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Stemflows and Preferential Flows: A Historical Review and Challenges for the Future

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ABSTRACT

This paper provides a historically-grounded review and research agenda on a generally neglected issue in hillslope hydrology and hydrological modelling: the role of stemflow in initiating preferential flow in soils. While stemflow typically represents a small fraction of incident rainfall, it can concentrate water fluxes by up to ~20-fold at tree bases, creating localised infiltration intensities that exceed those from throughfall. Some new historical context for throughfall and stemflow studies from the 19th Century is presented, including a summary of stemflow research in a wide range of vegetation types and environments. The evidence for preferential flows resulting from stemflows as a 'double-funnelling' effect is reviewed, emphasising tracer-based studies used to follow flow pathways. Although stemflow-driven preferential flows have been shown to occur commonly and, in some cases, to rapidly transport water to zones of saturation and consequent downslope flows, such processes have not been included in hydrological models to our knowledge. Thus, their significance at hillslopes and catchment scales remains an open question. The paper concludes with a needs analysis that identifies key observational and modelling challenges required to quantify stemflow-preferential flow impacts at larger scales.

1 | Introduction

One of the fascinating things about hydrology is the challenge of dealing with the complexity of the processes we can perceive in different flow pathways in trying to make quantitative predictions of water flows for practical applications (Beven and Chappell 2021). Our qualitative perceptual model of hydrological processes has evolved over time to be more complex (K. J. Beven 1987, 2012; McMillan et al. 2023; McDonnell 2026); but even the most physically-based process models of catchment responses are gross simplifications. Indeed, recent studies in machine learning suggest that they might sometimes be the wrong simplifications, in the sense that they do not extract all the information available in the observations (e.g., Shen et al. 2023), though we also have to allow that some data might be disinformative for the purposes of model calibration (e.g., K. J. Beven 2019).

One long-recognised source of such complexity is the role of vegetation in modifying inputs to a catchment area (Van Stan and Friesen 2020). It is a subject that has been intrinsically involved in the study of the effects of forests on water yields and flood peaks—one of the continuing questions for research in hydrology (e.g., Sopper and Lull 1965; Hewlett and Nutter 1969; Lee 1980; McCulloch and Robinson 1993). Hydrological models tend to assume that there is a single input rate over the area of a catchment, hydrological response unit, or other element of discretisation. Vegetation is usually also assumed to lose water back to the atmosphere at some areally average rate. But this contrasts with a long history of studies showing that, for some plants, the canopy can channel input rainfall into stemflows, producing highly heterogeneous inputs at the soil surface of both water, and dissolved nutrients in the water, to the advantage of the plant (Van Stan and Pinos 2023; Smith et al. 2024). In many dryland and strongly seasonal climates, this has been interpreted to be an evolutionary adaptation to low or variable rainfall (Li et al. 2009; Magliano et al. 2019).

A particular question that then arises is whether the concentration of inputs around the stems of trees and plants might lead to the instigation of preferential flow pathways vertically and laterally downslope in the soil (e.g., Levia and Frost 2003). This has been called the 'double funnelling effect', with an initial partitioning above the ground surface, as well as the concentration or funnelling of the stemflow flux entering the soil (Johnson and Lehmann 2006). There is then also a subsequent question as to whether the repeated nature of such fluxes across multiple events might lead to the self-organisation of preferential flow networks arising from stemflows (e.g., Sidle et al. 2001).

The implications of these preferential flow networks extend beyond water transport, for they can act as control points for catchment biogeochemistry and ecology (Aubrey 2020; Stubbins et al. 2020; Van Stan, Morris, et al. 2020). By concentrating resource-rich stemflow into specific soil zones, these flow paths have been documented to create 'hot spots' and 'hot moments' that drive soil microbial community structure (Bollen et al. 1968; Teachey et al. 2022) and the chemistry of soils and soil solutions (Gersper and Holowaychuk 1971; Chang and Matzner 2000). Over time, this localised moisture and nutrient availability can dictate understory vegetation patterns (Andersson 1991) and reciprocally shape the soil structure through biological activity and weathering (Metzger et al. 2021).

Although this spatial heterogeneity of inputs as a result of stemflows and the pattern of drip from canopy surfaces and gaps in throughfall has long been documented by biologists and hydrologists, it has been largely ignored by hydrological modellers. In particular, the role of stemflows in inducing preferential flows in the soil has not been addressed in any hydrological model to our knowledge (Murray et al. 2013; Gutmann 2020). Indeed, there has largely been a neglect of preferential flows in hydrological models, despite more than a century of observations that indicate their importance (e.g., K. Beven 2018). This contribution to the Special Issue on Preferential Flow Eco-Hydrological Processes in the Vadose Zone has three aims: (i) to provide a concise historical context for stemflow measurement and the emergence of the double-funnelling concept; (ii) to synthesise direct evidence that stemflow can initiate preferential flow pathways, focusing on tracer-based studies; and (iii) to explain why such localised inputs remain largely absent from hillslope and larger-scale hydrological models, and (iv) to outline an observational and modelling research agenda.

2 | Evidence for the Concentration of Rainfall Inputs in Stemflow

There is a long history, practical and scientific, of examining how rainfall inputs are partitioned into throughfall and stemflows in a variety of tree and crop species. Systematic ecohydrological work dates back into the 19th Century (see the reviews of Llorens and Domingo 2007; Friesen and Van Stan 2019; Levia et al. 2025). Throughout this history, the distinction between stemflow and near-stem throughfall has often been blurred by methodological choices; specifically, whether experimental set-ups classify near-stem drip and rough-bark water-shedding as stemflow or canopy drip (Voigt 1960; Van Stan and Allen 2020). Yet the basic awareness that rain can be channelled down trunks is far older, already noted by Theophrastus and Pliny the Elder (Van Stan and Friesen 2020). Over the centuries people found ingenious, sometimes life-saving applications for stemflow water. On El Hierro in the Canary Islands, for instance, stemflow from a single tree sustained a community's human and livestock needs (de Galindo and Glas 1764):

> Its leaves constantly distill such a quantity of water as is sufficient to furnish drink to every living creature in [El] Hierro; nature having provided this remedy for the drought of the island. … On the north side of the trunk are two tanks or cisterns… One of these contains water for the drinking of the inhabitants, and the other that which they use for their cattle, washing and such like purposes. Every morning, near this part of the island, a cloud or mist arises from the sea, which the south and easterly winds force against the fore-mentioned steep cliff; so that the cloud … advances slowly … and then rests upon the thick leaves and wide-spreading branches of the tree, from whence it distills in drops.
>
> (Chapter 13, pp. 275–277)

Conversely, stemflow could be weaponised. Caribbean oral history tells of enemies bound beneath the poisonous manchineel (*Hippomane mancinella*), where rain running over toxic bark produced blistering runoff (Exquemelin 1684; Cresswell 1924; Schwarz 2013). While documentary proof of that legend was not able to be found by the authors, case studies of soldiers and students blistered by the manchineel's draining dew (Satulsky 1943) or rainfall (Blue et al. 2011) confirm the deleterious effects of its draining waters, sometimes causing temporary blindness (Lauter et al. 1952). These citations show that stemflow was of cultural interest long before it became a subject of scientific study.

The first explicit scientific framing of stemflow as a concentrating mechanism appears in the parallel work of two 19th century scholars who wrote in German: the 1860s–1870s lectures of plant morphologist Anton Kerner von Marilaun, and the field experiments of forest meteorologist Ernst Ebermayer (1873). Kerner, in lectures later compiled in *Pflanzenleben* (Kerner von Marilaun 1888), used vivid classroom demonstrations to show how leaf form directs water:

> A portion of the rain does run down the bark of the trunk… One may even replace raindrops with small lead shot and then, especially on plants with stiff leaves, see with perfect clarity the track that every drop falling on the plant is obliged to follow. (Note all original German provided in Supporting Information.)

Kerner's shot-pellet demonstrations impressed young foresters, among them Wahrmund Riegler. Riegler (1881) openly credits that inspiration as giving his stemflow experiment its conceptual grounding:

> Professor Kerner … dealt with this topic in greater detail in his lectures … On that occasion he pointed out that the path taken by meteoric water over a plant's leaves and branches can be traced and demonstrated at any time by sprinkling small pellets of shot upon them.

Working independently on the hydrological side, Ebermayer (1873) recognised the budgetary significance of stemflow—reportedly after much discussion with Carl Eduard Ney (Ney 1893, 1894). After comparing rainfall totals beneath forest canopies with those in nearby clearings he concluded:

> In a normally closed forest stand the tree crowns intercept on average 26 percent… In reality, however, the water loss experienced by the forest floor, compared with an arable field, is smaller, because only part of the rain and snow falling on the crowns evaporates; the rest runs down branches, twigs and trunks, and snow falls directly to the ground… do not enter the rain-gauge and therefore cannot be quantified with that instrument. At the Johanniskreuz station preparations have already been made to measure the quantities that run down the tree stems.

This quote was also included in Riegler (1881) as the motivational relevance for his experiments. The preparations for measuring stemflow at Johanniskreuz involved a simple yet groundbreaking device, a zinc gutter fitted snugly around the trunk and draining into a measuring cylinder, which Ebermayer described as follows:

> … surrounding the tree trunk with a gutter made of sheet-zinc and collecting the runoff in a measuring cylinder. If the horizontal projection of the crown has been measured in square Paris feet, one can calculate how much water per square foot is supplied to the forest soil in this way.

Unfortunately, as Ney (1893, 1894) later reported, most data from his 1869–1870 Johanniskreuz stemflow measurement campaign were lost when he was mobilised for the Franco-Prussian War, though the method itself survived. Riegler (1881) adopted the Ebermayer-Ney collar-and-cylinder concept, applied it to multiple species, and confirmed Kerner's prediction that crown architecture controls the amount of rainwater that can be concentrated to the stem base.

Still, both the conceptual question—*what factors cause rainfall to be concentrated as stemflows?*—and the hydrologic relevance of stemflows remained relegated to discussions at research stations and academic lectures. This changed dramatically in September 1893, when the emerging international forestry research community gathered to formalise scientific cooperation across European borders. At the historic meeting of September 16, 1893 (part of the founding proceedings of what would become the International Union of Forest Research Institutions) stemflow measurement took centre stage as agenda item 6. Ney (1894), now holding the prestigious title of Imperial Government and Forest Councillor, presented 'Ueber die Messung des an den Schäften der Bäume herabfliessenden Regenwassers' (On the measurement of rainwater flowing down tree trunks). In the audience sat the 'Imperial-royal aspirant' Dr. Eduard Hoppe, whose own work on forest hydrology was gaining recognition. The discussion that followed between Ney and Hoppe proved to be a watershed moment for ecohydrological science. Their exchange focused on the critical question of whether, and under what conditions, trees could effectively concentrate rainwater inputs through stemflow mechanisms. This was no longer merely an academic curiosity or practical concern for individual forest stations; it had become a foundational question for the emerging science of forest hydrology, one that demanded standardised methods and international coordination to resolve.

Ney, drawing on his Johanniskreuz experiences, presented compelling evidence for stemflow's concentrating power:

> The water running down the trunks makes demands on those points in the soil that it touches for absorption capacity far exceeding what we have hitherto considered possible. I repeat: 1200 litres have been observed at the trunk of a single tree in a single, admittedly heavy rain; if I am not mistaken, 56 or 57 mm fell in one day.

The magnitude of these figures (representing a concentration factor of nearly twenty-fold) made an impression on the international audience. But Ney's appeal was as much methodological as empirical. His makeshift zinc gutters, paid for from his own pocket and sealed with cotton wadding, had proven the concept but highlighted the urgent need for standardisation:

> As to how the matter should be arranged, I cannot offer detailed proposals. We have such excellent mechanics and inventors among us that they will surely find better means than I could… When it rained hard I had to hurry a great deal, because the vessel would simply have overflowed before I arrived.

Dr. Hoppe rose to offer a detailed proposal for stemflow measurement which was accepted, deployed, and its results were presented in 'Regenmessung unter Baumkronen' Rain Measurement under Tree Canopies (1896) (Figure 1). Hoppe (1896) also provided the first photograph of the instrumentation (Figure 1). Here is the full gauge description:

> The device for collecting the rain-water that runs down along the tree trunks was as simple as could be imagined. …a closely fitting metal collar 8–10 cm high was nailed around the trunk at an angle of about 20° and soldered together at the front… forming a gutter …that sloped toward … a small outlet tube. … the gap [between collar and bark] was sealed with hot

> paraffin; then a 0.5 cm layer of putty was applied over the narrow paraffin strip... The outlet tube led into ... a 1 m-high cylindrical metal container with exactly the same cross-section as the rain gauges commonly used in Austria (25.2 cm diameter)... so that every centimetre of water depth corresponded to half a litre of water. A float—a ruler fixed to a cork plate—projected above the rim by as many centimetres as there were half-litres of water inside.

This 19th-century work established that rainfall could be concentrated by trees and channelled down their trunks, but their collectors allowed only bulk volumes, rather than rates of flow, to be recorded as collected in events or over longer time-periods. Hoppe recognised this limitation, insisting that rainfall duration be logged because 'a long, gentle rain generated much more stemflow than a short cloudburst' (Ney 1894). However, with rain gauges read only once daily, he could only recommend supplementing daily totals with shower duration to calculate intensity.

FIGURE 1 | Stemflow and throughfall observations from Hoppe (1896) showing his metal gutter, pipe and container apparatus (image feature identification done by GPT o4-mini-high constrained by the translation quoted in the text).

While this allows an assessment of the proportions of the input that can be assigned to stemflows, it does not provide information about (i) the duration of stemflows or (ii) the area of soil that is supplied by stemflow. Both remained unexplored until manual sampling was replaced by automated measurement devices (uncommon until the 1950s: Kurtyka 1953). The first continuous stemflow rate measurements were reported by Herwitz (1986), who used tipping buckets with digital recorders on 6-min intervals during intense Australian storms. His observations revealed stemflow rates of 809–19 167 mL min^{-1} infiltrating into areas of 0.1–3 m^2 tree^{-1}, although he noted that these 'represent minimum areas because no correction has been made for the throughfall that was also infiltrating into the same area'.

This caveat by Herwitz (1986) highlights a critical, lingering ambiguity that persists despite a century of global observation. Following the foundational European work, the study of precipitation partitioning expanded rapidly: from Horton's (1919) detailed observations in New York (Figure 2), to widespread campaigns in the 1920–1950s spanning African savannas, North American pine barrens, and tropical rainforests (e.g., Phillips 1926; Wood 1937; Freise 1936; Pereira 1952). By the late 20th century, researchers had confirmed stemflow generation across virtually all biomes, from the rainforests of Malaysia (Manokaran 1979) to the plantations of Indonesia (Bruijnzeel et al. 1987) and the Amazon (Lloyd and Marques 1988). Notably, Soviet studies (Pozdnyakov 1956, 1963; Mina 1967) had already shifted focus from volume accounting to stemflow's biogeochemical signature, documenting persistent soil acidification and aluminium mobilisation in 30–50 cm zones around pine trunks. While this catalogue of studies developed, the intensity of the input at the soil surface (a critical metric for preferential flow initiation) remained a subject of debate (Carlyle-Moses et al. 2018, 2020; Van Stan and Allen 2020; Allen and Van Stan 2021; Llorens et al. 2022).

Here, 'stemflow infiltration area' is used in an operational sense, as the effective surface area over which stemflow inputs are delivered to the forest floor and enter the soil. We acknowledge

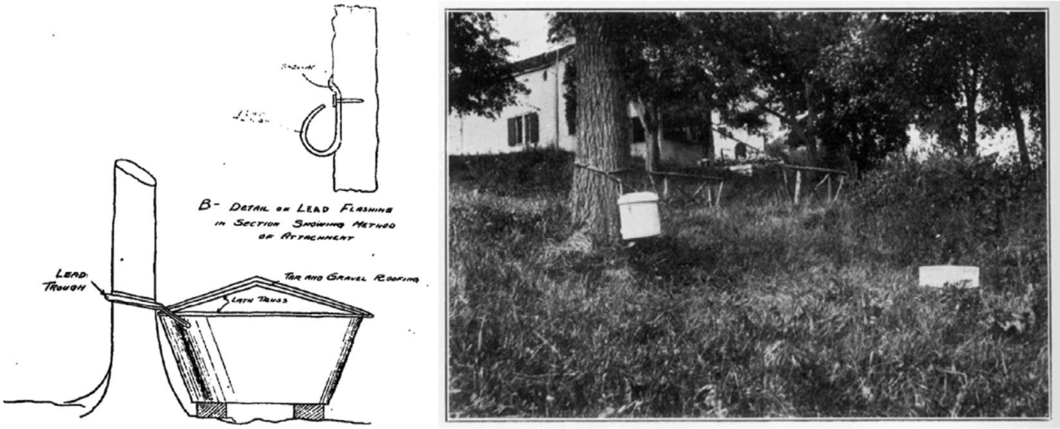

FIGURE 2 | Horton's experiments on stemflow at Voorheesville, NY.

that this area (i) is method-dependent, (ii) may vary across events and bark/canopy conditions, and (iii) is more realistically represented as a near-stem gradient than a discrete boundary. This review does not aim to resolve the ongoing debate over the most appropriate definition of the stemflow infiltration area for any given context. Rather, the concept highlights that the infiltration area assumed strongly controls the calculated local input intensity and, therefore, the plausibility of preferential flow initiation. This has been well demonstrated in, for example, Llorens et al. (2022).

As noted by early researchers and refined by later studies (Voigt 1960; Tanaka et al. 1991), the distinction between 'stemflow' and 'throughfall' is often an artefact of the collector rather than the process. Rough bark and canopy architecture can induce a zone of 'inner throughfall', intense dripping close to the stem that does not adhere to the bark but hydrologically functions as part of the concentrated stem input (Van Stan, Hildebrandt, et al. 2020). Additionally, observations of stemflow-infiltrating surface area have been collected using diverse methods—from isotopes and dyes (Pinos et al. 2023; Zuecco et al. 2025) to litter marks (Tanaka et al. 1991; Iida et al. 2005; Rashid and Askari 2014). Soviet researchers approached this question pedologically; Mina (1967) used soil acidification patterns to trace stemflow influence, finding effects extending 40–50 cm radially from pine trunks and to 1 m depth, affecting approximately 4%–5% of mature (pine) forest stand area. Elegant trenching experiments confirmed the mechanism; after mixing acidified near-trunk soil, original pH gradients (from 4.5 between trees to 3.5 at trunk bases) re-established within ~2 years, definitively implicating ongoing stemflow rather than legacy litter accumulation (Mina 1967).

Overall, reported stemflow infiltration areas span orders of magnitude (10^{-2}–10^{1} m^2 $tree^{-1}$). Compared to the whole canopy capture area, the largest infiltration surface area observation is still an order of magnitude smaller (Wischmeyer et al. 2024). This wide range in observations reflects genuine variability in bark morphology, root architecture, soil structure, and measurement approach. It also poses a fundamental challenge for hydrological modelling. Standard soil physics models, which typically require spatially uniform boundary conditions, are ill-equipped to represent the heterogeneous, high-intensity moisture gradient that stemflow can create near stem bases.

This uncertainty compounds when integrating the effects of individual vegetation elements to stand, catchment, or larger scales. An early attempt to upscale the observations of stemflows from individual trees to larger scales was that of Aboal et al. (1999). Taking account of the stand characteristics at their site in a laurel forest on Tenerife in the Canary Islands, they concluded that stemflow would represent 6.85% of the annual gross precipitation, with a threshold of about 2 mm of event rainfall before significant stemflow would be recorded. Relative to a gross precipitation over the observation period of 626 mm, they calculated a concentration factor of up to 12.8 times (2328–7975 mm) in the infiltration area around the stems. However, this concentration factor depends directly on the area of infiltration which, in their work, was determined using the empirical function due to Tanaka et al. (1991).

3 | Stemflow and Surface Runoff Generation

Given the potential for some types of trees to channel incidental rainfall towards their stems, then it is expected that in significant rainfall events there will be relatively large effective rainfall intensities in the area immediately surrounding the tree trunks. It has been argued both that this will increase the potential for the generation of infiltration excess overland flow (Douglas 1967; Ruxton 1967; Herwitz 1986; Neave and Abrahams 2002), and that the repeated wetting will create preferential pathways for infiltration around the tree roots thereby increasing infiltration capacities (Ney 1893; Burger 1923; Metzger et al. 2021).

The most extensive study of surface runoff generation by stemflow is that of Herwitz (1986) in Queensland, Australia. Herwitz describes stemflow volumes for individual trees as much as 2 orders of magnitude over incident rainfall volumes when calculated with respect to the basal area of the trunk. Calculated fluxes up to 314 mm/min over the basal area are then compared to a mean infiltration capacity of the topsoil of 6.2 mm/min (372 mm/h, with a range from 100 to 1000 mm/h), a rate that is greater than any recorded rainfall intensity at the site. A shallow topsoil at the site is described as having decomposing vegetation material and a high density of roots. Photographs also suggest there is significant microtopography around and between surface visible roots. Stemflow does not infiltrate over the basal area of the tree, of course, but Herwitz then provides calculations of the area required to absorb the stemflow, either as infiltration over an annular ring around the trunks or as runoff downslope. These estimates were based on the average infiltration rates for different rainfall intensities, stemflow ratio, and basal area. However, no information is given about where the infiltration capacity measurements were made, and no direct observations of overland flow at the site are reported for comparison with these calculations.

There have been few other studies that provide strong evidence for stemflow as a significant source of overland flow generation and erosion, mostly under agricultural and urban contexts. In cultivated systems, Keen et al. (2010) quantified stemflow-driven erosion around macadamia trees using continuous stemflow measurements and high-resolution microtopographic surveys. Over 16 months concentrated stemflow input generated 6.5 mm m^{-2} $year^{-1}$ of net soil loss from the 2.1 m^2 area beneath each tree, equivalent to ~3.8 t ha^{-1} $year^{-1}$ when scaled to typical orchard spacings, with conspicuous root exposure and small gullies radiating from the trunk base. At the plot scale, Charlier et al. (2009) explicitly incorporated stemflow into a runoff model for a 3000 m^2 banana field on highly permeable Andosol in Guadeloupe, with stemflow increasing rainfall intensities 18–28-fold at the plant foot. Their analysis shows that canopy-induced spatial heterogeneity in near-surface fluxes is sufficient to generate runoff from small, highly loaded stemflow patches while the surrounding soil remains below saturation, and that these patches strongly influence the transport of solutes and particulates (fertilisers, pesticides, eroded sediment) exported from cropped plots. A review by Dunkerley (2020) presents photographic examples where concentrated stemflow detaches soil, creating centimetre-deep scour channels and fan-shaped sediment lobes at the foot of shrubs and small trees.

There are few studies on run-off potential of non-woody plants' stemflow. One, by Neave and Abrahams (2002), was carried out on small 1 and 2 m plots under artificial rainfalls for grassland, degraded grassland, shrub and intershrub surfaces. Their results suggested that there was more surface runoff generated on the more vegetated plots. They inferred that this was the result of the concentration of the input water by the grass stems. However, it has also been shown that stemflows from individual trees in natural forest sites ($n = 1–2$ per study) will infiltrate into the soil quite quickly (e.g., Tischer et al. 2020 and references therein).

4 | Evidence for the Generation of Preferential Flows by Infiltrating Stemflow

While it is still possible that the concentration of rainfall inflows in stemflows might in some cases lead to the generation of local surface runoff, it is often the case that, despite the higher local intensities, all the stemflow infiltrates into the soil within a few meters' distance from the stem base. Where the structure of the plant is such as to channel water to the roots, there has been an evolutionary preference for infiltration. The question then is how that water will infiltrate into the soil to benefit the plant when it is added where the soil contains many root channels and other macropores. Stemflow observations have been used to hypothesize, 'If I pour all the stemflow from this storm into this small patch and fill the local pore space from initial water content to saturation, how deep could the wetting front go?' (Návar 2011). The resulting hypothetical model employed by Návar (2011) yielded mean stemflow wetting depths of ~7–21 cm for < 10 mm storms and ~0.6–1.7 m for 50 mm storms in thornscrub and temperate forests, respectively. These computations (and other indirect water-balance estimates: e.g., Buttle et al. 2014; Bialkowski and Buttle 2015) are valuable in highlighting the possible magnitude of stemflow inputs, but they rely on strong assumptions about infiltration area, soil homogeneity and uniform vertical wetting and therefore provide only a first-order constraint on the preferential flow field.

Standard soil physics methods for measuring surface infiltration and soil water contents and potentials, are not best suited to such investigations given the local nature of the preferential flows that might be induced by the stemflow, though there are studies that have shown how stemflows can enhance wetting and recharge to shallow water tables using soil water observations and mass balance methods (e.g., Durocher 1990; Chappell et al. 1996; Taniguchi et al. 1996; Tanaka et al. 1996; Liang et al. 2007, 2011; Li et al. 2008; Liang 2020).

More can be revealed by the use of tracers of different types, albeit that this has often involved destructive sampling after the addition of a tracer. One of the earliest such studies was that of Reynolds (1966). A review of tracers in soil hydrology is provided by Flury and Wai (2003), though they do not directly mention the tracing of stemflows. There are many tracing experiments that have been carried out on undisturbed soil cores and field plots that have concluded that preferential flows can be important and ubiquitous in transferring water quickly to depth, particularly in the case of surface saturation (see, e.g., Anderson et al. 2009; Weiler 2017), even in the case of ponded paddy fields (e.g., Sander and Gerke 2007).

There have, however, been a number of studies where tracers have been used to follow the direct pathways of stemflow water into the soil. Table 1 provides a summary of studies of tracing stemflow pathways into the soil. It does not include studies where tracers have been used to tracer preferential flows more generally without any mention of stemflows (e.g., Noguchi et al. 1999; Weiler and Naef 2003; Weiler and Flühler 2004; Wang and Zhang 2011; Kodešová et al. 2012; Wu et al. 2015; Mei et al. 2018; Luo, Niu, Xie, et al. 2019; Luo, Niu, Zhang, et al. 2019; Wang et al. 2022). These studies do, however, demonstrate through the use of tracers that preferential flows are important to water movement both vertically and laterally downslope. One recent study, Valtera et al. (2023), does not address stemflow directly, but uses dye tracing to demonstrate preferential flows into the soil induced in pit-mount topography from fallen trees at hillslope scales.

The studies summarised in Table 1, from a variety of environments, slope, soil and vegetation conditions suggest that stemflows will often be important in generating water flows to depth in the soil profile. Where root channels are orientated downslope, then there may be bypassing of the soil matrix in the downslope direction that will exceed fluxes resulting from matrix potential gradients. Where there is a relatively shallow impeding layer of lower conductivity then this might also lead to a build-up of a saturated zone during wet conditions, providing downslope connectivity and faster celerities (e.g., Lin 2006; Jost et al. 2012, though they did not explicitly differentiate stemflows). However, nearly all the studies reported are still at sub-hillslope scales and the question of how important such stemflows might be at the hillslope and catchment scale remains open.

4.1 | Geophysical Techniques

The potential for using geophysical techniques, in conjunction with tracing experiments, to investigate preferential flows arising from stemflows has been revealed by repeated Ground Penetrating Radar (GPR) and Electrical Resistance Tomography (ERT) transects, downslope from where artificial stemflow inputs were applied. The first study of this type by Guo et al. (2020) showed how the stemflow from a single tree was channelled into the soil along coarse root channels, and how the velocities of penetration could be estimated from the geophysical time lapses. Downslope velocities of 2.8 m in 30 min were demonstrated. A complementary experiment using time-lapse ERT around a beech tree by Zuecco et al. (2025) demonstrated that similarly-simulated stemflow infiltrated mainly along the maximum slope gradient, remained largely within the upper ~45-cm of soil, and enabled quantitative estimates of a relatively large stemflow infiltration area. A further study using high-resolution GPR by Di Prima et al. (2023) suggested that there were connected networks of preferential flow pathways induced by the addition of stemflows, and that stemflow from several trees might contribute to the flows in individual pathways. Note that all these geophysical experiments were conducted under

TABLE 1 | Examples of studies of the use of tracers to investigate the pathways of stemflow into the soil. Note that where inputs are given as depths per unit area, these refer to raingauge measurements in clearings or above the canopy.

References	Tracer used	Water applied	Scale	Comments
Saffigna et al. (1976)	Rhodamine WT	Rainfall event of 18 mm after tracer application to soil	Rows of potatoes, tracer event on plants 98 days after emergence.	4%–23% of input as stemflow, higher in irrigation events (38 mm h^{-1}) and high intensity natural rainfalls. Dye moves deeper in root channels—also deeper movement under furrows from runoff and ponding.
Vincent and Clarke (1982)	'Point' sources of dispersive dye particles	3 month periods of natural rainfall (108 and 152 mm totals resp)	4 16–26 m transects, 4 point additions on each	Only vertical profiles sampled at each point, seasonal variation demonstrated with less penetration under fully closed tree canopy. More throughfall than stemflow.
Crabtree and Trudgill (1985)	Fluorescent dye and weight loss of gypsum spheres	I year, 740 mm/year	Individual trees on 105 m hillslope plot	Thin soils on limestone under beech trees in UK Dye placed on stems follows root channels, primarily vertical movement to base of soil profile.
Nulsen et al. (1986)	Dye applied around individual shrubs	Destructive sampling after rainstorms	Mallee scrub vegetation in W. Australia, up to 25% stemflow on individual shrubs.	The stemflow caused saturated conditions around the bole of the mallee and dye tracing showed that the water penetrated the soil via the annular pathways of the soil-root interface.
van Noordwijk et al. (1991)	Methylene Blue dye	Equivalent of 100-200 mm rain applied in cylindrical tubes at surface	Infiltration followed by destructive sampling	Shallow tropical soils in Nigeria and Sumatra. Modified model of N leaching to include stemflow induced preferential flows
Martinez-Meza and Whitford (1996)	Rhodamine-B powder around stems	40 mm artificial sprinkling above vegetation surface—time of application not given	Single shrubs	3 species of desert shrubs in New Mexico. Dye tracing showed root channels as pathways for infiltration to depths up to 35 cm.

(Continues)

TABLE 1 | (Continued)

References	Tracer used	Water applied	Scale	Comments
Devitt and Smith (2002)	KBr solution	150 or 300 mm applications over 1–5 days	1 m^2 plots	Infiltration around desert shrubs—deeper with old root channels and larger shrub root systems. Excavations at 10 cm depth intervals
Li et al. (2009)	Rhod-B powder	3 Natural Rainstorms (4.9, 9.1 and 32 mm totals). Powder left around stems of single shrubs	Stemflows measured for natural events for 14 individual plants from 2 desert shrub species. 6 other individuals used for tracing experiments. Destructive sampling after 1 day	Pits dug adjacent to stems along main root channels, staining photographed
Liang et al. (2011)	New Coccine and Brilliant blue dyes used to differentiate throughfall and stemflow	Amounts equivalent to a 50 mm rainstorm event applied with sprayers over soil surface for throughfall and against tree for stemflow	Hillslope plot with cover of Stewartia trees in Japan. Destructive sampling after 2 days.	Preferential flows associated with tree roots important in generating subsurface saturation even when stemflows intercepted on individual trees. Asymmetry of stemflows on upslope and downslope sides of trees.
Schwärzel et al. (2012)	Brilliant Blue dye	120 L over 180mins applied as stemflow at breast height on individual beech and spruce trees	Destructive sampling after 1 day.	Beech and Spruce show different effects. Stemflow water was preferentially funnelled along heart and sinker roots, laterally oriented coarse roots, and congregations of fine roots grown into decayed root channels of felled trees, and triggers fast lateral subsurface flow bypassing large parts of the soil matrix at least during rainstorm events
Germer (2013)	Brilliant Blue dye	Supplied as stemflow for 10 mm rain event	Sample of young and adult babassu palms in N.E. Brazil—destructive sampling after 1 dat	Stemflow ~10% of incident rainfall. Tracer experiments at adult palms revealed initial preferential horizontal flow, with subsequent downward water movement leading to perched water tables.

(Continues)

TABLE 1 | (Continued)

References	Tracer used	Water applied	Scale	Comments
Spencer and van Meerveld (2016)	Brilliant Blue dye	Amount equivalent to observed stemflow for 50 mm rain event sprayed onto tree stems	Wet Western Hemlock forest—destructive sampling after 2 days	Stemflow intensity time series measured—dye tracing shows preferential movement in organic topsoil and along root channels and around rocks. Concentration factors from < 1 to almost 20.
Gonzalez-Ollauri et al. (2020)	Brilliant Blue dye	Amounts equivalent to a 45.7 mm h^{-1} rainstorm event applied with sprayers against tree for stemflow	Two *Acer pseudoplatanus* trees—destructive sampling after 36 h.	Dye infiltration largely confined to upper soil (350–400 mm below ground level), with localised preferential-flow zones aligned with thicker roots.
Deng et al. (2021)	Deuterium + 18-oxygen	Natural rainfall over 23 events	*Toona sinensis* forest plot with epikarst borehole	Stemflow was ~1.5% of rainfall but supplied ~57% and 37% of epikarst recharge in the wet and dry season, respectively.
Llorens et al. (2022)	Different coloured dyes (FLT red, green and blue)	36.5 L added at breast height (equivalent to stemflow from a 12 mm natural event added at 3 intensities)	4 individual American Beech trees	Stained infiltration areas estimated from gridded pattern around trees (with litter removed). Funnelling ratio depends on intensity. Preferential flows inferred from high infiltration rates.
Pinos et al. (2023)	Deuterium + Brilliant Blue dye	41 L at 7 L h^{-1} artificial additions around trunk at 1.3 m above soil (equivalent to stemflow from a 50 mm rainstorm)	Single Scots Pine Tree – destructive sampling after 1 day	Clear preferential pathways. Deuterium strongly correlated to dye staining. Concentrations decreasing away from tree trunk. Some lateral preferential flow detected
Zuecco et al. (2025)	Deuterium + 18-Oxygen + NaCl	Artificial addition, 6.61 L h^{-1}, totalling 26 L.	Single European beech tree—soil and seepage sampling, complemented by time-lapse ERT	Preferential pathways observed close to the tree trunk, downslope and along the maximum slope gradient.

deliberately hydrologically 'quiet' conditions (dry antecedent soils, no concurrent subsurface flow). Thus, although they characterise how a single stemflow pulse activates fast pathways, they leave open questions regarding how those pathways interact with early-event moisture and slower matrix flows during real storms. Those interactions, under different antecedent conditions and input rates, still need to be better understood.

Di Prima et al. (2025) begin to close this gap by deploying time-lapse ERT and repeated GPR to bridge the gap between tree-scale infiltration and hillslope-scale response. Their findings demonstrate that stemflow at their beech site can trigger vertical fast-flow regions beneath stems that are largely independent of antecedent moisture. This vertical preferential flow connected to lateral subsurface pathways at 1–2.5 m depth, providing a physical mechanism for rapid groundwater fluctuations observed during intense storms.

4.2 | Experimental Evidence for the Role of Stemflows in Groundwater Recharge

If stemflows are going to be important in inducing preferential flows to depth in the soil then it is evident that they might be important in controlling 'hot spots' and 'hot moments' for recharging water tables, at least under certain conditions. In order to do so, it will be necessary for the wetting front in the preferential flow pathways to propagate deep enough before it is caught by the drying front after the stemflow ceases (see, e.g., the kinematic analysis of Germann 2014). It is therefore more likely that this will be the case for shallow water tables than deeper unconfined aquifers. There have been suggestions that the effect of stemflows on recharge can be large based on mass balance arguments (e.g., Taniguchi et al. 1996). This has been reinforced by the analysis of Tanaka et al. (1996), who by calculating an effective infiltration area for stemflow as a ring around each stem, show that the relative ratio of recharge from stemflow and throughfall infiltration calculated from a Chloride mass balance can be matched. A more recent study by Deng et al. (2021) used isotope data to suggest that stemflows, while only a limited proportion of the input rainfalls, were important in concentrating large volumes of water into preferential flow pathways that bypass the root-rock interface to provide recharge to epikarst groundwater. Di Prima et al. (2025) provided direct observational support for these mechanisms by coupling controlled infiltration experiments, geophysical imaging, and hillslope piezometry. They found that while the fast-flow domain occupied 6% of total soil porosity, near-stem infiltration rates of stemflows (~1030 mm h^{-1}) were nearly 5 times greater than those of the surrounding soil matrix. Piezometers on the same hillslope recorded water-table rises within 5–35 min of intense rainfall, consistent with a conceptual model in which vertical, stemflow-driven pathways connect to deeper lateral subsurface flow.

5 | The Neglect of Preferential Flows in Hydrological Models

The previous sections have demonstrated that there is no lack of evidence for stemflow-induced preferential flows in the soil. In fact, this is but one potential cause of preferential flows in the soil that might be important in controlling water, nutrient and pollutant fluxes to depth and laterally down hillslopes (e.g., Beven and Germann 1982, 2013; Tsuboyama et al. 1994; Bundt et al. 2001; Johnson and Lehmann 2006; Weiler 2017; Liang et al. 2011; Cheng et al. 2017; Friesen 2020; Nimmo 2021), including having impacts on soil chemistry and horizon characteristics (Gersper and Holowaychuk 1970; Chang and Matzner 2000). Most modelling studies of stemflow to date, however, have concentrated on the partitioning of rainfalls into throughfall and stemflow by the vegetation canopy, rather than what happens to the stemflow when it enters the soil profile (e.g., Liu 1997; Aboal et al. 1999; Xiao et al. 2000; Zimmermann et al. 2015; Ghimire et al. 2017). This has included the highly detailed modelling of flows and solute transport in the network of 'furrows' on tree bark by Tucker et al. (2020), though in that case they did not consider what might happen when the resulting fluxes reached the soil. There are also reviews of preferential flows in soil that do not mention stemflows as a potential source term at all (e.g., Allaire et al. 2009; Jarvis et al. 2016; Zhang et al. 2018).

Guo and Lin (2018) suggest that there are both theoretical and technological bottlenecks to modelling preferential flows in soils. The theoretical bottleneck is the lack of a consistent framework for the representation of different types of preferential flow at larger scales. The technological bottleneck is the lack of appropriate observational techniques for the detection and characterisation of preferential flows in situ. They suggest that networks of soil moisture sensors and geophysical imaging might help overcome the latter constraint but to date that does not yet seem to have been achieved, in part because of the resolution and uncertainties of both soil moisture sensors and the inversions required for geophysical imaging (even if the study of Di Prima et al. 2025, moves in this direction). Ideally, of course, such data from in situ studies would be available for the evaluation of modelling results, but an examination of both models and evaluation data suggests that both have their limitations. Certainly networks of soil moisture sensors with high resolution in time can reveal the occurrence of preferential flows (e.g., Wiekenkamp et al. 2016), but not in ways that can securely quantify the fluxes associated with preferential flows.

One example is the study of Liang et al. (2009) where a three-dimensional finite element model of soil on a hillslope based on the Richards equation was implemented to examine the effects of stemflow around a single tree trunk. Soil moisture data at different levels in the soil profile were available for comparison with the model simulations. In this case, the stemflow is treated as a local concentration of boundary flux. Soil water characteristics were varied with depth, based on samples at the site, but no explicit account was taken of the effects of root channels (or other preferential flow pathways) on soil water movement except to spread the stemflow inputs over a 'source region' close to the tree, rather than only at the surface. Some channelling of stemflow infiltration was demonstrated in this way.

6 | Impacts at the Hillslope and Catchment Scales

Of course, we are not only interested in the effects of stemflows at the local scale around individual trees but also in their effects on responses at the hillslope and catchments scales. There have been a number of attempts to model preferential flows at such scales but again there are important limitations in the data available for model evaluation. There are also issues about how to characterise the soil, root, macropore and microtopography structures that might lead to the occurrence of preferential flows. We do not consider here papers that have modelled spatially variable throughfall inputs on hillslopes using 2D and 3D Richards equation models that do not take any account of preferential flow pathways. Those papers have generally concluded that the spatial variability of throughfall and stemflow is relatively unimportant on subsurface stormflows at the hillslope scale, but they ignore the potential for the concentration of stemflows at the surface to induce preferential flows (e.g., Sansoulet et al. 2008; Hopp and McDonnell 2011; Coenders-Gerrits et al. 2013).

The study of Sidle et al. (2001) is of interest at these scales. For a forested site in Japan, they demonstrate the importance of lateral preferential flows in root systems, bedrock fracture systems and animal burrows on hydrological responses at hillslope scales. They used staining dyes to show the connectivity of macropores in the forest soils and suggest that the macropore systems may self-organise into networks, particularly under wetter conditions. Based on these destructive experiments they develop a three-dimensional model that is based on a statistical representation of macropore numbers, lengths, sizes, orientation and tortuosity in topsoil and subsoil layers. They also allow for zones of high permeability in the soil profile from their detailed sampling and for interactions between macropores and mesopores that might vary with wetness. They do not, however, compare any model results with observations, and do not explicitly consider stemflow as a source for preferential flows.

One implementation of the Sidle concepts was provided by Cheng et al. (2017) who tested four simplified models of vertical matrix and vertical and lateral preferential flows at the small catchment scale for a tropical forest site in Panama. To get round the problem of identifying preferential flow pathways explicitly, they use the statistics of tree root channels as determined by Sidle et al. (2001) and of vertical earthworm channels, assuming linear Poiseuille flow for all preferential flows. The input to their model, however, is throughfall intensity; they do not partition stemflow separately as an input. They show that observed water contents and catchment discharges are better reproduced by models that explicitly represent preferential flows. They do suggest that a small number of vertical macropores that transport water below the root zone can be important in getting a realistic response at the catchment scale.

An earlier attempt at modelling downslope preferential flows using explicit networks of flow pathways in the hillvi model was described by Weiler and McDonnell (2007) and applied to data from the forested Maimai catchment in New Zealand. Their model incorporated downslope pipes of randomly chosen depths and densities in the soil profile. Downslope transport of water in the pipes was limited to a 2 m grid cell. They showed how they could reproduce both hydrographs and bromide tracer experiments more closely using a model with rather than without pipes. Ensemble experiments with different pipe networks showed that the exact configuration of the network was less important than not including the pipes as preferential flow pathways. Their model did not explicitly differentiate the concentrated inputs of stemflows as a potential source of preferential flow. In fact, the detailed perceptual model of hillslope hydrology for the Maimai catchment presented by McGlynn et al. (2002) does not mention stemflows at all.

The hillvi model was later also applied to the Panola catchment in Georgia, US by Tromp-van Meerveld and Weiler (2008). They showed that at Panola, information on bedrock seepage and bedrock topography was as important as the inclusion of preferential flow pathways in reproducing observed water tables and hydrographs. Again, however, this paper does not explicitly mention stemflow, nor do they consider the potential for stemflow to induce preferential flows.

Other attempts to incorporate preferential flow pathways at hillslope scales have been reported. The CATFLOW model of Wienhöfer and Zehe (2014) does so by explicitly incorporating zones of higher conductivity in a Richards equation solution. This is a form of dual porosity Richards equation solution that requires strong assumptions about equilibration of potentials in different pathways that are difficult to justify in soils containing macropores and root channels (e.g., Simunek et al. 2003; Jarvis et al. 2016). Dual permeability models are equally unsatisfactory (Beven and Germann 2013). Indeed, while we have become used to a physics based on the Darcy-Buckingham-Richardson-Richards equation, it is a physics that was based on the wrong experiment because of the way that using air pressure to induce different capillary pressures excluded the possibility of preferential flows in larger pores (K. J. Beven 2014, 2018). This suggests that in nonhomogeneous and macroporous soils, alternative representations will be justified.

The Multiple Interacting Pathways (MIPS) model of Davies et al. (2011, 2013) incorporates preferential flow pathways implicitly, by allowing for a distribution of velocities in the soil, and tracking all water using particle tracking techniques under kinematic assumptions. This approach can already represent concentrated stemflow inputs by adjusting the probabilities that parts of the input will enter faster velocity flow pathways, but this could be made more explicit by localising the inputs and assigning asymmetric directions as well as velocities (see Figure 3). Another Lagrangian particle tracking model incorporating preferential flow pathways is that of Sternagel et al. (2019). The model of Zehe et al. (2013), based on thermodynamic principles, includes preferential flow pathways as part of the self-organisational system of hillslope hydrology. They argue that preferential flow pathways act as dissipative structures for higher pressure gradients on hillslopes, speeding the return towards longer term energy equilibrium between events. However, none of these papers mention the potential impacts of stemflows on their simulations.

7 | A Needs Analysis for Research on Stemflow and Preferential Flows

Since the late 19th and early 20th Century there have been many measurements of stemflow on vegetation types ranging from many types of trees to a variety of crops. On single trees it is not

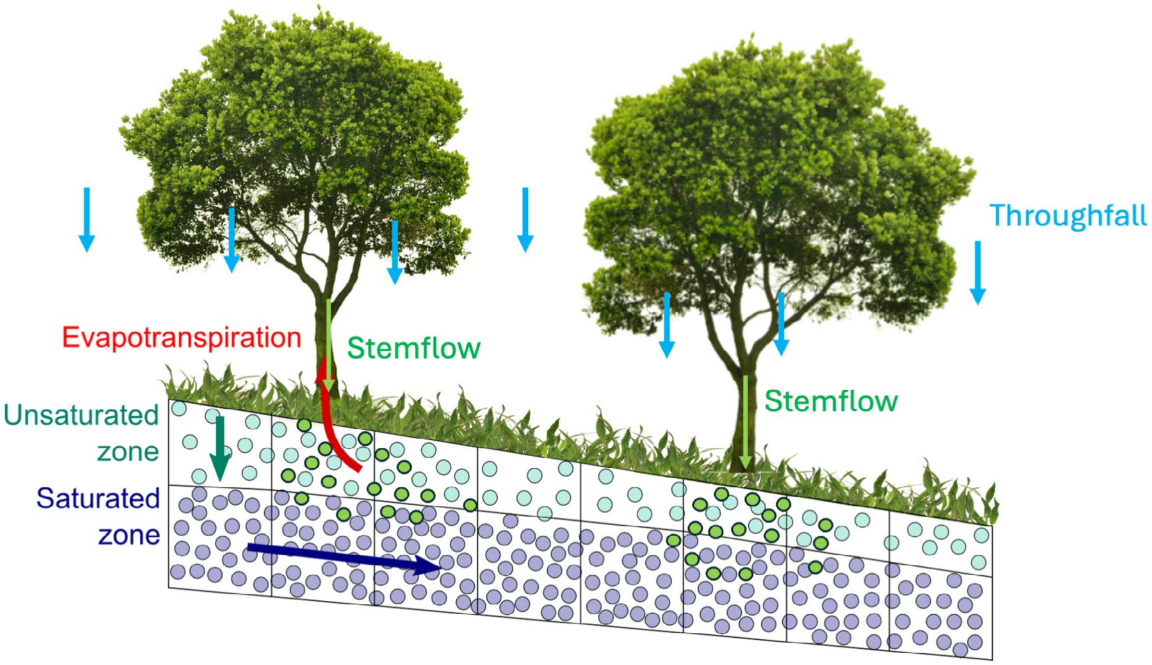

FIGURE 3 | Possible implementation of stemflow in the MIPS model where all water in the system is represented as particles in pathways of specified velocity. Stemflow (green particles) can be treated as a localised input with probabilities of entering higher velocity pathways than throughfall, depending on the input rates. In the original model, particles in the unsaturated zone (light blue) move vertically with a distribution of velocities (which can include preferential flows) and in the saturated zone move downslope. At each time step there is a transition probability for particles to change velocity pathways. Modified from an original figure prepared by Jess Davies of Lancaster University.

a difficult observation to make. It is much more difficult to get a representative sample of throughfall fluxes beneath the canopy (Zimmermann and Zimmermann 2014; Voss et al. 2016), or of the stemflow from stands of trees at the field or hillslope scale (Hanchi and Rapp 1997; Zimmermann et al. 2015). Consequently, while this review has demonstrated that there is no lack of evidence for localised, concentrated stemflow inputs capable of initiating preferential flows in soils, there remains a lack of evidence for whether these localised processes produce detectable consequences at hillslope and catchment scales. This needs analysis is not intended as a general review of preferential flow modelling; instead, it identifies the minimum observational and modelling requirements needed to test whether stemflow-induced preferential flow has measurable consequences at hillslope and catchment scales. It is not difficult to include such a process in a perceptual model of hydrological responses; it is much more difficult to quantify the fluxes and their impacts. This remains a primary research need that represents a significant challenge given available observational technologies.

In this context, 'significance at scale' requires a definition. We suggest that stemflow-induced preferential flow would be significant if it produces one or more of the following observable outcomes beyond what would be expected from throughfall-driven infiltration alone: (i) earlier or more spatially coherent pressure responses in downslope saturated zones (celerity-dominated signals); (ii) measurable changes in event water fractions or breakthrough of conservative tracers in throughfall, drains, or first-order streams; (iii) shifts in the threshold behaviour of runoff generation with antecedent wetness or rainfall intensity; (iv) disproportionate contributions to solute export (including known near-stem biogeochemical signals: e.g., Behnke et al. 2023); or (v) detectable changes in the spatial connectivity of transient saturation during events.

The only way of addressing this need, without significant disturbance to the system, would appear to be through the use of artificial tracers that would allow the labelling of stemflows and their consequent collection downslope in a throughflow trough, first order stream or field drain. Sampling of soil solutions might also be valuable (e.g., Chang and Matzner 2000), but results will depend on whether such sampling can reflect the local nature of preferential flow pathways. Replication would be essential because any signal is expected to be conditional on antecedent wetness, rainfall sequencing, and the spatial relation between trees and functional preferential pathways. The objective would not be to 'map all macropores', but to test whether a stemflow-labelled input yields (i) a distinguishable tracer signature and/or (ii) a consistent celerity response that differs from nearby non-stemflow control locations.

Two questions immediately arise: the choice of a suitable tracer given the potential for sorption on the organic materials of forest soils (Deuterium might be one possibility for a conservative tracer, see Leuteritz et al. 2026), and the role of any preferential flows in displacement of stored water during an event. This is because what is detected in any downslope flow collector will depend on the celerities in the system, not only on the velocities in any flow pathways that might be revealed by the breakthrough curve of the tracers (e.g., K. J. Beven 1989; McDonnell and Beven 2014). The preferential flows might then induce a downslope response in a saturated zone on a hillslope even if the tracer breakthrough is itself delayed. This suggests therefore, that any tracer response might also need to be complemented by observations of pressure responses that will reflect celerities. A further issue is the expectation of the significance of the impact under different antecedent wetness and input conditions (as indicated, e.g., by the results of Mulholland et al. 1990, and Williams et al. 2023, albeit that they do not mention stemflows in their papers). Will the impact be greater when the soil is relatively dry and more general infiltration less effective in getting water to depth in the profile (i.e., the experimental conditions under which current geophysical studies have been conducted), or under wet conditions when the connectivity of downslope preferential flows might be greater?

These are clearly questions that are impossible to resolve completely using single tracer experiments. Such experiments might only reveal if there is a pressure or tracer concentration signal that can be attributed to the effects of stemflow induced preferential flows. More general conclusions about the significance of stemflows at hillslope and field scales might then depend on exercising a model to investigate a wider range of conditions. Such a model should, of course, be consistent with any experimental results available but, as pointed out above, there do not appear as yet to be any satisfactory models of preferential flow pathways at larger scales, nor can the nature and characteristics of preferential flow pathways at a site be easily known even probabilistically.

In terms of modelling, preferential flow has been represented in several established ways: dual-porosity/dual-permeability formulations, explicit macropore domains, and related approaches reviewed elsewhere. The issue raised by the present review is that stemflow provides a highly localised and temporally structured boundary flux whose spatial support (the effective infiltration area) and coupling to a functional preferential network are rarely parameterized at hillslope or catchment scale. In this sense, the stemflow-preferential flow problem is best viewed as a sub-grid source-term and connectivity problem: that is, how to represent intense, localised inputs and their probability of intercepting connected preferential pathways within models. Even if individual pathways cannot be identified deterministically, experiments can constrain the statistics of when stemflow inputs intersect functional preferential networks, which is the level at which a hillslope-scale parametrization would have to operate.

The approaches outlined above seek to represent stemflow inputs and preferential pathways and the statistics of their intersection within sub-grid parametrizations. A complementary systems-level perspective is to view how stemflows and preferential flows might influence hydrological responses at hillslope and field scales as a problem of emergent properties of the aggregation of small-scale processes involved in preferential flows. One such mechanism, suggested by Sidle et al. (2001) and Zehe et al. (2013), is that networks of preferential flow pathways might be self-organising in that because water will take pathways of least resistance, those pathways will become enhanced. We suspect that such self-organisation might be limited, for two reasons. One is that the development of preferential flow pathways by the growth and decay of roots and the development of cracks, animal and earthworm burrows is largely independent of water fluxes (indeed cracks and the growth of fine roots will be more a result of lack of water). Secondly, outside of special cases (piping, shrink-swell clays or karstic dissolution, etc.), event-scale water flows are expected to be predominantly laminar and exert limited shear stress on pore walls. Thus, they have only limited potential for the modification of pathways by the mobilisation and transport of particles (albeit that there is evidence of translocation in the cutans at the edges of macropores to be seen in soil thin sections, e.g., Brewer 1960, Sokolova 2008).

It might, however, be important here to distinguish between the structural network of all larger voids in the soil that might potentially act as preferential flow pathways for water fluxes, and the functional network of voids that do act as preferential flow pathways. There are many tracing studies that show that not all larger voids are involved in preferential flows, lacking either connectivity or a source of inputs. It is also possible that there might be preferential flow pathways that are not stained by visible tracers, for example where saturation at the ends of 'dead-end' pores or root channels results in displacement of stored water into larger voids nearby; a form of indirect connectivity. If the functional network of preferential flow pathways is frequently used, for example where stemflows often provide an input source, then some self-organisation of the functional network might still occur over time. Limited self-organisation does not, however, eliminate emergence. Aggregation of heterogeneous pathways whose structure is largely governed by root dynamics, cracking, and bioturbation will still yield emergent hillslope-scale behaviour that reflects the integration of such small-scale processes.

It does imply, however, that it will be challenging to determine the impact of such preferential flow pathways and stemflow inputs from hillslope or catchment scale observations. We can always recognise such complexities in a qualitative perceptual model of the processes that we consider important but quantifying the effects of such complex processes will always be a challenge and subject to significant uncertainties. Any emergent properties will, however, necessarily be implicit in a more holistic approach to hydrological responses to events, something that Beven et al. (2026) have described as the Great Hysteresis Challenge for hydrological research. Whether such an approach will be more successful than process-based modelling of complex small-scale processes in making predictions of hydrological systems away from experimental sites remains to be seen.

8 | Conclusion

This review has traced the recognition of stemflow as a concentrating mechanism from 19th-century field observations to contemporary tracer, geophysical and modelling studies. The historical record demonstrates that researchers recognised stemflow's *potential* to deliver highly localised, intense water inputs to forest soils well over a century ago. Modern observations confirm that stemflow can spatiotemporally concentrate rainfall, with variation depending on bark morphology, root architecture, and measurement methods. The evidence for stemflow-induced preferential flow at the local scale now includes tracer studies, geophysical experiments, and research integrating a range of these methods. However, these experiments have predominantly been conducted under dry antecedent conditions (i.e., simulations during non-rain periods), leaving open questions about pathway behaviour during natural storms with variable antecedent moisture and competing matrix flows. The significance of stemflow-induced preferential flow at hillslope and catchment scales is, therefore, essentially empirically unquantified.

In addition, existing hillslope-to-larger scale models either ignore preferential flow entirely or activate it via matrix saturation without accounting for the spatial concentration of near-stem inputs. This represents a conceptual and practical limitation for predicting subsurface stormflow, solute transport, and groundwater recharge in vegetated landscapes. Addressing this gap will require coordinated advances in observation and modelling, including hillslope-scale tracer experiments that label stemflow sources and track contributions to downslope collectors alongside model frameworks capable of representing localised high-intensity inputs with asymmetric directional preferences. Until such advances are made, the role of stemflow in catchment hydrology will remain a plausible but unquantified component of our perceptual models.

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Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** hyp70556-sup-0001-supinfo.docx.