Goren, 2021; Wang; Willett; Wu, 2023; Harel et al., 2025; Qu et al., 2025; Figure 4E). By contrast, neighbouring divides tend to retreat through incision into adjacent hillslopes and interfluvies, where relief is higher and where the substrate commonly lacks the same low-gradient inherited valley floor and reworkable sedimentary fill. For this reason, lateral retreat of these divides may be slower than windgap migration along the inherited valley axis (Harel et al., 2019; Shelef; Goren, 2021; Qu et al., 2025; Figure 4D–4E).

As the windgap retreats along the beheaded valley, it encounters confluences inherited from the pre-capture configuration. When these junctions are crossed, tributaries may be captured sequentially by the reversed river (Harel et al., 2019; Shelef; Goren, 2021; Figure 4E–4F). Because tributaries tend to retain their inherited planform orientation while the reversed river inverts the flow direction along the main valley axis, a drainage pattern with barbed confluences may emerge. This pattern is particularly informative because it records the mismatch between

the inherited geometry of the tributaries and the present flow in the reorganised valley (Harel et al., 2019; Shelef; Goren, 2021; Figure 4F).

This sequence, however, does not necessarily imply sustained reversal or a long cascade of captures (Whipple et al., 2017; Figure 4G–4H). Windgap propagation depends on a sustained contrast in relative surface lowering across a low divide and on geomorphological conditions that allow efficient advance through the beheaded valley. Over time, this contrast may decrease: the beheaded system loses incision capacity owing to the abrupt reduction in drainage area, but rock uplift persists. As a result, the beheaded upper course tends to adjust through a gradual increase in slope and, therefore, in relative incision capacity, reducing the asymmetry in relative surface lowering between the two sides of the windgap (e.g., Shelef; Goren, 2021; Figure 4H). This weakening may decelerate, render episodic, or interrupt the migration of the windgap.

External perturbations may also interrupt or reorganise the process. For example, if the beheaded drainage is subsequently captured by another drainage farther downstream, it may also respond to base level fall, which may reduce the contrast in relative surface lowering on the two sides of the windgap and limit further propagation (Figure 4G–4H).

5.4. *A diagnosis of instability is not a reconstruction of capture*

Individual captures require a distinct evidential logic from gradual divide mobility because the inferential target is past connectivity (Bishop, 1995). The question is not merely “which side appears more erosionally efficient today?”, but “is there evidence that a fluvial connection existed but was interrupted or redirected?”. For this reason, divide-instability metrics should be treated as context: they help locate where contrasts between basins are strong and where adjustments may be underway, but, in isolation, they do not constitute the identification of discrete events.

When attempting to identify capture events exclusively from topographic data, the most robust interpretative anchor is an archive directly linked to past connectivity, especially windgaps and inherited valley-scale geometry (Bishop, 1995). Nevertheless, this hypothesis of past fluvial connectivity should be strengthened by convergence with other morphological evidence, such as an underfit condition, a reversed river, barbed tributaries, capture elbows, knickpoint patterns, paired elevation- χ profiles, and the continuity of the former valley across the interpreted windgap. Where available, independent evidence can test the hypothesis directly. Among geological archives, fluvial deposits associated with a valley now interrupted at the divide are especially important, such as abandoned terraces and gravel deposits (e.g., Clark et al., 2004; Prince; Spotila; Henika, 2010; Andrews et al., 2012; Harel et al., 2019; Stokes et al., 2023b), together with sedimentological palaeoflow indicators (e.g., Fan et al., 2018) and other sedimentary or volcanic units, such as lavas that filled fluvial valleys, whose distribution and geometry are incompatible with the modern drainage network (e.g., Bishop, 1995). Biogeographical and genetic archives, especially in aquatic organisms, may record former connections between basins that are now separated and their subsequent isolation (e.g., BurrIDGE; Craw; Waters, 2006; Waters et al., 2015; Craw et al., 2016; Albert et al., 2017; Ruzzante et al., 2020; Musher et al., 2022; Cassemiro et al., 2023; Stokes et al., 2023a; Vance et al., 2025), sometimes allowing relative ages to be discussed on the basis of independent calibrations.

5.5. *Topographic archives of capture: what to observe, what they mean, and how ambiguous they are*

A productive way to organise the identification of captures is to treat each topographic archive according to three aspects: (i) what it records, (ii) its expected persistence in the landscape, and (iii) its susceptibility to alternative origins. Interpretation becomes more defensible when multiple archives converge spatially and when the observed assemblage is more convincingly explained by a change in connectivity than by lithological, structural, or climatic controls, or by regional perturbations unrelated to capture.

Because several terms associated with captures are used unevenly in the literature, this section adopts explicit operational definitions. Table 1 summarises the main features, the type of evidence they provide, their relative persistence, and their most common ambiguities. The function of the table is not to turn interpretation into an automatic checklist, nor to assign a formal probability to the occurrence of capture, but rather to reduce terminological ambiguities and make explicit which combinations of evidence make the inference more robust.

Table 1. Explicit operational definitions of the topographic archives used to identify capture events.

Feature or metric	Operational definition	What it suggests	Main ambiguities
Windgap	Low-elevation divide segment with geometry compatible with a valley floor and cross-divide morphological continuity	Former fluvial passage now incorporated into the divide	Structural control, weak lithology, differential erosion
Beheaded valley	Remaining valley of the beheaded river that lost part of its pre-capture drainage area due to the capture	Loss of connectivity and reduction in discharge	Climatic inheritance, lithology, structure, sedimentary variation
Underfit condition	Modern river small relative to the width or morphological scale of the valley	River valley carved under a drainage area larger than the present one	Climatic changes, sedimentation, lithological control
Reversed river	River segment that follows an inherited valley axis but flows opposite to the pre-capture flow direction of that palaeovalley	Post-capture reorganisation and incorporation of inherited valley	Structural control or local drainage rearrangements
Barbed tributaries	Tributaries that join a trunk river at upstream-pointing or obtuse junction angles, or more generally retain inherited planform orientations relative to a trunk valley whose present flow direction differs from the pre-capture configuration	Flow reversal along the trunk valley and preservation of inherited tributary geometry	Structural control, local confluence adjustment, DEM-extraction artefacts in low-gradient junctions, asymmetric dendritic pattern
Elbow of capture	Abrupt, high-angle change in the direction of the valley or river axis, commonly expressed as a sharp bend where a captured valley is diverted into a differently oriented drainage pathway	Annexation of a valley with a distinct orientation	Faults, fractures, lithological contacts
Paired profiles in elevation-χ space	Comparison between captured/reversed river and beheaded river under the same x_b and θ_{ref}	Gain versus loss of area and post-capture disequilibrium	Re-equilibration, U or K heterogeneity, inappropriate x_b
Spatially coherent knickpoints	Concentration of knickpoints within similar ranges of χ or elevation	Common response to a perturbation, such as capture or base level fall	Lithological contacts, regional transients, structures

With these definitions established, the following subsections and examples do not reintroduce each term from first principles; they show how these archives combine spatially, how they vary in detectability, and how their interpretative strength depends on convergence among features, metrics, and alternative controls.

Although the focus of this technical note is conceptual and operational, rather than the presentation of a regional case study, three examples from the southern Germany Scarplands help illustrate how the topographic archives discussed below combine at different stages of preservation and post-capture re-equilibration. Tectonic subsidence in the Upper Rhine Graben, a Cenozoic rift, established a newly formed regional drainage system oriented towards the graben, with preferential flow to the northwest, structuring the regional morphology (Villinger, 1998). In this context, rivers draining to the Upper Rhine Graben increased their erosional power from the Late Miocene onwards (Ziegler; Dèzes, 2007). The Neckar River, one of its main tributaries, expanded its area through gradual divide migration and repeated discrete captures, reversing the flow of former Danube tributaries that previously flowed to the southeast and leaving a landscape marked by multiple inherited signatures of reorganisation (Strasser et al., 2009; Villinger, 1998; Morel et al., 2003; Ziegler; Fraefel, 2009; Yanites et al., 2013). Figures 5–7 are not presented as complete case studies, but as an illustrative preservation sequence: an example

with a capture point and multiple well-preserved topographic archives (Figure 5), an example in which the original capture point is no longer unequivocal from topography alone, but inherited geometry remains clear (Figure 6), and an example in which inherited geometry is still recognisable, although the contrast in elevation- χ is small, suggesting advanced re-equilibration and highlighting the temporal bias of diagnoses based only on present disequilibrium (Figure 7).

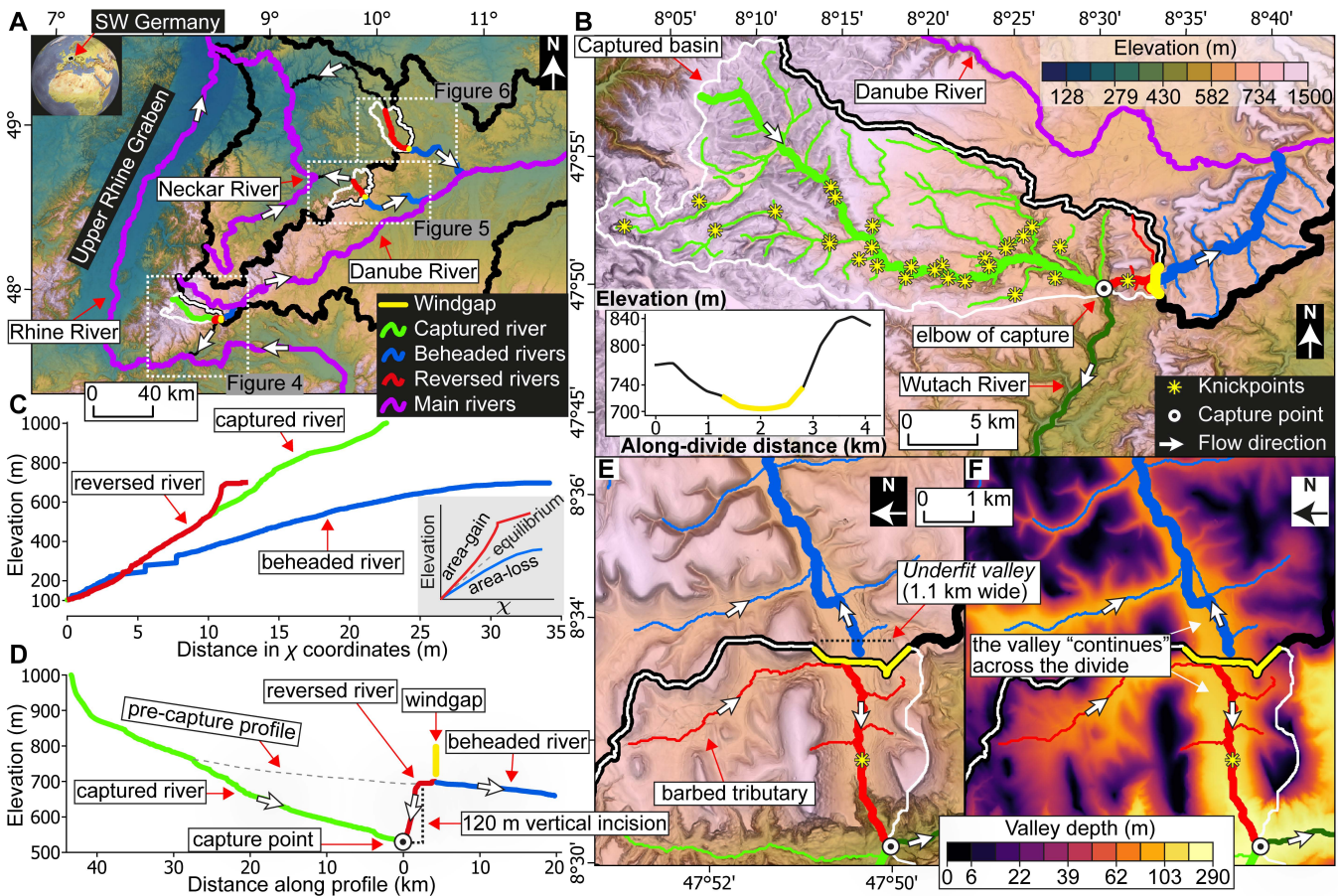


Figure 5. Example of a recent river capture event (~18 kyr; Morel et al., 2003) and resulting drainage reversal in the Wutach River, southwestern Germany. (A) Regional context of the expansion of Rhine tributary drainage, resulting from discrete captures of headwaters formerly connected to Danube drainage; the locations of the empirical examples discussed in this section are indicated. (B) Hypsometric map of the Wutach capture sector, highlighting topographic archives associated with reorganisation, such as windgap, capture elbow, captured river, reversed river, beheaded river, and the distribution of knickpoints in the newly annexed drainage; the inset shows elevation variation along the divide and highlights the windgap as a low divide. (C) Paired elevation- χ profiles for the captured river, reversed river, and beheaded river, illustrating the expected asymmetry between gain and loss of drainage area. (D) Longitudinal profiles along the valley, highlighting the capture point, the windgap, and vertical incision associated with post-capture lowering, as well as a schematic reference to the pre-capture profile. (E–F) Morphological detail of the windgap sector, with north rotated to show valley continuity along the divide. (E) Hillshade showing elevation continuity and valley geometry on both sides of the windgap. (F) Valley depth calculated using the Valley Depth module in SAGA GIS, showing continuity of the valley-depth signal along the divide. DEM: LGL-BW ATKIS Digitales Geländemodell DGM 5 m (2005).

5.5.1. Windgaps: low-elevation divide segments with inherited valley geometry

Windgaps are topographic archives directly linked to past fluvial connectivity because they preserve, within the present-day divide section itself, the inheritance of a valley axis that no longer conveys the main watercourse (Shelef; Goren, 2021). Operationally, they are recognised as a segment of the divide with low relative elevation, valley-floor morphology, and hillslope convergence compatible with a former fluvial passage (Figures 5–7).

The interpretation of a windgap from topographic data is not automatic or unambiguous. Low divide segments may also reflect lithological weaknesses, structural controls, or erosional inheritances unrelated to capture. The interpretation of former fluvial connectivity through the identification of windgaps from topographic data is more robust where valley-scale geometric coherence is observed and other elements of the system support the interpretation, such as signs of beheading downstream of the windgap and evidence of adjustment on the side that gained area.

5.5.2. Beheaded valleys and underfit condition

After capture, the valley associated with the beheaded river may remain too large for the present discharge (Bishop, 1995). This mismatch may appear as a wide valley floor occupied by a small river, or as flat or terraced surfaces disproportionate to the modern drainage area (Figures 5 and 6). Interpreted in isolation, the underfit condition is particularly ambiguous. Wide valleys may result from differential erosion in weak lithologies, structural corridors, climatic inheritance, localised sedimentation, or regional changes in base level. The interpretation becomes more convincing where the underfit valley is aligned with a plausible windgap, where its geometry is consistent with drainage-area loss, and where other associated elements are present, such as a reversed river, barbed tributaries, capture elbow, knickpoints, or continuity of cross-divide valley surfaces.

Where possible, the underfit condition should be shown not only by textual description but also by morphological comparison. Examples include valley-floor width, valley depth, continuity of flat or terraced surfaces, the contrast between valley scale and modern drainage area, and longitudinal profiles that show the disconnection between inherited geometry and present drainage. In Figure 5E–5F, for example, continuity in the hillshade and in the valley-depth signal across the windgap reinforces the interpretation that the valley preserves inherited geometry predating drainage reorganisation.

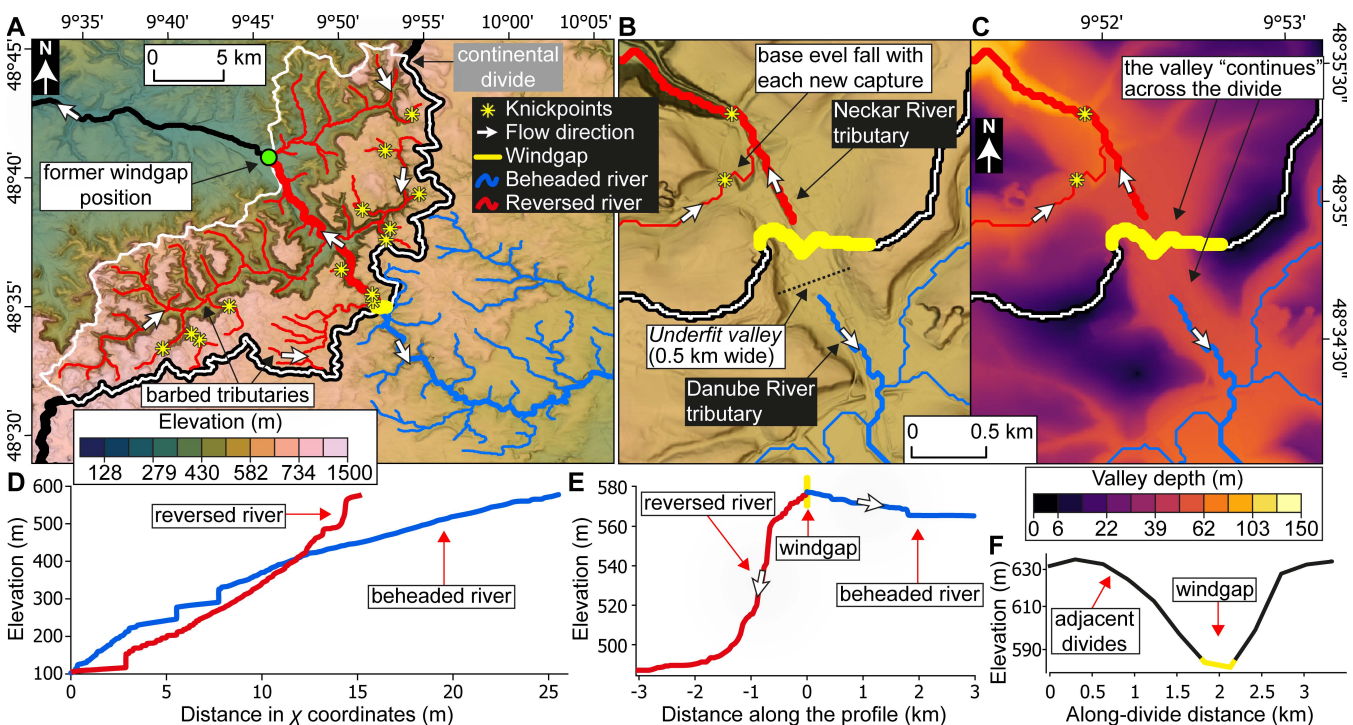


Figure 6. Example of a capture event at a more advanced stage than the Wutach capture (Fils River), with preservation of the windgap and inherited valley-scale geometry, but without unequivocal identification of the original capture point from topography alone. (A) Overview of the system, with reversed river, beheaded river, barbed tributaries, mapped knickpoints, and indication of a probable former windgap position, inferred from the most downstream barbed tributary along the reversed river. (B) Morphological detail of the divide, highlighting the low elevation of the windgap in comparison to neighbouring divide sections and the underfit valley in the context of repeated drainage reorganisations. (C) Valley depth calculated using the Valley Depth module in SAGA GIS, highlighting the morphological continuity of the valley along the divide in the windgap region. (D) Paired elevation-

χ profiles of the reversed river and the beheaded river, showing a contrast consistent with discrete reorganisation and gain versus loss of area. (E) Longitudinal profile crossing the windgap, showing flow reversal in the reversed sector and disconnection in the beheaded sector, which preserves a lower-gradient reach associated with the pre-capture valley. (F) Elevation profile along the divide, showing local lowering of the windgap relative to neighbouring divides. DEM: LGL-BW ATKIS Digitales Geländemodell DGM 5 m (2005).

5.5.3. Capture elbows and planform discontinuities

Captures may annex valley segments with distinct orientations, producing abrupt, high-angle changes in the direction of the valley or river axis, known as capture elbows (Bishop, 1995; Figure 5). In many cases, these appear as sharp bends, sometimes close to right-angle deflections, where a former valley is diverted into a differently oriented drainage pathway. The signal is more persuasive when it appears at valley scale, fits the expected context, lies close to a windgap, and is associated with evidence of river beheading. However, this archive is highly ambiguous because faults, fractures, and lithological contacts can impose reorientations without any topological reorganisation. For this reason, capture elbows work better as supporting evidence than as primary interpretative anchors for identifying river capture events. Their interpretation becomes more robust when evaluated systematically, for example through sustained changes in azimuth along the valley or channel axis, rather than by point-based inspection of a single bend.

5.5.4. Flow reversal and barbed tributaries

Migration of the windgap through the beheaded valley may lead to the development of a reversed river in the former upper course of the pre-capture river (Bishop, 1995; Harel et al., 2019). Tributaries, however, may preserve their inherited planform orientation because their lateral valleys were organised to converge towards the former direction of the trunk river. This preservation is most likely where windgap retreat along the inherited valley axis outpaces the retreat of adjacent divide segments, so that the trunk valley is progressively reversed while lateral tributary valleys retain their pre-capture geometry. The result is a pattern of junctions “against the flow”, forming barbed tributaries, which records the mismatch between inherited tributary orientation and the present flow direction in the reorganised trunk valley (Figures 5–7).

Barbed geometry is commonly described using junction angles, especially where tributaries enter the trunk river at obtuse or upstream-pointing angles relative to the present downstream direction. This criterion is useful, but should not be treated as definitive on its own. Junction-scale geometry may be difficult to extract reliably from DEMs in low-gradient confluence zones, and local junction angles may be modified during post-capture adjustment even whereas the broader inherited valley geometry remains clear. For this reason, barbed tributaries are better evaluated using both local confluence angles and segment-scale planform orientation, including the orientation of tributary valleys relative to the reversed trunk valley. Their interpretation is strengthened when they occur within the same spatial arrangement as a windgap, underfit valley, reversed river, and other evidence of inherited drainage geometry.

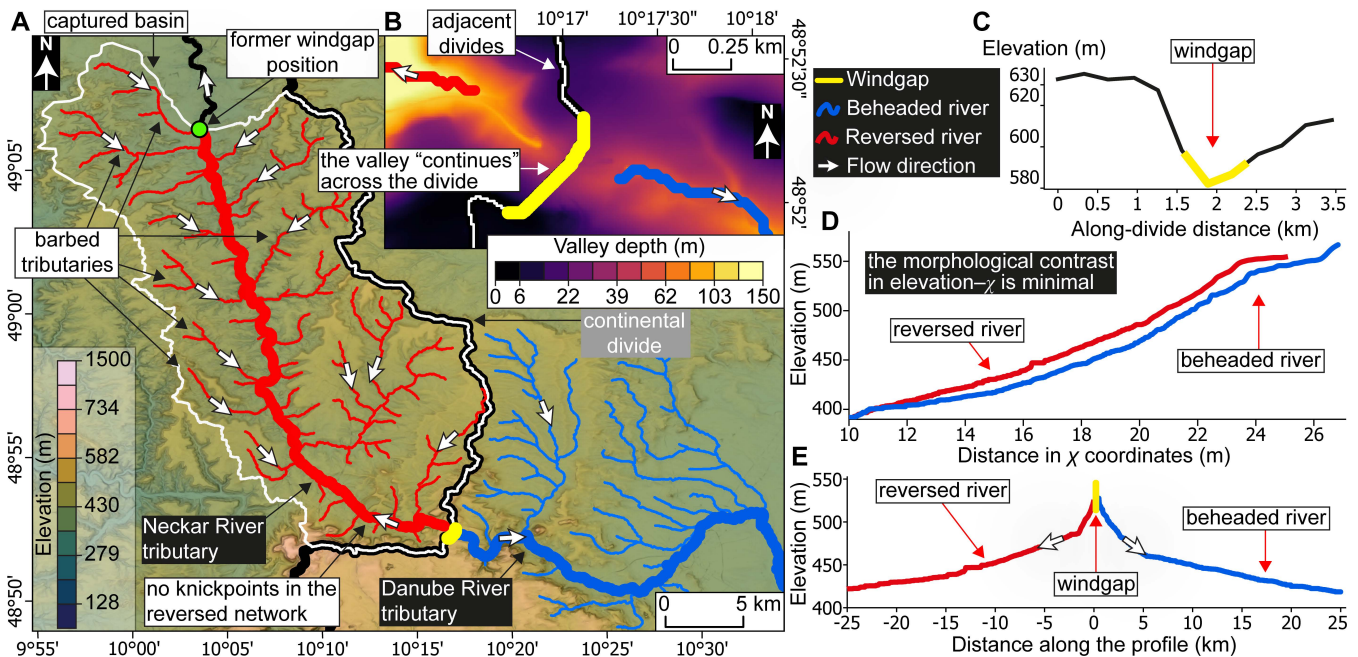


Figure 7. Example of a capture event suggesting advanced post-capture re-equilibration (Jagst River), in which inherited geometry, represented by the windgap and valley-scale continuity, persists, but the contrast in elevation- χ is small. (A) View of the system with reversed river, beheaded river, and barbed tributaries; indication of a former windgap position and absence of knickpoints in the reversed system, consistent with post-capture re-equilibration. The former windgap position is inferred from the most downstream barbed tributary along the reversed river. (B) Valley depth calculated using the Valley Depth module in SAGA GIS, showing valley continuity across the divide and the location of the windgap in a lowered segment. (C) Elevation profile along the divide, showing the windgap as a local elevation minimum. (D) Paired elevation- χ profiles of the reversed river and the beheaded river, showing a reduced morphological contrast, consistent with advanced re-equilibration. (E) Longitudinal profile crossing the windgap, illustrating the reduction in morphological contrast between the reversed and beheaded sectors around the lowered divide. DEM: LGL-BW ATKIS Digitales Geländemodell DGM 5 m (2005).

5.5.5. Paired longitudinal profiles in elevation- χ space

Elevation- χ profiles are especially useful where capture is relatively young or where the event was sufficiently large to maintain measurable disequilibrium. Because χ is an integral weighted by upstream drainage area, a reorganisation that transfers area between basins changes the relationship between distance along the profile and χ , producing systematic offsets in elevation- χ space (Willett et al., 2014; Figure 5D).

The expected pattern is expressed in paired profiles (e.g., Willett et al., 2014; Beeson; McCoy; Keen-Zebert, 2017; Hu et al., 2021). The river that gains area tends to show lower χ values for a given elevation, corresponding to a leftward network shift, and may reach higher maximum χ values where the event incorporates a more extensive upstream network in χ space. By contrast, the river that loses area tends to show higher χ values for a given elevation, corresponding to a rightward shift, and to occupy a smaller χ interval, compatible with shrinkage of the drained area and disconnection of part of the headwaters. When this “gain versus loss” signature appears consistently in paired profiles, it constitutes one of the most direct quantitative indicators inferable from topography alone.

Methodological caution remains essential. The comparison is interpretable only when the profiles share the same base level reference, a domain that preserves connectivity to that reference, and a consistent χ parameterisation. In addition, the contrast tends to weaken as the landscape re-equilibrates; thus, the absence of a clear offset in elevation- χ space does not rule out capture where robust evidence is anchored in windgaps and inherited valley-scale geometry (Figure 7).

5.5.6. Knickpoints and internal coherence of the transient

A capture can impose, at the capture point, an effective base level fall on the newly annexed network, initiating an incision transient that propagates upstream and is frequently expressed as knickpoints. When several tributaries respond to the same perturbation and erodibility heterogeneity does not dominate the dynamics, these knickpoints may display internal coherence: instead of occurring diffusely, they tend to concentrate within narrow ranges of χ and, often, also of elevation (e.g., Schwanghart; Scherler, 2020; Calegari et al., 2021; Figure 5). This alignment suggests a common origin and is especially informative when it fits a scenario anchored in windgaps, beheaded valleys, and planform discontinuities.

Because knickpoints may also be controlled by lithological contacts, structures, or regional base level transients (Kirby; Whipple, 2012), two checks are simple and decisive: (i) verify whether coherence is stronger in the candidate basin, especially in the basin that gained area, than in neighbouring basins; and (ii) test for systematic coincidence with mapped geological features. Where coherence persists as an internal pattern and is not explained by geology, it provides useful quantitative support, although it is not conclusive on its own.

5.5.7. Operational quantification and reproducible inventories

Although the initial identification of topographic archives of capture is often visual, most of the evidence discussed in this section can be quantified. This has two direct benefits: (i) it allows candidates to be compared using explicit criteria; and (ii) it enables reproducible inventories, reducing the weight of subjective judgement and facilitating comparisons between areas and studies.

Windgaps can be measured using metrics extracted along the divide, such as the amplitude of their low elevation relative to the local elevation envelope of neighbouring divides, the length of the low-elevation divide segment, and measurements of elevation continuity of the valley axis across the divide (Figures 5–7). The underfit condition can be operationalised through relationships between valley-floor width and modern drainage area along the beheaded valley, beginning the analysis near the windgap and proceeding downstream, so as to express “how much” the valley is oversized relative to a regional reference rather than merely stating that it “looks wide” (e.g., Clubb; Weir; Mudd, 2022; Harel et al., 2022; Figures 5 and 6). Barbed tributaries can be quantified using confluence angles and, more robustly, planform-orientation statistics calculated along segments of the trunk river and tributaries (e.g., Hackney; Carling, 2011; Strong; Mudd, 2022; Figure 5). Similarly, planform discontinuities, including elbows, can be detected as sustained changes in the azimuth of the valley or channel axis within moving windows along the drainage network, reducing sensitivity to local sinuosity (e.g., Ma; Li; Wang, 2023; Figure 5).

The spatial distribution and magnitude of knickpoints can also be extracted using objective procedures. Two common approaches are: (1) statistical segmentation of longitudinal profiles based on variations in k_{sn} calculated from the χ coordinate (e.g., Gailleton et al., 2019); and (2) detection of deviations from a strictly concave reference profile fitted to the real profile within a predefined concavity tolerance, marking knickpoints where vertical displacement exceeds this limit (e.g., Stolle et al., 2019; Calegari et al., 2021). Finally, paired profiles in elevation- χ space for rivers directly involved in the event allow relative disequilibrium to be quantified through simple measurements, such as differences in maximum χ between the analysed rivers (e.g., Hu et al., 2021).

From an operational standpoint, topographic-analysis software such as TopoToolbox and LSDTopoTools, together with GIS environments such as QGIS, SAGA, and ArcGIS Pro, offer routines to extract and summarise these metrics. In TopoToolbox, for example, segmentation of the drainage network allows planform attributes to be estimated by reach, such as orientation and systematic changes in azimuth. A common implementation uses the *networksegment* algorithm applied to a *STREAMObj* (i.e., a drainage “object” within TopoToolbox), which makes it possible to quantify barbed tributaries and map planform discontinuities consistently along the drainage network.

5.6. Detectability, biases, and regional context

The detectability of river captures is not constant through time. In general, the most commonly used quantitative diagnoses emphasise transient archives, such as paired longitudinal profiles in elevation- χ space and spatially coherent patterns of knickpoints. These signals tend to be clearer in recent or large-magnitude captures because geomorphic disequilibrium has not yet been attenuated (Bishop, 1995; He et al., 2024). Over time, longitudinal profiles and hillslopes re-equilibrate (Whipple et al., 2017); mismatches between paired profiles in elevation- χ space decrease, and knickpoints migrate, dissipate, or leave the analysed domain (e.g., Gallen;

Wegmann; Bohnenstiehl, 2013). Thus, old events may “disappear” from conventional diagnoses even when topological reorganisation was effective.

There is also a recurrent interpretative bias: the absence of measurable disequilibrium is frequently confused with the absence of an event. This shortcut ignores the asymmetry of the record discussed in Section 5.1. Capture is rapid, but adjustment is relatively slow. Part of the record is transient; another part is more durable, especially inherited valley-scale geometry preserved in windgaps and beheaded reaches. In many contexts, it is precisely this durable component that supports the hypothesis when transient signals have already been attenuated.

Finally, the interpretation of any local case must be placed within a minimum regional background, because regional forcings may affect several basins simultaneously (Bishop, 1995). Base level changes, tectonic pulses, climatic variations, and lithological contrasts may produce incision waves and knickpoints distributed at regional scale. Without this reference, a broad pattern may be interpreted as the signature of a single capture when, in fact, it reflects a regional perturbation that “imitates” part of the expected signal. The converse is also true: even where the focus is a single event, the regional context strengthens the interpretation by providing a test of spatial contrast. If the explanation is regional, compatible records should exist in neighbouring basins; if the signal is local and coherent with a windgap and inherited geometry, this helps separate the local mechanism from the regional background.

5.7. Investigation strategy, alternative controls, and auditable record

There is no universal protocol for identifying river captures in every landscape. What exists is a defensible logic based on a hierarchy of evidence and checks that reduce false positives. The first step is to state which evidence anchors the capture hypothesis. This statement should include the geomorphological context in which the hypothesis will be evaluated, especially tectonic, lithological, and climatic controls that may produce similar morphologies, alter rates of relative lowering, or modify preservation of the topographic records. In discrete captures, the most robust anchor is usually an archive directly linked to past connectivity, especially windgaps and inherited valley-scale geometry. From this anchor, transient evidence acts as support when present, but not as a necessary condition, avoiding the bias of recognising only recent events.

This technical note does not propose a formal probability of capture occurrence because this would suggest a level of calibration that is not yet robust for most topographic applications. Robustness should be expressed as convergence of evidence: a hypothesis is stronger when a windgap, an inherited valley-scale geometry, an underfit condition, paired profiles, knickpoints, planform indicators, and regional context all point towards the same reorganisation, and when alternative controls have been explicitly evaluated.

Nor does this technical note propose a formal scale of the “evolutionary stage” of captures. Although cases can be compared within the same geomorphological context, the preservation and expression of archives depend on lithology, climate, sedimentation, event scale, incision rate, subsequent episodes of reorganisation, and time since capture. Thus, terms such as recent, intermediate, or advanced may be used descriptively and relatively, but not as universal classes. The aim is to emphasise reporting and comparison criteria, not to establish a closed evolutionary classification.

A clear operational strategy can be described in three steps:

1. **Screening and candidate selection:** state whether the search was systematic, for example, a survey of the entire divide network, or targeted, that is, based on cases selected by inspection. Record minimum inclusion criteria: (i) a low-elevation divide segment with geometry compatible with a valley floor and hillslope convergence; (ii) morphological continuity of the valley axis to this segment on at least one side; and (iii) an upstream or downstream valley compatible with beheading, that is, a valley corridor whose scale and organisation make sense as the inheritance of a larger drainage area.
2. **Testing internal coherence with topographic metrics:** use metrics such as paired elevation- χ profiles, knickpoint patterns, and planform indicators as consistency indicators. The function of these metrics is to answer questions such as: does the capturing side show signals compatible with post-capture adjustment? Does the beheaded side preserve a valley scale compatible with area loss? Is the assemblage of evidence spatially coherent with the position of the windgap? Where incompatibilities exist, treat them as diagnostic: they may indicate superimposed regional transients, lithological heterogeneity, or a weak candidate site.
3. **Explicit checking of alternative controls:** instead of listing possible causes, formulate simple tests for the most likely alternatives. Verify whether the geometry of the candidate is controlled by geology, such as contacts

and lithological heterogeneity, or by structure, such as lineaments that organise valleys and changes in direction, and evaluate whether the transient pattern is local or regional by comparing it with neighbouring basins. If the cause is regional, spatial repetition is expected; if the capture is local, the assemblage of signals is expected to concentrate around the windgap and beheaded valley. The interpretation is strengthened where this comparison favours the capture scenario and where the observed assemblage is not better explained by a single alternative control.

The result is not simply “capture occurred”, but an auditable interpretative record. In practical terms, this means reporting: (i) which archives anchored the capture hypothesis; (ii) which supporting evidence was used and with which parameterisations; (iii) which alternative controls were evaluated; and (iv) which uncertainties remain. This record allows the interpretation to be reproduced, challenged, or refined by other studies, without depending solely on an implicit visual judgement.

6. Good practices and minimum reporting criteria

This section brings together the minimum information required for topography-based inferences of capture and gradual divide migration to be reproducible, auditable, and comparable. The central rule is to state precisely the inferential target and the chain of decisions that links data, parameters, and conventions to interpretation. For gradual divide migration, the target is a diagnosis of instability compatible with progressive displacement, under the assumptions made explicit. For discrete captures, the target is evidence of past connectivity, anchored in topographic archives and, where available, tested against independent evidence. Whenever possible, a supplement containing scripts, parameters, and essential intermediate layers should allow third parties to reproduce the extraction of drainage and divide networks, the calculation of metrics, and the comparisons between basins.

6.1. Gradual migration: minimum reporting for χ and hillslope metrics

In studies of gradual migration, the DEM used should be reported, including its source, resolution, and spatial reference, together with the main hydrological-conditioning steps that affect connectivity, drainage-network extraction, and divide delineation. It is also necessary to specify the fluvial scale represented, reporting the drainage-area threshold adopted for network extraction and the geomorphological justification for this choice. Whenever feasible, a simple sensitivity test should be included to verify whether the main pattern persists across a plausible range of thresholds. The geomorphological context relevant to the interpreted signal should also be described, including tectonic, lithological, or climatic controls where pertinent.

The calculation of χ requires the reference frame to be described explicitly. The adopted base level x_b , the calculation domain, θ_{ref} , A_0 , the drainage-area threshold used to define the network, the method used to pair channel heads along the same local divide segment, and the sign convention adopted for $\Delta\chi$ should be reported. The choices of x_b and θ_{ref} should also be justified. The calculation domain is understood here as the spatial subset within which the drainage network was extracted, integrated, and compared, with verification that connectivity to x_b was preserved in all networks compared. Where feasible, robustness should be assessed by testing plausible alternatives for x_b and θ_{ref} , and by reporting whether χ and hillslope metrics converge or diverge, treating divergence as a result to be interpreted.

When a study uses χ' or discusses spatial variations in U or K , the independent source of these estimates should be reported, together with how they were translated into relative functions U^* or K^* , and whether the magnitude and polarity of $\Delta\chi$ remain stable under these choices. When such independent estimates are not available, the interpretation should be presented as conditional, accompanied by complementary metrics and geomorphological consistency checks.

6.2. Discrete capture: interpretative anchor, quantification, and comparisons

For discrete captures, indicate which evidence anchors the hypothesis of past connectivity. In topography, this is usually a windgap and the inherited valley-scale geometry associated with the beheaded valley. Where independent evidence exists, such as deposits associated with the interrupted valley, palaeoflow indicators, or biogeographical signals, describe the logical link with past connectivity and why this evidence is incompatible with the modern drainage network.

If the interpretation is anchored in windgaps, provide an operational and reproducible definition: how the low-elevation divide with valley geometry was distinguished from low-elevation divide segments potentially controlled by lithology or structure. Indicate whether the identification resulted from a systematic search within the domain or from targeted selection, and which minimum criteria were required for including a candidate. Where the archives were quantified, report how the evidence was converted into numerical form, at what scale, and with which choices, such as windows, segmentation, and thresholds, as well as the domain and χ parameterisation where applicable. Finally, to support comparability, it is good practice to indicate how the case behaves relative to neighbouring basins analysed under the same set of choices, making explicit whether the signal is localised, and therefore coherent with an individual capture, or broad, and therefore compatible with a regional control.

Author Contributions: Daniel Peifer: conceptualisation, literature synthesis, development of the operational framework, visualisation, writing – original draft, and writing – review and editing. The author read and approved the final version of the manuscript.

Data Availability: The topographic data used to produce Figures 2 and 3 are available from <https://opentopography.org>. The topographic data used to produce Figures 1, 5, 6 and 7 correspond to the LGL-BW ATKIS Digitales Geländemodell DGM 5 m (2005). Figure 4 is conceptual and does not depend on topographic data.

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Declaration on the Use of Artificial Intelligence: During the preparation and revision of this manuscript, the author used ChatGPT (OpenAI, GPT-5.5 Thinking) as an editorial aid, including consistency checks throughout the manuscript and response letter, targeted language refinement, and assistance with translating the manuscript into English. All content produced with the support of this tool was reviewed, edited, and critically verified by the author, who has expertise in the subject and fluency in English. The scientific interpretation, conceptual selection, methodological decisions, and final wording remained entirely under the author's responsibility. No generative artificial intelligence tools were used to create scientific data, analytical results, figures, maps, or images. The author assumes full and complete responsibility for the final content of the manuscript.

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