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Reviews and syntheses: Threshold shifts in riparian plant water sources along hydrological gradients

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Abstract

The hydrological connection between riparian plants and the river underpins riparian ecosystem functioning and informs ecological water delivery and buffer-zone delineation, yet isotope evidence remains scattered across case studies. From a library of 131 stable hydrogen and oxygen isotope (δ^2H, $\delta^{18}O$) water-source studies, we selected 25 studies with an explicit gradient design and re-analysed their data in a standardised form, 11 distance-calibrated transects (41 sites), three time series (158 records) and one water-uptake-depth sequence (43 records). Distance to channel, depth to water table and flow permanence were unified on a single "hydrological connectivity" axis to test for comparable thresholds in water-source switching.

In arid and semi-arid regions plant water sources switch abruptly along the distance gradient, and the transition zone in which the stable-water fraction (deep soil water plus groundwater) crosses 50 % consistently falls at 50–400 m from the channel (shrubs 50–100 m and trees 100–400 m in hyper-arid regions, 50–200 m in semi-arid regions). In humid regions no such switch occurs; the river-water signal attenuates over metre-to-hectometre distances, with the attenuation scale increasing with aridity. Recharge mode determines the form of the gradient: channel-recharged systems produce a switch, precipitation-recharged systems attenuation. Life form shifts transition-zone position through rooting depth, and woody species show greater seasonal plasticity than herbs. Distance to channel is itself only a proxy for connectivity, since groundwater contribution increases with distance in a channel-recharge system but decreases with distance in a reservoir-recharge system.

We propose defining the functional width of a riparian zone by the outer edge of the transition zone (400–1000 m for trees in arid inland rivers, 100–200 m in semi-humid rivers) and replacing a single target water level with a zoned combination of depth and fluctuation, together with a species-configuration list along the gradient. The synthesis provides water-

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source-based evidence for delineating restoration widths and scheduling ecological water delivery.

Short summary: Stable-isotope evidence synthesised into a hydrological-connectivity axis reveals a comparable water-source transition zone at 50–400 m from channels, with implications for riparian restoration width.

Keywords: riparian zone; stable hydrogen and oxygen isotopes; plant water sources; hydrological connectivity; water-source transition zone; depth to water table; ecological water delivery

1 Introduction

The riparian zone, the ecotone between terrestrial and aquatic ecosystems, maintains biodiversity, traps sediment and nutrients, and provides corridor connectivity. The hydrological basis of these functions is the water connection between riparian plants and the river. In arid inland basins this connection is very nearly the sole condition for the persistence of riparian forest. The *Populus euphratica* and *Tamarix* forests of the Tarim and Heihe basins depend on channel leakage and shallow groundwater (Zhou et al., 2017; Li et al., 2017; Wang et al., 2017), and channel cutoff and declining groundwater tables have caused extensive forest decline in the downstream reaches, where the lower Heihe has been cut off since the 1950s (Chen et al., 2016). Since 2000, the ecological water delivery programmes of the Heihe and Tarim basins have had to set management targets for the volume of water to convey, the groundwater table to be raised and the width of the forest belt to be protected (Li et al., 2017). All of these are, in substance, questions about where plants take up water. In humid and semi-humid regions, riparian buffer zones have likewise long been delineated by empirical values and flood-management lines, without a functional basis derived from plant–water relationships (Han and Zhang, 2020; Wang et al., 2024). Answering where riparian plants obtain water, and how this dependence varies in space, is therefore both a fundamental question in ecohydrology and a direct technical requirement for riparian restoration and management.

Stable hydrogen and oxygen isotope tracing (δ^2H, $\delta^{18}O$) provides a direct observational means of addressing these questions. Since Dawson and Ehleringer (1991) showed that streamside trees do not necessarily use the water of the adjacent stream, comparing xylem water with candidate water sources (precipitation, river water, stratified soil water, groundwater) in isotopic space has become the standard method for plant water-source partitioning. Quantitative tools have evolved from direct comparison and linear mixing models to IsoSource (Phillips and Gregg, 2003) and Bayesian mixing models (Stock et al., 2018). Three

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decades of accumulation have created the data conditions for synthesis. In the literature library assembled for this paper, 131 of the collected studies address plant water sources, 97 of them in riparian settings, and 85 report measured xylem-water δ^2H and $\delta^{18}O$ values, of which 62 also report δ^2H. Study areas span the inland rivers of north-western China, semi-humid rivers of north China, the south-western United States, Australia's Murray–Darling basin and the European Alps, with climate gradients running from hyper-arid regions receiving under 50 mm of annual precipitation to cold-humid regions.

Existing isotope water-source studies, however, organise their conclusions by species, climate zone or life form. Each study answers which water a given plant uses, but the environmental gradient information embedded in the study is rarely extracted for quantitative cross-study integration. The consequence is that we know that *P. euphratica* switches to groundwater as burial depth increases (Zhou et al., 2017) and that *P. tomentosa* in the Chaobai River relies mainly on soil water (Han and Zhang, 2020), yet we cannot answer the more general questions: at what distance from the channel does the water source switch? Is that position comparable across climate zones and life forms? What controls it? The relevant gradient variables (distance to channel, depth to water table, flow permanence) are scattered across the literature as ready-made but systematically unexploited dimensions for synthesis. Accordingly, we hypothesise that the variation in riparian water-source patterns is not random but structured along a hydrological-connectivity gradient, and we pose three progressively nested questions: (1) how do riparian water sources switch along a hydrological gradient comprising distance to channel, depth to water table and flow permanence? (2) Does this switching exhibit a threshold, or a transition zone, that is comparable across studies? (3) What regulates the position and morphology of that transition zone: climate, life form, or recharge mode?

To address the hypothesis and these three questions, we start from a library of 131 publications and select those riparian studies that incorporate a spatial or hydrological gradient design. Distance to channel, depth to water table and flow permanence are unified on a single "hydrological connectivity" axis (Fig. 1), against which the isotopic contribution data are re-analysed in a standardised form. We then test the water-source transition zone hypothesis and discuss its mechanisms, its management implications for redefining the functional width of riparian zones and the critical depth to groundwater, and the methodological boundaries of cross-study integration. The paper concludes with recommended ranges for riparian width, groundwater depth and species configuration aimed at riparian restoration and ecological water delivery.

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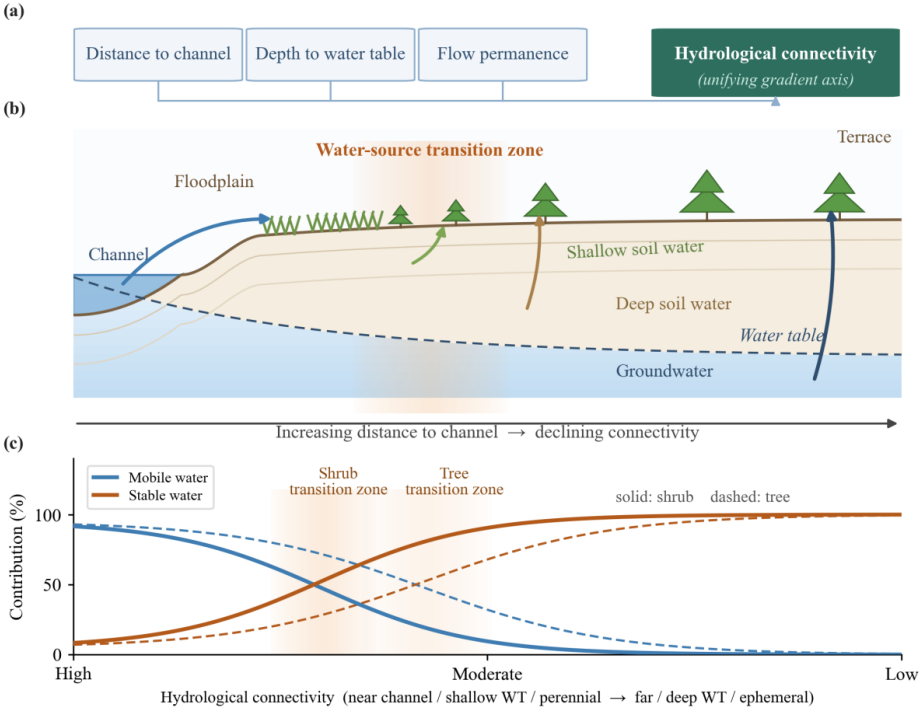


Figure 1. Conceptual framework for water-source transitions in riparian zones, organised along a single unifying axis of hydrological connectivity. **(a)** The three control axes — distance to channel, depth to water table and flow permanence — converge on hydrological connectivity, which acts as the unifying gradient axis. **(b)** Conceptual cross-section from channel to terrace, showing the water table, the mobile-water pool (river water and shallow soil water) and the stable-water pool (deep soil water and groundwater), the dominant water-source pathways for contrasting life forms, and the position of the water-source transition zone; connectivity declines with increasing distance from the channel. **(c)** Conceptual gradients of mobile- and stable-water contribution along the same axis, drawn for a shrub (solid line) and a tree (dashed line); the transition zone is marked on each curve. Connectivity decreases from near-channel, shallow-WT and perennial conditions (left) to far-channel, deep-WT and ephemeral conditions (right).

2 Data and methods

2.1 Construction and screening of the literature library

A systematic literature library on "water sources of riparian plants" was assembled by searching CNKI and Web of Science using combinations of riparian zone, isotope and plant water-use keywords, followed by manual verification (131 publications: 39 in Chinese and 92 in English; covering the inland rivers of north-western China, rivers of north China, North America, Australia and Europe). For each publication, information was extracted using a uniform template with 17 attributes, including study location, coordinates, climate type, plant names, methods, and the isotopic composition and contribution of each water source (precipitation, river water, shallow, intermediate and deep soil water, and groundwater).

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From the 131 publications, 56 riparian-focused studies were retained (34 quantitative and 22 qualitative) meeting the following criteria: (1) the study object is riparian vegetation; (2) water sources are partitioned using $\delta^2H/\delta^{18}O$ isotopes; and (3) either water-source contribution fractions or a gradient design are reported. Of these, 25 studies contain an explicit spatial or hydrological gradient design and form the core dataset of this synthesis. From these we could extract 11 distance-calibrated water-contribution transects (41 sampling sites, 8 publications) and one longitudinal water-uptake-depth sequence (43 records); three monthly or seasonal time series (158 records) and connectivity and ontogenetic evidence were added from the wider set of 56 riparian-focused studies (Table S1). The screening flow and the number of records at each stage are given in Fig. 2.

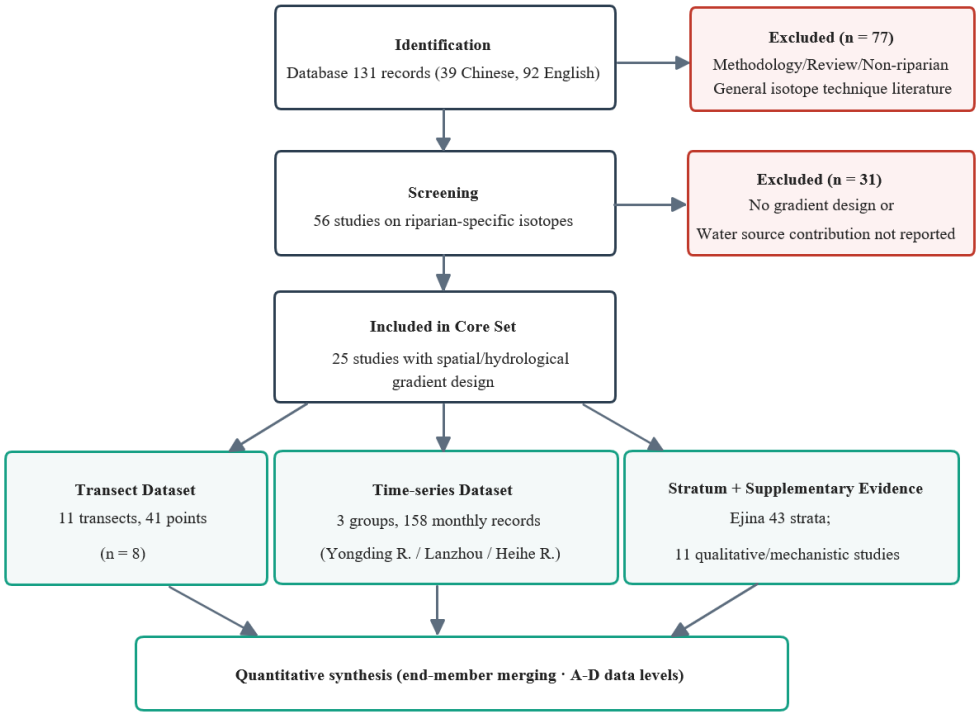


Figure 2. Literature screening flow (PRISMA style) for assembling the synthesis dataset. From a library of 131 stable-isotope water-source publications (39 Chinese, 92 English), 77 records were excluded as methodological or review literature, non-riparian studies, or generic isotope-technique papers, leaving 56 riparian-focused studies; a further 31 records were excluded because they lacked a gradient design or did not report water-source contribution fractions, leaving 25 studies with an explicit spatial or hydrological gradient design. The retained studies yielded three data sets: 11 distance-calibrated water-contribution transects (41 sampling sites; 8 publications), 3 monthly or seasonal time series (158 records), and 1 longitudinal water-uptake-depth sequence (43 records), supplemented by connectivity and ontogenetic evidence from the 56 riparian-focused studies. All extracted values were integrated using a unified end-member pool and graded A–D by traceability.

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2.2 Standardisation of gradient variables

Three classes of gradient variable were harmonised. For distance to channel, exact distances are taken as reported; for graded transects (e.g. < 50, 50–200 and > 200 m) the class midpoint is used (recorded as 25, 125 and 250 m respectively) and flagged in the data table (Yu et al., 2021); profile codes (e.g. S0–S5) are converted to distance from the bank according to the definitions in the original papers (Zhou et al., 2017). For depth to water table (WTD), values reported in the papers are used directly; where only categories are given, they are classified into shallow (< 3 m), intermediate (3–10 m) and deep (> 10 m). Flow permanence is classified as perennial, intermittent or ephemeral following the original papers. Studies whose gradient variables cannot be standardised (for example, east- and west-facing banks without distance calibration) are excluded from the transect analysis and used only as end-member case references.

2.3 Pooling of water-source end members

Because soil-layer definitions and end-member naming vary widely among studies, all water sources were pooled into four end-member pools: precipitation, river water, shallow soil water (0–50 or 0–60 cm, assigned to the nearest layer definition in the original paper), deep soil water (below 50/60 cm to the lower limit of rooting), and groundwater. Precipitation, river water and shallow soil water are further combined as "mobile water", hydrologically connected to contemporary surface processes, whereas deep soil water and groundwater together form "stable water". The stable-water fraction is the core metric for cross-study comparison in this paper. Special cases are handled as follows: (1) the Ejina Delta study (Li et al., 2017) distinguishes only a two-end-member river water/groundwater system, and its site-level data are flagged separately under that convention; (2) the lower Heihe seasonal series (Meng, 2024) contains an independent rain end member, which is retained as a separate column; (3) studies without a groundwater end member (for example Sejila Mountain; Chen et al., 2026) are flagged during pooling.

2.4 Data grades and quality control

All extracted values are assigned to four grades according to traceability: A (values given in tables or text), B (values annotated in figures), C (digitised from figures) and D (semi-quantitative or interval estimates). Statements in the text are based on grade A–B data only; grade C data are used only in figures and are annotated as such; grade D data do not enter quantitative arguments. Two quality-control cases are worth reporting. First, two plots in the Yellow River transect at Jiaozuo (Wang et al., 2024) were sampled 3 d and 15 d after rainfall

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respectively, so that sampling lag was confounded with distance across a span of only 5 m; these were excluded from the gradient arguments. Second, cross-checking of the Ejina water-uptake-depth sequence against repeated multi-period records showed that single-month data produce the erroneous inference that uptake depth deepens monotonically along the river (in reality the shallowest values occur in the middle reaches). An admission rule was therefore adopted: gradient inferences require support from multi-period records.

2.5 Analytical approach

Transition-zone identification: the transition zone is defined as the distance interval over which the stable-water fraction crosses 50 %, and the knickpoint is placed where the rate of change of that fraction between adjacent sampling sites is maximal. Attenuation-scale comparison: on transects for which a direct river-water contribution is reported, the spatial scale over which the river-water contribution declines with distance is compared (metre, hectometre or hectometre–kilometre). Grouped comparison: transition-zone position and seasonal plasticity are compared across climate zones (hyper-arid, arid, semi-arid, semi-humid and cold-humid) and life forms (tree, shrub, herb). Connectivity test: the direction of change in groundwater contribution with distance is compared between channel-recharge and reservoir-recharge systems. All data preprocessing, analysis and plotting were carried out in Python (Python 3.13.5).

3 Results

3.1 Overall patterns along the hydrological gradient

Of the 56 riparian-focused isotope studies, 25 contain an explicit spatial or hydrological gradient design, from which 11 distance-calibrated water-contribution transects (41 sites), three monthly or seasonal time series (158 records) and one longitudinal water-uptake-depth sequence (43 records) can be extracted. Study sites are strongly clustered geographically (Fig. 3). About two thirds lie in the inland rivers of arid north-western China (Tarim, Heihe and Shiyang; Zhou et al., 2017; Wang et al., 2017; Li et al., 2017; Meng, 2024; Gun et al., 2025) and in the semi-humid rivers of north China (Yongding, Chaobai and Yellow River; Ren and Luo, 2025; Han and Zhang, 2020; Su et al., 2020; Wang et al., 2024). Western North America (Snyder and Williams, 2000; Thorburn and Walker, 1994) and western Europe each contribute one cluster, while South America, Africa, South-East Asia and the boreal zone are essentially empty. The climate gradient spans the full sequence from hyper-arid (under 50 mm of annual precipitation) to cold-humid, which makes cross-climate comparison possible.

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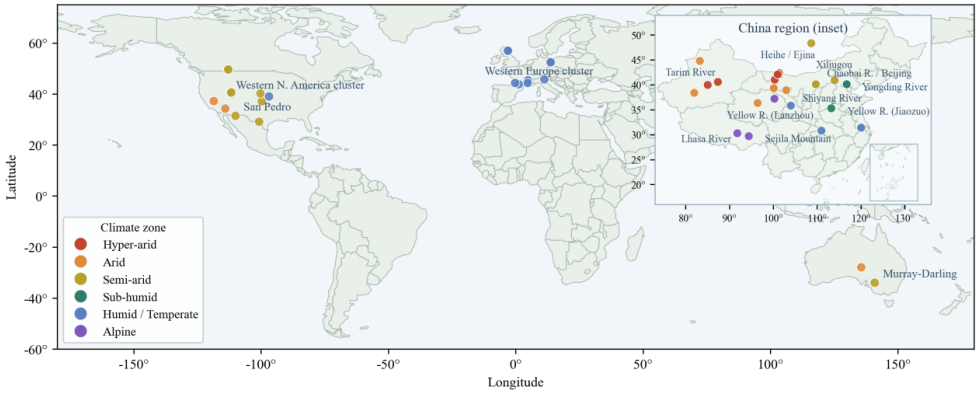


Figure 3. Geographic distribution of the riparian-zone stable-isotope water-source studies compiled for this synthesis (n = 56). Symbols are coloured by climate zone. Sites cluster in the inland rivers of arid north-western China (Tarim, Heihe/Ejina, Shiyang) and the semi-humid rivers of north China (Jiaozuo on the Yellow River, Yongding, Chaobai/Beijing), with the Lanzhou reach of the Yellow River (324 mm) transitional between semi-arid and semi-humid, and smaller clusters in western North America (San Pedro) and Australia (Murray–Darling), whereas South America, Africa, South-East Asia and the boreal zone are essentially unrepresented. The China region is shown enlarged in the inset.

After pooling all sites into mobile-water and stable-water end-member pools, a clear overall pattern emerges. Variation in the stable-water fraction follows the hydrological gradient: within a single river system, the closer to the channel, the shallower the groundwater table and the more persistent the flow, the stronger the plant's reliance on mobile water; the reverse applies where these conditions do not hold. Synthesis of the stable-water fraction across 22 study × species combinations (Fig. 4) show that stable-water reliance increases overall with aridity. Yet variation within a single climate zone reaches 60 percentage points (woody plants in the hyper-arid region range from 32.0 % in Ejina *P. euphratica* to 89.7 % in juvenile *P. euphratica* in the lower Tarim), and local hydrological conditions can reverse the expectation set by climate. At Beijing site B, where the water table is shallow (1.7–2.5 m), the stable-water fraction (56.9 %) approaches twice that of the deep-water-table site with the same climate and species (28.6 %; Li et al., 2022). Climate thus sets the baseline of the water-source pattern, while local connectivity factors (distance to channel, depth to water table and recharge mode) determine where a system actually falls.

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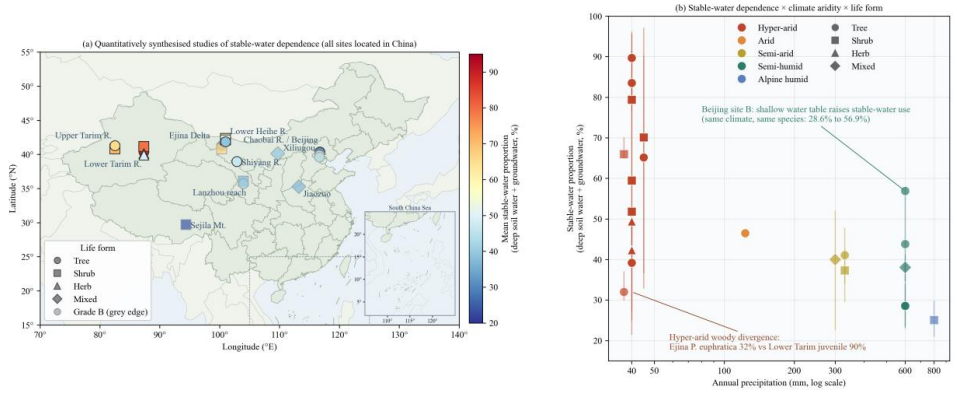


Figure 4. Global patterns of stable-water dependence across 22 study × species combinations. **(a)** Location of each study site, coloured by the mean stable-water fraction (deep soil water plus groundwater); vertical bars give the within-study range (maximum minus minimum along the distance gradient or across seasons). **(b)** Mean stable-water fraction against mean annual precipitation on a logarithmic axis, with symbols denoting life form (circle = tree, square = shrub, triangle = herb, diamond = mixed community) and colours denoting climate zone. Symbols with a black outline are grade A data and those with a grey outline grade B data. Stable-water reliance increases overall with aridity but varies by up to 60 percentage points within a single climate zone (woody plants in the hyper-arid region, from 32.0 % in Ejina *P. euphratica* to 89.7 % in juvenile *P. euphratica* in the lower Tarim). At Beijing site B, where the water table is shallow (1.7–2.5 m), the stable-water fraction (56.9 %) approaches twice that of the deep-water-table site of the same climate and species (28.6 %), showing that local hydrological conditions can reverse the expectation set by climate.

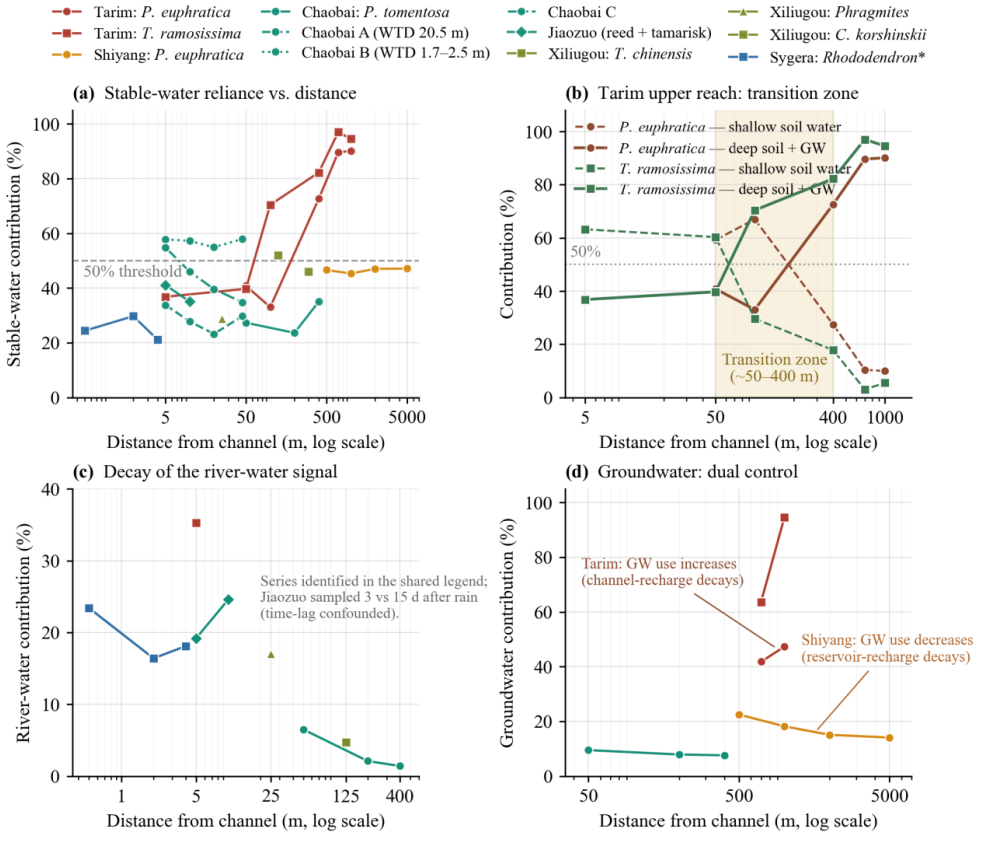
3.2 Complete switching of water sources and location of the transition zone along the distance gradient

Transects in arid and semi-arid regions consistently show a complete switching of plant water sources along the distance gradient, and the switch is concentrated within a comparatively narrow distance range (Fig. 5a, b).

The upper Tarim transect (hyper-arid, under 50 mm of annual precipitation; Zhou et al., 2017) is the most complete (six sites from the S0 floodplain to S5 at 1000 m from the bank): the stable-water fraction of *T. ramosissima* rises from 36.8 % on the floodplain (5 m) to 70.4 % at 100 m, 82.2 % at 400 m and 97.0 % at 700 m (of which 63.6 % is direct groundwater), reaching 94.5 % almost exclusively on groundwater at 1000 m; its 50 % crossing point lies between 50 and 100 m. The switch in *P. euphratica* is clearly later and non-monotonic within the zone: 40.8 % at 50 m, falling back to 33.0 % at 100 m, rising to 72.6 % at 400 m, 89.6 % at 700 m (41.8 % direct groundwater) and 90.1 % at 1000 m (47.3 % direct groundwater), so its crossing point lies between 100 and 400 m (Fig. 5b). For both species the switch is step-like rather than gradual: for *T. ramosissima* the stable-water fraction jumps by 30.7

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254 percentage points between 50 and 100 m, and the increment per log-distance interval far
255 exceeds that of all subsequent intervals.



* Bank-edge site (0 m) plotted at 0.5 m for the log axis.
Stable water = deep soil water + groundwater; shallow water includes river water. Markers: circle = tree, square = shrub, triangle = herb, diamond = mixed.

256 **Figure 5.** Signals of water-source transition along the distance gradient. **(a)** Stable-water contribution as a
257 function of distance from the channel for all 11 distance-calibrated transects (41 sampling sites), on a logarithmic
258 distance axis, with the 50 % threshold shown as a horizontal line; symbols denote life form (circle = tree, square
259 = shrub, triangle = herb, diamond = mixed community) and colours denote climate zone. **(b)** Enlargement of the
260 upper Tarim River transect, showing the transition zone (shaded band, ca. 50–400 m) for *Tamarix ramosissima*
261 and *P. euphratica*; solid lines denote deep-water series and dashed lines shallow-water series. **(c)** River-water
262 contribution against distance, illustrating attenuation scales ranging from metres in cold-humid regions through
263 hectometres in semi-humid and semi-arid regions to hectometres-to-kilometres in arid regions. **(d)** Groundwater
264 contribution against distance for the two arid transects, whose trends are opposite: groundwater contribution
265 increases with distance in the channel-recharge system (Tarim) and decreases with distance in the reservoir-
266 recharge system (Shiyang). The three Beijing sites are distinguished by line style (A: dashed, B: dotted, C: dash-
267 dotted). The Jiaozuo transect is not used in the gradient argument because its two plots were sampled 3 d and 15
268 d after rainfall, confounding sampling lag with a distance span of only 5 m. The bank-edge site (0 m) is plotted at
269 0.5 m for the logarithmic axis. Stable water = deep soil water + groundwater; shallow water includes river water.
270 Data from Zhou et al. (2017), Wang et al. (2024), Yu et al. (2021), Gun et al. (2025), Han and Zhang (2020), Li
271 et al. (2022) and Chen et al. (2026).

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The distance-graded plots in the semi-arid Xiliugou catchment (a tributary of the Yellow River, ca. 300 mm of annual precipitation; Yu et al., 2021) reproduce this pattern: in the near-bank < 50 m zone, herbs (*Phragmites*, *Typha*) reach only 22.8–28.7 % stable water, whereas shrubs such as *T. ramosissima* in the 50–200 m zone rise to 51.9 %, and *Caragana korshinskii*, *Salix matsudana* and *Limnodendron scoparium* beyond 200 m remain at 43.7–46.9 %. The transition zone in the semi-arid region therefore also falls in the 50–200 m interval, matching the magnitude found in the hyper-arid region (Table S2).

Two contrasting situations are equally informative. In the lower Shiyang River (arid; Gun et al., 2025), the stable-water fraction of *P. euphratica* is almost invariant between 500 and 5000 m (45.3–47.1 %), indicating that the transect as a whole already lies outside the transition zone, or that it is governed by reservoir infiltration recharge. In the semi-humid Chaobai River, *Populus tomentosa* (Han and Zhang, 2020) remains below 50 % throughout 50–400 m (23.6–35.0 %), and the gradient signal takes a different form.

3.3 Attenuation scale of the river-water signal and its differentiation along the climate gradient

On transects for which a direct river-water contribution is available, the river-water signal declines with distance, but the spatial scale of that decline changes systematically along the climate gradient (Fig. 5c). At cold-humid Sejila Mountain, the river-water contribution of *Rhododendron* falls from 23.4 % at 0 m to 16.4 % at 2 m (18.1 % at 4 m), a metre-scale attenuation (Chen et al., 2026). In the semi-humid Chaobai River, the river-water contribution of *P. tomentosa* declines from 6.5 % at 50 m to 2.1 % at 200 m and 1.4 % at 400 m, a hectometre-scale attenuation (Han and Zhang, 2020). In the semi-arid Xiliugou, a Yellow River tributary with about 268 mm of annual precipitation, near-bank riparian plants draw mainly on shallow soil water rather than on river water, and the river-water share reported for the 50–200 m zone is correspondingly low (Yu et al., 2021). In the hyper-arid Tarim River, by contrast, the isotopic signal of river water (mixed into the shallow soil water end member) remains identifiable over hectometre-to-kilometre distances (Zhou et al., 2017). The attenuation scale therefore extends from metres in cold-humid regions through hectometres in semi-humid regions to hectometres-to-kilometres in arid regions, varying in the same direction as aridity, because dilution by precipitation is weak in arid regions and channel leakage is the only source of shallow soil water, which allows the river-water signal to be preserved over long distances.

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3.4 Distance as a proxy variable and a hydrological-connectivity interpretation of groundwater contribution

Evidence from flow permanence and depth to water table indicates that the control exerted by distance to channel on water-source patterns operates through hydrological connectivity (Fig. 6). Along the perennial to intermittent to ephemeral sequence of the San Pedro River, shallow soil water (0–50 cm) use by *Populus fremontii* rises from 8 % to 26 % and that of *Prosopis velutina* from 0 % to 57 %, whereas the obligate phreatophyte *Salix gooddingii* remains at 0 % throughout. The lower the surface-water connectivity, the more facultative species shift towards alternative sources such as precipitation-fed shallow soil water (Snyder and Williams, 2000). Along the streamside to seasonal channel to 40 m inland sequence, stream-water use by *Eucalyptus camaldulensis* on the Murray River declines from about 50 % to 30 % to about 0 %, and the inland site still does not use floodwater despite being inundated for two months (Thorburn and Walker, 1994).

A manipulative comparison of depth to water table gives the same conclusion. Among three *Salix babylonica* sites in the Jian River–Chaobai riparian zone (Li et al., 2022), groundwater is used not at all at the site with a 20.5 m water table (71.5 % of uptake from upper soil water at 0–80 cm), whereas the site with a 1.7–2.5 m water table draws mainly on deep water below 80 cm (56.9 %). More telling is the in situ response of that site to a 0.8 m drop in the water table (1.7 to 2.5 m). Deep-water uptake on near-bank plots (5 and 10 m) decreased significantly by 47.3 % and upper soil water uptake increased by 28.6 % ($p < 0.05$), whereas the groundwater contribution on far-bank plots (20 and 45 m) instead increased significantly by 14.4 % ($p < 0.05$). Under the same water-level fluctuation, plots at different distances from the channel respond in opposite directions.

The same near-bank confinement of water uptake has been documented by in situ monitoring of xylem and soil water isotopes in temperate riparian willow (*Salix alba*) at the Müggelsee lakeshore, where a Bayesian mixing model attributed about 90 % of root water uptake to the upper 20 cm of soil despite a shallow and stable water table at 2.2 m, shifting to roughly 30 % from depths below 40 cm only during a dry period in late summer (Landgraf et al., 2022; Smith et al., 2022).

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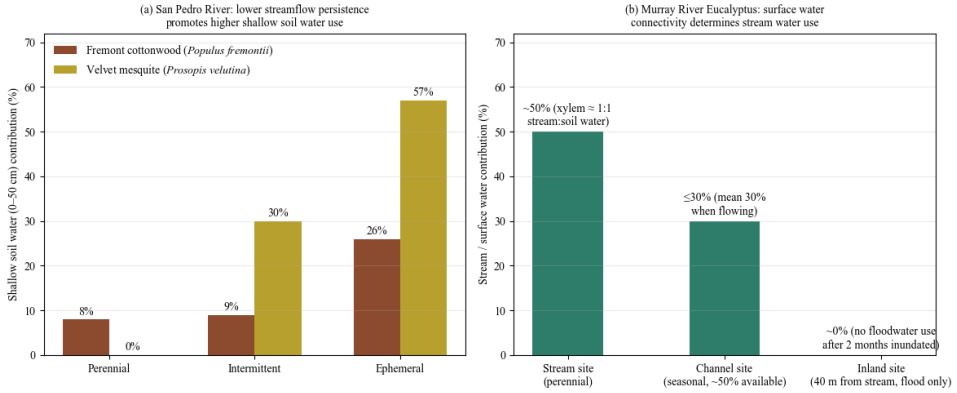


Figure 6. Evidence that water-source partitioning is controlled by hydrological connectivity rather than by distance. **(a)** Use of shallow soil water (0–50 cm) by three riparian tree species across the perennial, intermittent and ephemeral classes of the San Pedro River, Arizona: *Populus fremontii* 8 %, 9 % and 26 %; *Prosopis velutina* 0 %, 30 % and 57 %; and the obligate phreatophyte *Salix gooddingii* 0 %, 0 % and 0 %. Error bars are ±1 SE (n = 5–11 tree clusters per species per site); the dashed outline for *P. fremontii* at the ephemeral reach gives the regional-endmember estimate (33 ± 7 %). **(b)** Stream- and floodwater use of *Eucalyptus camaldulensis* along an access gradient on the Murray River, Australia: streamside (ca. 50 %, stem water : soil water ≈ 1 : 1), seasonal channel (≤ 30 %, error bar = ±1 SD across access-duration classes of 2 weeks to 10 months) and inland at 40 m from the creek (ca. 0 %, floodwater unused even after two months of inundation). Values in (b) are semi-quantitative. Background shading encodes decreasing surface-water connectivity. Data from Snyder and Williams (2000) and Thorburn and Walker (1994).

The clearest illustration is the divergence in the direction of groundwater contribution between two arid transects (Fig. 5d). In the upper Tarim, the direct groundwater contribution increases with distance (from 0 to 41.8–47.3 %; Zhou et al., 2017), because channel leakage declines with distance and plants are forced downwards. In the lower Shiyang, the groundwater contribution decreases with distance from the reservoir shore (from 22.5 % to 14.1 %; Gun et al., 2025), because groundwater there is recharged by reservoir infiltration and flow paths lengthen away from the source. These two opposite patterns are unified on the connectivity axis: what controls water-source switching is not distance itself, but the accessibility of each water source and how it declines with connectivity.

3.5 Systematic control of the transition zone by life form and ontogeny

The position of the transition zone varies systematically among life forms. In the upper Tarim, the transition zone of the shrub *T. ramosissima* (50–100 m) lies closer to the channel than that of the tree *P. euphratica* (100–400 m; Zhou et al., 2017). In Xiliugou, herbs remain bound to shallow water sources within the near-bank zone and undergo no switch, whereas shrubs in the same plots complete the switch between 50 and 200 m (Yu et al., 2021). The shallower the rooting system, the more tightly the water-source pattern is locked to near-bank mobile water,

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and the closer to the channel the transition zone lies; where roots are shallowest, no spatial switch occurs at all (Table S2).

Plasticity in the time dimension is likewise differentiated by life form (Fig. 7a). Between May and August in the Yongding River basin, mean river-water use in trees falls from 32 % to 12 % and in shrubs from 30 % to 9 %, while herbs change little (38 % to 36 %; Ren and Luo, 2025): woody plants shift their main uptake from river water to soil water at the height of the wet season, whereas herbs, with shallow roots, maintain dependence on near-bank sources.

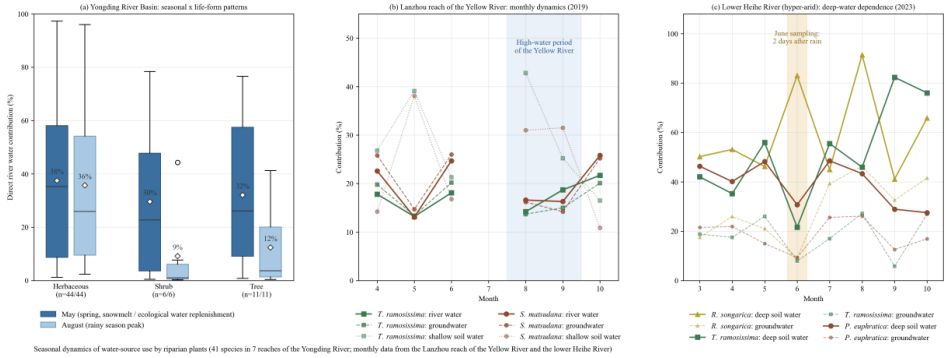


Figure 7. Temporal dynamics of water-source use. **(a)** River-water use by life form in the Yongding River basin in May and August, showing that woody species shift their main uptake from river water to soil water through the wet season whereas herbs, with shallow roots, change little (38 % to 36 %). **(b)** Monthly dynamics of water-source use at site S1 in the Lanzhou reach of the Yellow River during the 2019 growing season, showing enhanced shallow soil water use (up to 42.8 % in *Tamarix ramosissima* in August) and a minimum in groundwater use (ca. 13–16 %) during the August–September high-flow period, with contributions recovering in October after the water level falls. **(c)** Monthly dynamics of deep-water (120–200 cm soil water plus groundwater) dependence of *Reaumuria songarica*, *Tamarix* and *P. euphratica* in the lower Heihe River during 2023, showing swings between ca. 22 % and 91 % and rain-water contributions of 47–67 % two days after rainfall. Data from Ren and Luo (2025), Su et al. (2020) and Meng (2024).

Evidence at the ontogenetic scale points to the same mechanism. Along the diameter-at-breast-height sequence from seedling to young tree of *Abies smithii* on the mountain slope (not the riparian zone) at Sejila Mountain, reliance on 0–20 cm soil water declines from 46.4 % to 30.4 % while use of the 40–100 cm layer rises from 15.6 % to 40.2 %, so the main water source shifts from the surface to the mid-deep layer (Chen et al., 2026). In the lower Tarim, juvenile and adult *P. euphratica* both rely on stable water throughout the year (totals of ca. 79–96 %), but the difference between them is amplified in the most water-stressed period: in July the deep soil water fraction of juvenile trees reaches 66.2 %, far above the 39.6 % of adults, and the two converge again by September (75.6 % versus 75.2 %; Wang et al., 2017). Complementarily, in the same area the shallow-rooted legume *Alhagi sparsifolia* depends on

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shallow soil water to 56.8 % during the green-up period (May) and shifts to the mid-deep layer after the onset of midsummer (Wang et al., 2017). Different life forms therefore partition water-source niches through rooting differentiation, and this partition is dynamically reorganised under water pulses.

3.6 Temporal dynamics of water-source use and legacy effects of flood and water-delivery pulses

Water-source use switches back and forth with hydrological regime, and the amplitude of that swing increases with aridity (Fig. 7b, c). In the semi-arid Lanzhou reach of the Yellow River (mean annual precipitation 324 mm), *T. ramosissima* increases its use of shallow soil water during the August–September high-flow period (42.6 % in *T. ramosissima* in August), while the same plant relies mostly on deep soil water in late spring (38.8 % in April–May) and shifts towards river water and groundwater in October after the water level falls (Su et al., 2020). In the hyper-arid lower Heihe, the stable-water fraction (120–200 cm soil water plus groundwater) of *Reaumuria songarica*, *Tamarix* and *P. euphratica* swings widely, from about 22 % to 83 % across months, and rain-water contribution two days after rainfall can surge to 47–67 % (47.3 % in *P. euphratica*, 66.5 % in *Tamarix*; Meng, 2024): even in an ultra-arid region receiving under 40 mm of annual precipitation, a single rainfall event can temporarily reconfigure the water-source pattern.

Legacy effects of ecological water delivery and flood pulses are especially pronounced in arid regions (Fig. 8). During the water-delivery period in the Ejina Delta, the river-water contribution of *P. euphratica* rises to 82–86 % (58–65 % outside delivery periods, an increase of 18–23 percentage points) and that of multi-branch *T. ramosissima* from 30–32 % to 47–48 %; the legacy extends into the intervals between deliveries: in early June of a non-delivery year, river-water contributions of *P. euphratica* and *Tamarix* were still 75 % and 38 % respectively, above their respective annual means, thanks to winter–spring delivery recharging soil water (Li et al., 2017). Water-uptake-depth records further show that the uptake depth of *P. euphratica* during delivery is overall slightly shallower than outside delivery (median means of 150 versus 156 cm), indicating that recharge shifts uptake upwards. Studies of *Arundo donax* on the Rio Grande provide the timescale of this legacy: use of floodwater left by the July 2010 flood reached 50 % in the month of the flood itself (δ^2H-based partitioning) and then declined, but was still detectable at 5–21 % from April to July of the following year across the two isotope partitions (Moore et al., 2016). The water-source legacy of a single flood can therefore persist for nearly a year.

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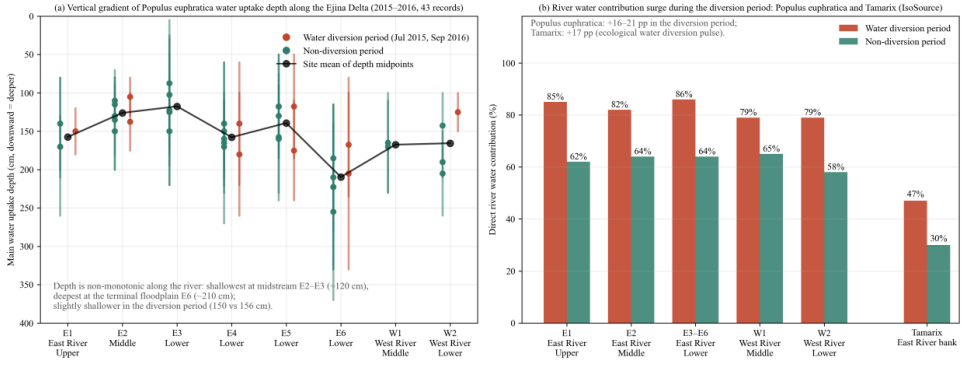


Figure 8. Longitudinal gradient of water-uptake depth and response to ecological water delivery in the Ejina Delta (lower Heihe River). **(a)** Median water-uptake depth of *P. euphratica* along the longitudinal gradient of the delta, from the upper sites E1–E2 to the terminal floodplain E6 (2015–2016; 43 records). Uptake depth varies non-monotonically along the river, being shallowest in the middle reaches (E2–E3, ca. 120 cm) and deepest at the terminal floodplain (E6, ca. 210 cm). **(b)** Direct river-water contribution of *P. euphratica* at each site, with *T. ramosissima* as a control, during and outside the ecological water-delivery period, showing a surge of 16–21 percentage points during delivery and a residual legacy persisting through the interval between deliveries. Values are IsoSource estimates from Li et al. (2017).

In summary, water-source switching appears spatially as a 50–400 m transition zone in arid and semi-arid regions or as metre-to-hectometre signal attenuation in humid and cold-humid regions, and temporally as seasonal-to-monthly back-and-forth switching plus a pulse legacy. Both forms are driven by hydrological connectivity and are systematically regulated by life form and ontogeny (Table S2).

4 Discussion

4.1 Conceptual definition and multi-process coupling of the water-source transition zone

This paper defines the water-source transition zone as the distance interval over which the stable-water fraction crosses 50 % along the distance gradient. The evidence above shows that this zone occupies a reproducible 50–400 m range in arid and semi-arid regions and that the switch is step-like rather than gradual: for *T. ramosissima* in the Tarim, the stable-water fraction jumps 30.7 percentage points between 50 and 100 m, far more than in any other interval (Zhou et al., 2017). Such critical behaviour indicates that the transition zone is not an arbitrary segment of a continuum but a threshold response where supply-side and access-side mechanisms meet.

Mechanistically, the transition zone arises from three coupled processes. First, supply-side attenuation: in arid basins channel leakage is the only source of shallow soil water and shallow groundwater, and it decays with distance from the channel, forcing a switch once it

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can no longer sustain plant-available shallow water. Second, access-side differentiation: rooting depth sets the water sources a plant can reach, so the transition migrates outward along the herb–shrub–tree sequence — shallow-rooted herbs in Xiliugou switch nowhere along the transect, *T. ramosissima* switches at 50–200 m there and at 50–100 m in the Tarim, and deep-rooted *P. euphratica* retains dual access to mobile and stable water out to 100–400 m (Yu et al., 2021; Zhou et al., 2017). Third, connectivity modulation: depth to water table and flow permanence alter the relationship between distance and supply attenuation, so the same distance yields different source combinations under different hydrological regimes (Li et al., 2022; Snyder and Williams, 2000).

The transition zone also offers a natural boundary case for the ecohydrological separation or "two water worlds" hypothesis (Brooks et al., 2010; McDonnell, 2014), which holds that plant-bound water and the mobile water feeding streams come from different reservoirs. Humid riparian trees indeed rely mainly on soil water with little stream input (Barbeta et al., 2019; Qian et al., 2017a). The riparian zone is where the two worlds meet: on the near-bank side, channel leakage converges soil- and river-water isotopes and connects plants to the river, whereas beyond the transition zone soil water reverts to precipitation-dominated recharge and separation is re-established. The transition zone is thus the spatial expression of the boundary between the two water worlds, and the riparian zone becomes a natural test case for the separation hypothesis rather than an exception to it.

4.2 Why switching occurs in arid regions and attenuation in humid regions

The sharpest contrast in the results is that complete switching of water sources occurs in arid and semi-arid regions, whereas semi-humid and cold-humid regions show only metre-to-hectometre attenuation of the river-water signal with no change in the dominant source. We argue that the division between these two forms is governed by the recharge mode of groundwater and soil water, with climate acting indirectly through that mode.

In hyper-arid regions where precipitation is negligible (Tarim and Heihe; Zhou et al., 2017; Li et al., 2017; Meng, 2024), channel leakage is the only source of water in the unsaturated zone, so distance to channel is effectively equivalent to source composition and the switch is hard-wired by the supply structure. In precipitation-rich humid regions, by contrast, soil water is repeatedly recharged by precipitation and mixed from multiple sources, and river water is only one component of near-bank soil water; the distance gradient then merely dilutes the river-water signal within the mixing end members without changing the dominant, precipitation-fed source (Han and Zhang, 2020). Metre-scale attenuation in the cold-humid

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zone (Chen et al., 2026) additionally reflects rapid lateral drainage promoted by steep topography and thin soils.

This distinction promotes climate zone from a descriptive grouping variable to a mechanistic explanatory variable: the first question for a given system is not how dry it is but who supplies water to the unsaturated zone. Semi-arid monsoonal rivers should therefore show arid-like switching in the dry season, when channel recharge dominates, and reservoir-fed reaches in arid regions should behave atypically. The Shiyang transect, in which groundwater contribution declines with distance from the reservoir shore and no switch occurs anywhere along the transect, is direct evidence that substituting the recharge source from channel to reservoir changes the form of the gradient.

4.3 Ecohydrological width of the riparian zone defined by the outer edge of the transition zone

How wide a riparian zone should be has long depended on empirical values and flood-management lines, without a quantitative basis derived from ecological process. The transition zone provides a functional criterion: the functional width of a riparian zone is the outer edge of the transition zone, beyond which plant water sources are no longer detectably connected to the river (Table 1):

Table 1. Estimated hydrological functional width of riparian zones by climate zone. Widths are given per life form; data grades follow Table S2.

Climate zone	Evidence system	Functional width (by life form)	Data grade
Hyper-arid inland rivers	Upper Tarim River	shrubs ca. 100 m; trees 400 m, with about 10 % mobile water still present at 700–1000 m	A
Semi-arid tributaries	Xiliugou	shrubs 200 m; herbs locked within < 50 m	B
Semi-humid rivers	Chaobai River	river-water signal attenuates to < 2 % within ca. 200 m	A
Cold-humid small rivers	Sejila Mountain	metre scale (main attenuation completed within 0–4 m)	B

Three management implications follow. First, the functional width of arid inland rivers is far larger than current delineations: trees in the Tarim reach 400–1000 m, so constraining riparian protection and delivery targets to the common hectometre-scale range will systematically miss stands that remain hydrologically connected to the river beyond the transition zone (Li et

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al., 2017). Second, width should be set per life form, since shrub regeneration zones and deep-rooted tree stands occupy different spatial ranges and a single line for all species is indefensible. Third, narrowness in humid regions does not imply unimportance: attenuation completing within metres in the cold-humid zone means the near-bank metres carry the entire connection and are extremely sensitive to disturbance (Chen et al., 2026).

4.4 Critical depth to groundwater: integrating isotope and physiological evidence

For groundwater-dependent phreatophytes, how deep the water table may fall before the system fails is central to ecological water delivery. The evidence here shows the critical depth is not a universal value but an interval that shifts with life form, ontogeny and rate of change, although independent lines of evidence converge on the key positions. In the shallow zone the isotopic response is highly sensitive: a *Salix babylonica* site with a 1.7–2.5 m water table draws mainly on deep water below 80 cm, whereas groundwater drops out of the source combination entirely at a 20.5 m table, and a fall of only 0.8 m reduced near-bank deep-water uptake by 47.3 % ($p < 0.05$; Li et al., 2022). Within the capillary reach, sub-metre fluctuation is therefore sufficient to reconfigure the water-source pattern.

Physiological evidence comes from sap-flow observations of *Eucalyptus victrix* along Weeli Wolli Creek in the Pilbara region, Australia: sap flow stayed high where the water table was stable at about 6 m, fell to its lowest range under both an abrupt 10 m-scale drawdown and a naturally deep (~29 m) table, and peaked where the table was raised (Pfautsch et al., 2015). Some 6–8 m thus appears to mark the boundary between maintenance and suppression of sap flow in this species, and the rate of change matters as much as absolute depth — a point that corroborates the 0.8 m isotopic result above (Li et al., 2022). At both levels, the water-table constraint therefore reflects depth combined with rate of change, not static depth alone.

The tolerance limit of deep-rooted plants is high but not unlimited. At 1000 m in the upper Tarim, *P. euphratica* still draws 90.1 % from deep soil water plus groundwater (47.3 % directly from groundwater) and *Tamarix* almost entirely from groundwater (94.5 %; Zhou et al., 2017). Yet juveniles in the lower Tarim must raise their deep-water fraction to 66.2 % in the driest month, far above the 39.6 % of adults (Wang et al., 2017), and in the lower Heihe, *P. euphratica* seedlings rely mainly on 0–20 cm soil water, using groundwater directly only to about 13 %, while shallow-rooted forbs use it at under 7 % (Chen et al., 2014). Seedling and shallow-rooted survival is thus bound directly to surface soil water, for which groundwater serves as indirect support through capillary rise and seepage rather than as a direct source.

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Groundwater management follows from this in three tiers. The near-bank regeneration zone, the inner edge of the transition zone, must keep surface (0–20 cm) soil water available, with shallow burial and no abrupt drawdown (Chen et al., 2014; Li et al., 2022). The intermediate zone allows seasonal fluctuation to induce rooting deepening and train the population's water-use plasticity. The distal stand zone tolerates greater burial but needs a limit on the rate of change. The objective of water-level management should therefore shift from a single target level to a zoned combination of depth and fluctuation.

Pulse-based recharge adds a temporal dimension that delivery scheduling can exploit. A single flood can supply water for nearly a year (*Arundo donax*, 50 % in the flood month, still 5–21 % the following April–July; Moore et al., 2016), and in Ejina a delivery pulse left 75 % river-water contribution the following June through winter–spring soil recharge (Li et al., 2017). Scheduling should therefore target dormant-season storage delivery plus responsive pulses at key phenological stages such as green-up and seed dispersal, rather than continuously high water levels, potentially achieving equal water security with less total water. Quantitative decay curves for the legacy effect, describing its rate, duration and differentiation along the distance gradient, should become core parameters in future delivery research.

4.5 Comparability limits and uncertainty sources in cross-study synthesis

The conclusions of this synthesis rest on the integration of contribution data across studies, and three classes of methodological issue define the comparability limits of that integration. First, the systematic effect of δ^2H offset. Xylem δ^2H in riparian trees can be systematically lower than all candidate sources (Barbeta et al., 2019); correcting for this offset, or using $\delta^{18}O$ alone, significantly raises stream-water and deep-soil-water contributions and lowers surface-soil-water contribution. Studies that do not correct may therefore systematically underestimate river- and deep-water contributions. For this synthesis the consequence is layered: the comparability of absolute values is limited, but the gradient morphology (the direction of relative change with distance and the knickpoint position) is unaffected, because the offset is systematic within a study and cannot generate a signal that varies monotonically with distance. This is why the arguments here rest on transition-zone position rather than absolute levels.

Second, end-member non-identifiability. In channel-recharge systems the isotopic compositions of river water and groundwater overlap strongly — in the Ejina riparian zone, for example, both fall within −7.63 ‰ to −5.57 ‰ (Yu and Li, 2018) — so distinguishing direct river-water from groundwater contribution in xylem is intrinsically unreliable. This

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study partly sidesteps the problem by assigning the two to mobile- and stable-water pools, but the direct groundwater values reported in Chapter 3 (41.8–47.3 % for *P. euphratica* and 94.5 % for *T. ramosissima* at 700–1000 m in the Tarim) should be read as deep-source contributions whose internal split carries structural uncertainty. In addition, the time lag between uptake and the xylem isotopic signal (Yu and Li, 2018) means sampling after a pulse event must be interpreted with care; the exclusion of the Jiaozuo transection, where 3 d and 15 d post-rainfall lags confounded the comparison, is an explicit instance of this handling.

Third, the choice of model and isotopic input. For the same dataset, running IsoSource with δ^2H alone, $\delta^{18}O$ alone, or both can yield strikingly different layered contributions (4.5 % versus 95.5 % for the 0–40 cm layer in August), and three Bayesian models can differ by 10–20 percentage points in growing-season means (SIAR 41.7 %, MixSIR 59.4 %, MixSIAR 46.1 %), with SIAR and MixSIAR fitting better than MixSIR (Wang et al., 2019). This synthesis responds with three principles (A–D data grading, multi-end-member pooling, and gradient morphology taking precedence over absolute values) but cannot eliminate the uncertainty.

4.6 Implications and limitations

For zoned management aimed at riparian restoration and ecological water delivery, the width and depth implications above translate into a species configuration along the gradient. The near-bank zone (inner edge of the transition zone) should carry shallow-rooted herbs and regeneration cohorts that depend on surface water (*Phragmites*, *Typha*, *P. euphratica* and *Tamarix* seedlings). The middle of the transition zone should carry shrubs such as *Tamarix*, whose source plasticity buffers hydrological fluctuations. The distal zone should rely on deep-rooted tree stands (adult *P. euphratica*) able to withstand greater burial and longer delivery intervals. The governing principle is to align the rooting-depth spectrum of life forms with the distribution of water sources along the gradient while retaining scope for temporal plasticity, because the seasonal switching capacity of woody plants is itself a drought asset.

Several limitations should be acknowledged. The number of transects is limited and the geographic bias is marked: two thirds of the 11 transects lie in north-western and north China, while South America, Africa, South-East Asia and the boreal zone are empty, so the climatic generalisability of transition-zone position remains untested. Standardising the abscissa by class midpoints (for example recording Xiliugou 50–200 m as 125 m; Yu et al., 2021) understates the attainable precision, and studies that carry a gradient design may themselves be biased towards systems where a gradient signal is expected, while "no-gradient" null

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results are rarely published. Finally, because contribution data are proportions and no cross-study uncertainty propagation was performed, transition-zone positions should be read as intervals rather than point values.

5 Conclusions

Based on the extraction, preprocessing and analysis of stable hydrogen and oxygen isotope data from 131 publications on riparian plants and their water sources, three main conclusions follow. Riparian water sources switch systematically along the hydrological gradient. In arid and semi-arid region the stable-water fraction undergoes an abrupt, near-complete switch within 50–400 m of the channel, whereas humid and cold-humid regions show no wholesale switch but only metre-to-hectometre attenuation of the river-water signal.

Transition-zone position is comparable across climate zones. Shrubs cross the transition at 50–100 m and trees at 100–400 m in hyper-arid regions; the corresponding interval is 50–200 m in semi-arid regions; attenuation is completed within about 200 m in semi-humid regions and within metres in cold-humid regions. The amplitude of temporal fluctuation is small in semi-humid rivers, where the dominant source remains shallow soil water and river-water contributions stay low, but reaches more than 50 percentage points in hyper-arid regions, where a single rainfall event or water-delivery pulse is sufficient to reconfigure the water-source pattern temporarily.

The transition zone is driven by hydrological connectivity, with distance to channel only a proxy. Recharge mode determines whether the gradient takes the form of switching or attenuation, and plant life form and ontogeny shift transition-zone position systematically through rooting depth. The transition zone can serve as a criterion for defining the functional width of a riparian zone, and groundwater management should likewise shift from a single critical depth to a zoned combination of depth and fluctuation. Sub-metre fluctuation in shallow zones suffices to reconfigure water-source patterns, whereas deep burial beyond the capillary reach or abrupt drawdown exceeding about 10 m causes physiological suppression; the rate of change matters as much as the absolute depth.

Data availability

The structured datasets underlying this synthesis (the distance-gradient water-contribution dataset of 11 transects and 41 sampling sites, the monthly or seasonal time-series dataset of 158 records, the longitudinal water-uptake-depth dataset of 43 records, and the transition-zone

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summary table), together with the Python scripts used for data extraction, analysis and plotting, are archived in the project data repository accompanying this submission and will be deposited in a public repository with a persistent identifier before publication. The literature library, comprising 131 structured extraction records with a uniform template with 17 attributes, is likewise available from the corresponding author on reasonable request. Because the numerical values reported here were extracted from published sources, the authoritative record for each value remains the original publication cited in the reference list.

Code availability

All preprocessing, analysis and plotting were performed in Python. The scripts used to generate every dataset and figure reported in this paper are archived with the data package described above and will be released together with it under an open licence at publication. No proprietary software or closed-source components were used.

Author contributions

LS.R. (conceptualisation, methodology, data curation, data collection, formal analysis, writing — original draft preparation, visualisation); FY.L. (data collection, investigation, validation, writing — review and editing); Z.J. (data collection, investigation, validation); YJ.Z. (validation, writing — review and editing). All authors have given approval for the final version submitted.

Competing interests

The authors declare that they have no conflict of interest.

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Declaration of generative AI use. Generative artificial intelligence tools were used during the preparation of this manuscript, specifically to assist with language editing of the text produced by the authors. All scientific content, data interpretation, and conclusions are those of the authors, who take full responsibility for the manuscript.

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