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The Transboundary Precipitationshed of a Non-Transboundary Watershed: Emerging Challenges for Water Resources Management

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Abstract

Terrestrial moisture recycling (TMR) plays a crucial role in the global distribution of water. This process establishes atmospheric connections between watersheds, which are often overlooked in traditional water management that focuses solely on surface hydrology. Located in northwestern South America, the Magdalena Watershed is a non-transboundary watershed that is essential for Colombia's water and energy security. However, its water availability depends heavily on evapotranspiration from other watersheds and countries. Using a moisture-tracking simulation, we show that this non-transboundary watershed becomes transboundary when analysed through its precipitationshed. We estimate that around 30% of the watershed's annual precipitation results from Regional Moisture Recycling (RMR), which is moisture originating in terrestrial areas outside the watershed, primarily the Orinoco and Amazon watersheds that span neighbouring countries. A key difference between watersheds and precipitationsheds lies in their physical nature. While watersheds are generally static, precipitationsheds are inherently dynamic. We illustrate this dynamic nature for the Magdalena's precipitationshed, showing both its seasonal variability and its sensitivity to the El Niño–Southern Oscillation (ENSO). These transboundary and dynamic atmospheric connections challenge the conventional approach to water management that is based solely on static watershed boundaries.

Keywords Transboundary water security · Terrestrial moisture recycling · Precipitationshed · Water management · Water challenges

1 Introduction

Watersheds are key units for water management (Cohen and Davidson 2011). When crossing international boundaries, they face transboundary challenges such as weak cooperation, geopolitical tensions, and fragmented governance (Kliot et al. 2001; Petersen-Perlman et al. 2017; Turhan 2021). These challenges have prompted substantial research on transboundary water security and watershed governance (Albrecht and Gerlak 2022; Posada-Marin et al.,

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2024). Physical interdependencies that influence water availability transcend watershed boundaries and include processes beyond surface hydrology. A growing literature underscores the relevance of atmospheric moisture flows for water systems (Makarieva et al. 2014; Keys et al. 2017, 2019, 2024; Posada-Marín et al. 2024), yet frameworks to address these atmospheric linkages remain limited (Ellison et al. 2012; Creed et al. 2019; Rockström et al. 2023).

Two fundamental concepts in this discussion are precipitationsheds—regions contributing atmospheric moisture to precipitation in a target watershed (Keys et al. 2017)—and terrestrial moisture recycling (TMR); when moisture evaporates from land, is transported, and precipitates elsewhere over land (Van der Ent and Savenije 2011). TMR can contribute over 30% of precipitation in tropical watersheds such as the Amazon, Congo, and Niger (Van der Ent et al. 2010; Gimeno et al. 2012). Unlike topography-based watersheds that are usually treated as static, precipitationsheds are dynamic, shaped by atmospheric processes and influenced by seasonal variability, climate change, and land-use and land-cover change (LULC) (Van der Ent et al. 2014; Enciso et al. 2022). Since they obey different dynamics, watersheds and their precipitationsheds generally do not coincide. Therefore, a non-transboundary watershed may have a transboundary precipitationshed. This hidden transboundary nature has major implications for water governance and challenges traditional assumptions of watershed-based management (Keys et al. 2019).

In this paper, we illustrate these challenges through a case study of the Magdalena Watershed, Colombia's principal watershed, which is geographically national but functionally transboundary in atmospheric terms. We demonstrate that its precipitationshed spans neighbouring countries, raising critical questions about moisture source protection, water security, and national sovereignty. Our approach is novel in that we are the first to quantify the terrestrial precipitationshed of the Magdalena Watershed, characterizing its spatial extent and variability, and analysing its implications for governance. The watershed is located in northwestern South America (NWS), a climate-biodiversity hotspot with limited understanding of key climate–hydrology interactions (Iturbide et al. 2020; Arias et al. 2021). Although we do not directly assess climate change impacts, our work contributes to identifying climate-sensitive hydroclimatological mechanisms, especially those modulated by ENSO variability.

ENSO is the dominant mode of global climate variability (Welhouse et al. 2016), with strong influence on precipitation patterns in tropical regions (Glantz 2015; Cai et al. 2020; Poveda et al. 2025). In NWS, El Niño phases are associated with reduced precipitation, partially linked to weakened TMR (Posada-Marín et al. 2023; Ruiz-Vásquez et al. 2024). Here, we provide new quantitative evidence of these changes, focusing on atmospheric moisture flows from the Orinoco and northern Amazon into the Magdalena. While previous studies have explored TMR in the NWS region (Hoyos et al. 2018; Agudelo et al. 2019; Escobar et al. 2022), they have not focused on the Magdalena Watershed or its TMR dynamics, nor have they examined the water governance implications of this hidden transboundary dependence. Our study addresses this gap using the Water Accounting Model – 2 layers (WAM-2layers) (Van der Ent et al. 2014), simulating moisture trajectories over the watershed under seasonal and ENSO conditions.

We address four questions: (i) What is the spatial distribution of the Magdalena Watershed's precipitationshed?, (ii) How does this precipitationshed vary seasonally and with ENSO?, (iii) How dependent is the watershed on TMR?, and (iv) What are the implications for water management? By combining quantitative modelling with governance insights, this work advances the precipitationshed framework and offers new evidence to inform watershed planning beyond traditional watershed boundaries.

2 Materials and methods

2.1 Study Area

Located in NWS (Fig. 1a), the Magdalena Watershed plays a crucial role in Colombia's water and energy security. It supplies most of the country's freshwater and hydroelectric power, hosting 49 of the 78 major artificial reservoirs (Angarita et al. 2018; Barón-Cáceres 2019). The river originates in the Andes Mountains and flows northward to the Caribbean Sea, draining an area of 261,205 km² with an average discharge of 7,317 m³/s. The watershed's topography is diverse, ranging from over 3,500 m in the headwaters to sea level at the delta, with steep slopes upstream and extensive floodplains downstream. Its hydrographic network is dense, with tributaries from both flanks of the Northern Tropical Andes. The landscape reflects tectonic uplift and includes incised valleys, alluvial terraces, and floodplains (Anderson et al. 2016). Hydrogeologically, it comprises fractured rock aquifers in the highlands and unconsolidated alluvial aquifers in lowland areas, though data on groundwater recharge and connectivity remain limited (Lora-Ariza et al. 2024).

Land-use in the watershed is heterogeneous and the watershed has been extensively degraded in terms of its terrestrial and aquatic resources. Agriculture dominates the inter-Andean valleys and lowlands, with activities such as cattle grazing, oil palm and sugarcane cultivation, and rice production. These areas are interspersed with forest patches and urban centres like Bogotá, Medellín, and Barranquilla (Salomão et al. 2024). Deforestation and land-use change, particularly in the mid and upper watershed, have altered hydrological regimes and increased soil erosion and sedimentation (Salgado et al. 2022). Climatically, the watershed features a bimodal precipitation regime (Fig. 1b) governed by the Intertropical Convergence Zone (ITCZ) and orographic effects (Urrea et al. 2019). Mean annual precipitation ranges from < 1,000 mm in the upper watershed to > 4,000 mm in some foothills. Temperatures vary from 12 to 16 °C in highlands to > 28 °C in lowlands. Evapotranspiration rates average 1,000–1,800 mm/year, supporting high relative humidity (60–90%).

Precipitation sources include local evapotranspiration and moisture advection from the Caribbean, Pacific, Amazon, and Orinoco (Hoyos et al. 2018; Poveda et al. 2025). The watershed's dominant climate driver is the El Niño–Southern Oscillation (ENSO), which induces severe hydrological extremes. El Niño episodes have historically caused droughts and hydropower crises, such as the 1992 collapse, while La Niña events have led to catastrophic floods, including the 2011 disaster with damages exceeding USD 2.7 billion. Understanding ENSO-related mechanisms remains critical for future water management.

2.2 Model Simulation

Precipitation (P) over a watershed can be divided into two components depending on its origin: oceanic (P_o), from sea evaporation, and terrestrial, derived from land-based evapo-

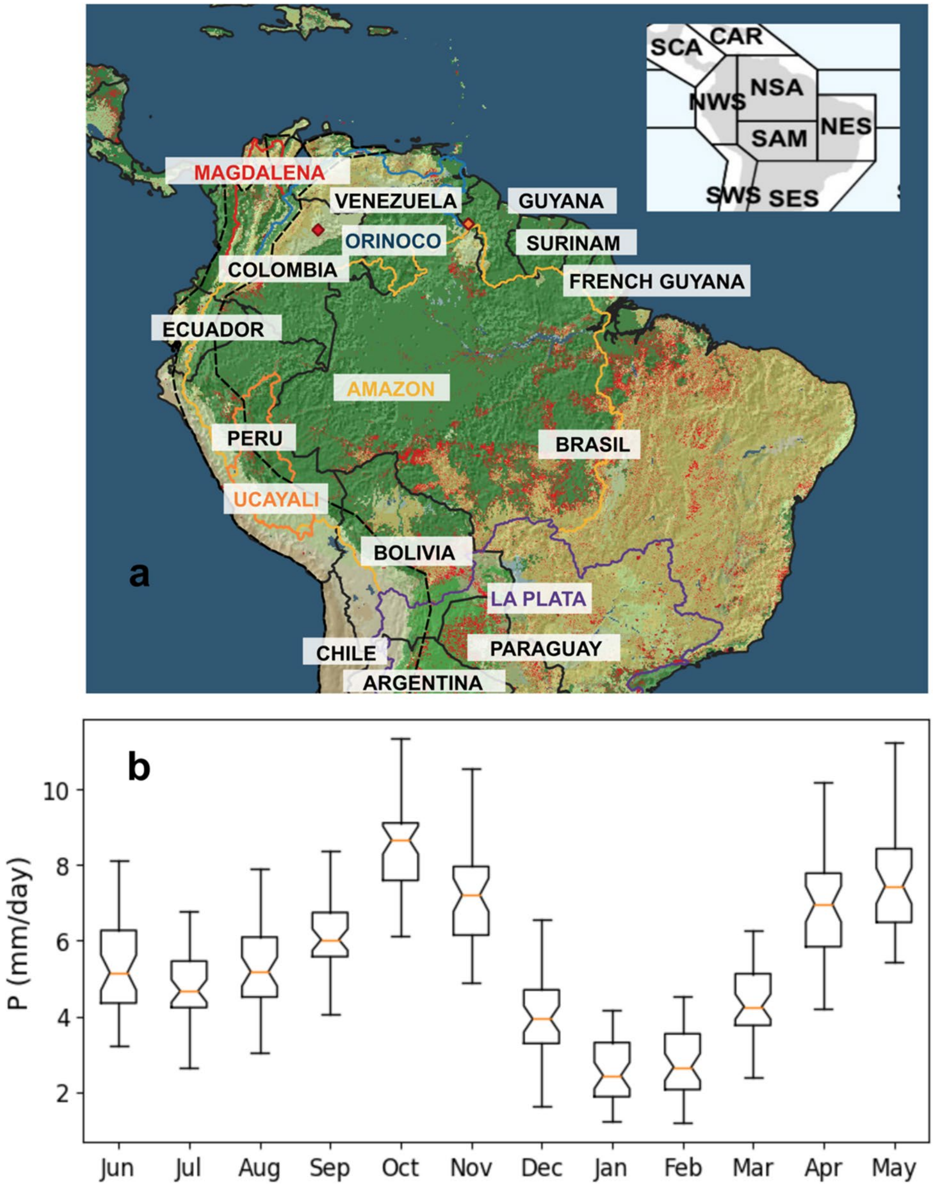

Fig. 1 (**a**) Major watersheds in northern South America: Magdalena (red), Orinoco (blue), Ucayali (orange), La Plata (purple), and Amazon (yellow). National boundaries are shown in black. Forest loss between 2001 and 2019 is indicated in red (Hansen et al. 2013). Red and orange dots mark the Llanos Orientales and Guiana Shield, respectively. The Andes Mountains are outlined with a dashed black line. The inset map shows the IPCC reference regions (Arias et al. 2021). (**b**) Mean annual precipitation cycle over the Magdalena Watershed, based on CHIRPS V2 data (Funk et al. 2015)

transpiration via TMR. This distinction enables quantifying the relative contributions of oceanic and terrestrial sources to local or regional precipitation:

$$P(t,\, x,\, y) = Po(t,\, x,\, y) + TMR(t,\, x,\, y) \tag{1}$$

where each component varies over time (t) and space (x, y). TMR can be disaggregated into: (i) Local Moisture Recycling (LMR), from evapotranspiration within the target region, and (ii) Regional Moisture Recycling (RMR), from land areas beyond it. This relationship is summarised as:

$$TMR(t,\, x,\, y) = LMR(t,\, x,\, y) + RMR(t,\, x,\, y) \tag{2}$$

To estimate TMR, LMR, and RMR, we used the WAM-2layers model (Van der Ent et al. 2014), an Eulerian moisture-tracking framework that solves the atmospheric water balance through:

$$\frac{\partial\, Wk}{\partial\, t} = \frac{\partial\ (Wku)}{\partial\, x} + \frac{\partial\ (Wkv)}{\partial\, y} + Ek - Pk + \xi\, k\ \pm\ QV \tag{3}$$

In this formulation, $\partial Wk/\partial t$ represents the change in atmospheric moisture in layer k, while the right-hand side includes horizontal advection ($\partial Wku/\partial x$, $\partial Wkv/\partial y$), evapotranspiration (E_k), precipitation (P_k), and vertical exchange between layers (Q_V). A residual term (ξ_k) accounts for small imbalances in the moisture budget, typically due to inconsistencies in the input fields.

The model domain spans a global grid from 79.5°N to 79.5°S, with the atmospheric column divided into two layers ($k = 1, 2$), broadly representing upper and lower wind regimes. Simulations use ERA-Interim reanalysis (Dee et al. 2011), incorporating specific humidity and wind fields at 24 pressure levels, surface pressure at 6-hour intervals, and 3-hourly precipitation and evapotranspiration, all at 1.5° spatial resolution (~25,680 grid cells). Moisture trajectories were tracked backward to identify evaporation sources contributing to TMR in the Magdalena Watershed. The analysis covers 1978–2018, excluding 1978 as spin-up (e.g., Wang-Erlandsson et al. 2018; Link et al. 2020).

From these simulations, we identified the upwind land areas supplying moisture to precipitation over the Magdalena Watershed—i.e., its terrestrial precipitationshed. We focus on the terrestrial rather than oceanic sources, given our interest in the implications of transboundary LULC. WAM-2Layers is a well-established model for analysing moisture recycling and transport across scales (e.g., Zemp et al. 2017; Wang-Erlandsson et al. 2018; Findell et al. 2019; Link et al. 2020). We used its Python implementation (https://github.com/ruudvdent/WAM2layersPython), adapting post-processing scripts to our needs. For complete model details, see Van der Ent et al. (2014).

2.3 ENSO Composite Analysis

We classified ENSO phases using NOAA's Oceanic Niño Index (ONI). El Niño events were defined as ONI ≥ 0.5 °C for five consecutive overlapping 3-month periods; La Niña as ONI ≤ −0.5 °C; and neutral phases as values between − 0.5 and 0.5 °C. Figure 2 shows the ENSO events used for composite analysis. To estimate anomalies, recycling values during El Niño

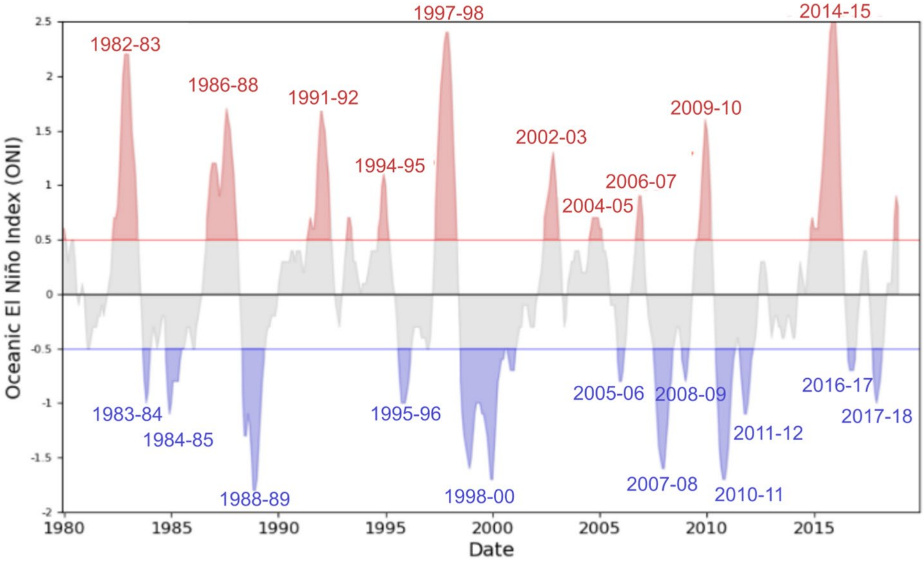

Fig. 2 Evolution of the Oceanic Niño Index (ONI) from 1980–2018, showing warm (El Niño, red), cold (La Niña, blue), and neutral (gray) ENSO phases used for the composite analysis. Labels show year and month of the peak anomalies. ONI data sourced from NOAA

and La Niña were averaged and differenced from neutral-phase means (e.g., Welhouse et al. 2016; Posada-Marín et al. 2023). Statistical significance was assessed via a two-tailed Student's t-test at the 95% confidence level.

2.4 Bias Correction

To quantify TMR, RMR, and LMR as fractional contributions to watershed precipitation, we used ERA-Interim atmospheric fields. Absolute values were derived by applying these fractions to CHIRPS V2 precipitation estimates (Funk et al. 2015), which have shown strong performance in Colombia (Valencia et al. 2023). This bias-correction approach—common in climate impact assessments—combines relative model outputs with observational data for improved accuracy.

3 Results

The terrestrial precipitationshed of the Magdalena Watershed (Fig. 3a) extends mainly eastward, indicating that a significant share of its precipitation originates from evapotranspiration over neighbouring countries—especially Venezuela, Guyana, Surinam and Brazil. These source regions include ecosystems such as the Llanos Orientales in Colombia ("eastern plains" in English), the forests and savannas of the Guiana Shield, and parts of the Amazon rainforest. This regional contribution (RMR) accounts for 29.9% of the watershed's long-term mean precipitation, highlighting that nearly one-third of its precipitation depends on upwind areas beyond the watershed's borders.

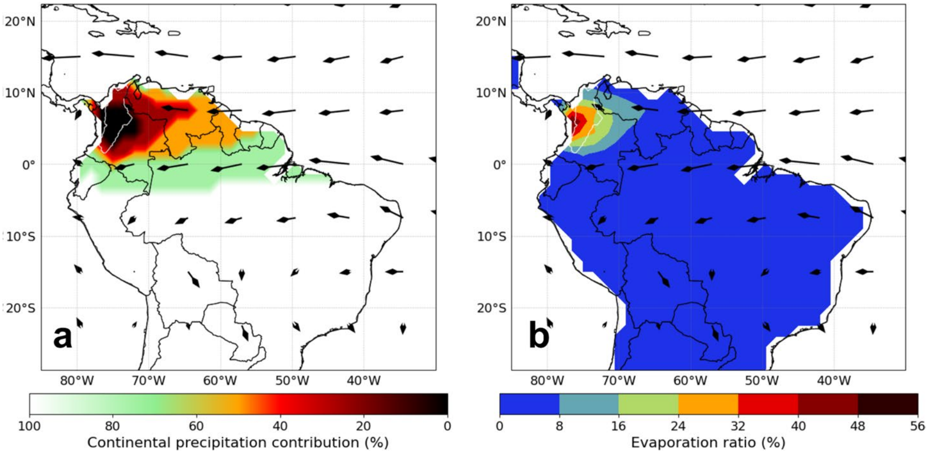

Fig. 3 (**a**) The terrestrial precipitationshed of the Magdalena Watershed. Coloured contours delineate areas contributing to different levels of TMR in the watershed. For example, the black to yellow contours encompass the areas that collectively contribute approximately 60% of the watershed's TMR. (**b**) Spatial distribution of the fractional contribution of evaporation to the Magdalena's TMR

Figure 3b shows the percentage of land evapotranspiration that precipitates over the Magdalena Watershed, calculated per grid cell. In green-shaded areas, 16–24% of local evapotranspiration reaches the watershed as precipitation. Overall, TMR supplies 37.3% of the watershed's long-term mean precipitation, meaning over one-third of its precipitation originates from terrestrial evapotranspiration inside and outside the watershed's boundaries. Figure 4 shows the long-term monthly seasonality of the Magdalena Watershed's terrestrial precipitationshed. Land-sourced moisture contributes year-round but peaks in June–July–August (JJA) can be observed, driven by the South American Low-Level Jet (SALLJ), which channels vapor from the Amazon and Orinoco watersheds to NWS (Hoyos et al. 2018; Montini et al. 2019; Poveda et al. 2025). During JJA, Mesoscale Convective Systems (MCSs) enhance this moisture influx (Robledo et al. 2024).

In contrast, during December–January–February (DJF), the precipitationshed retracts southward, and the Orinoco Low-Level Jet (OLLJ) becomes more dominant, transporting moisture from the Caribbean and Atlantic toward the Andes and Llanos (Arias et al. 2015; Builes-Jaramillo et al. 2022). Meanwhile, the SALLJ shifts further south, supplying > 60% of precipitation to the La Plata Watershed (Martínez and Dominguez 2014). The Magdalena Watershed averages 5.4 mm/day of precipitation, with two wet (September–October–November or SON, and March–April–May or MAM) and two dry (JJA, DJF) seasons (Fig. 1b). Moisture recycling peaks around JJA (Fig. 4), when the watershed is most connected to the Amazon and Orinoco via the SALLJ (Fig. 5a–c), highlighting the key role of upwind rainforests in transporting Atlantic and Amazonian moisture over 3,000 km to the Tropical Andes (Zemp et al. 2014; Staal et al. 2018; Molina et al. 2019).

The precipitationshed responds not only to seasonality (Fig. 5) but also to climate variability, particularly ENSO (Fig. 6). While its location and extent remain relatively stable across phases (Fig. 6a, b), evaporation contributions show marked anomalies (Fig. 6c, d).

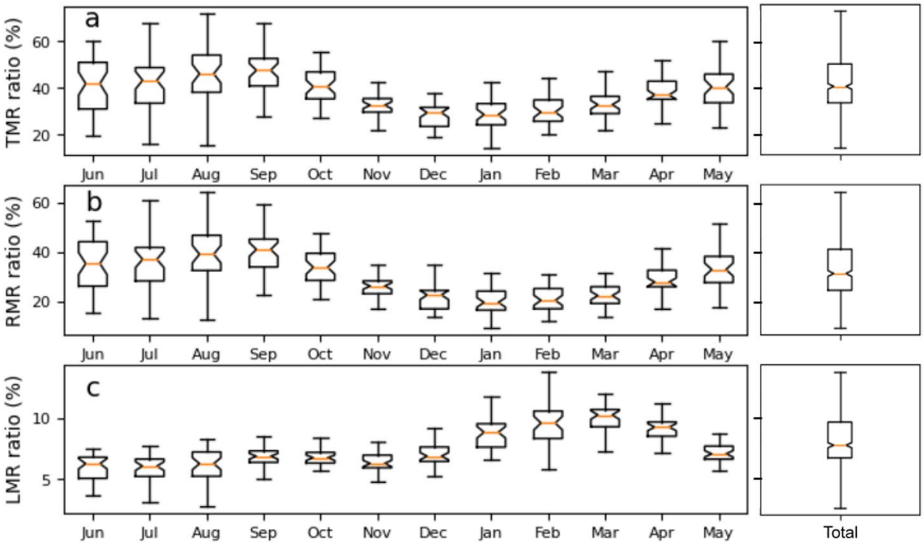

Fig. 4 Climatological seasonal cycles of (**a**) TMR, (**b**) RMR, and (**c**) LMR for the Magdalena Watershed

During El Niño, the northern Amazon's moisture contribution to the Magdalena decreases notably, helping to explain the associated decline in watershed precipitation. Interestingly, similar anomalies appear during La Niña—despite increased precipitation—suggesting a stronger role of oceanic moisture transport in that phase (Arias et al. 2015).

4 Discussion

4.1 Watershed vs. Precipitationshed: Shifting Paradigms in Water Management and Governance

Watersheds and precipitationsheds offer distinct but complementary lenses for water governance (Posada-Marin et al., 2024). Traditional management has focused on phenomena within watershed boundaries (Albrecht and Gerlak 2022; Yadav et al. 2024), often emphasizing how local LULC shapes water availability (Abbasi et al. 2022; Srivastava and Chinnasamy 2024; Valencia et al. 2024). In contrast, the precipitationshed framework highlights that a watershed's precipitation can depend heavily on upwind evaporation from distant regions. Our findings illustrate this with the Magdalena Watershed—a nationally bounded watershed whose precipitationshed spans multiple countries. This atmospheric interdependence implies that national water policies, if limited to watershed boundaries, may miss key external drivers of hydrological change. Effective governance must therefore account for both cross-scale and cross-border interactions.

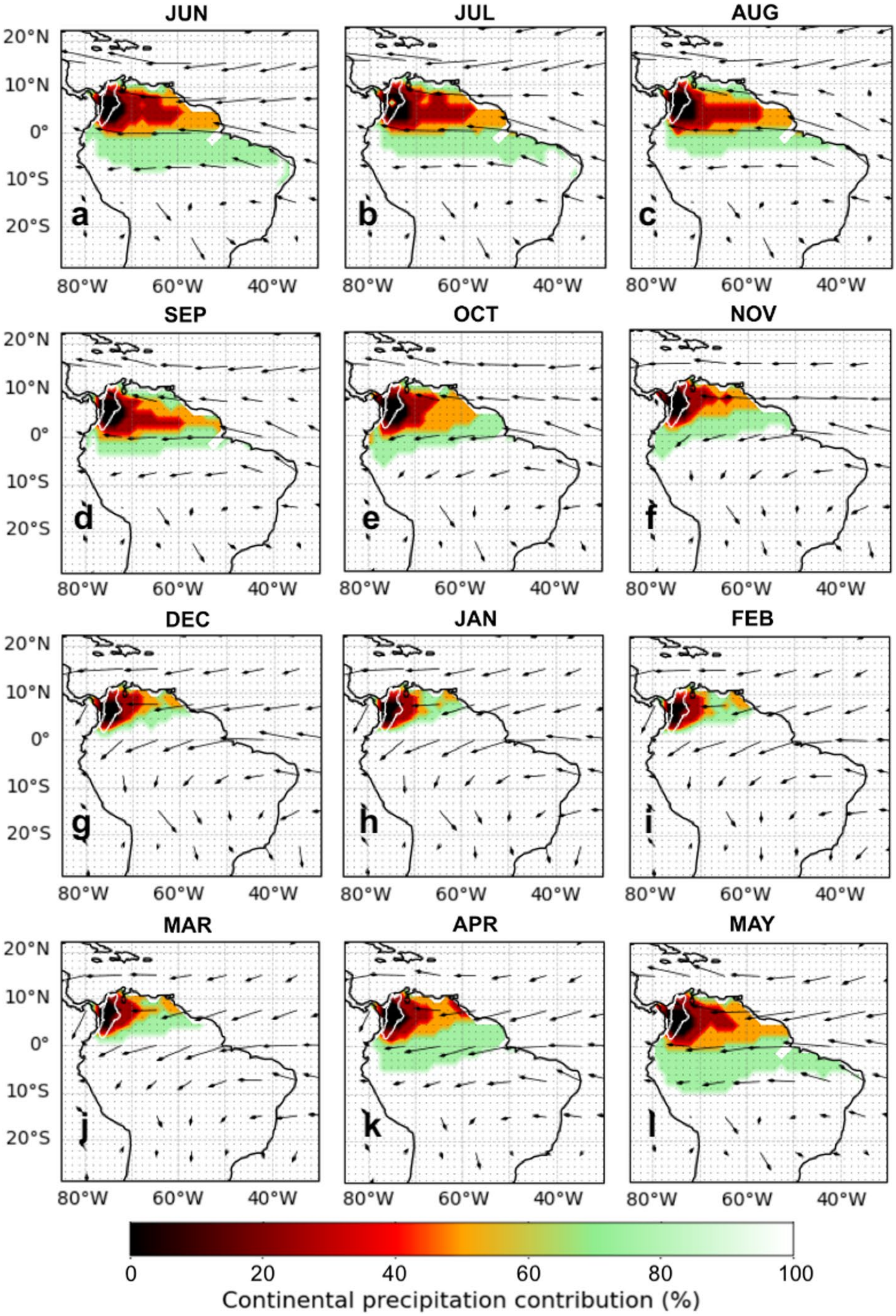

Fig. 5 Monthly seasonality of the Magdalena Watershed's terrestrial precipitationshed

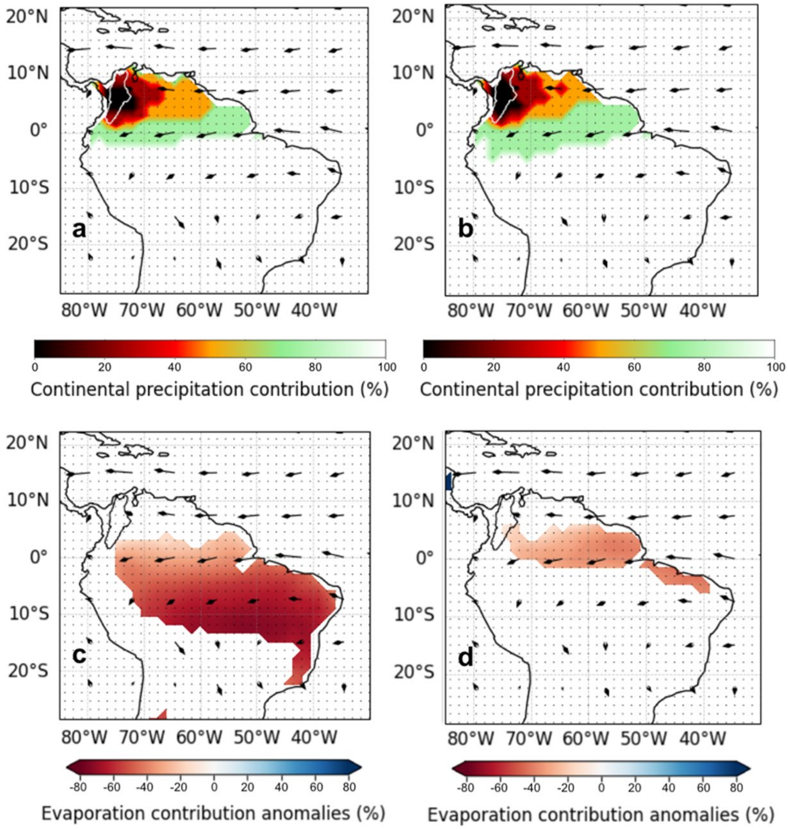

Fig. 6 The Magdalena's terrestrial precipitationshed during (**a**) El Niño and (**b**) La Niña phases of the ENSO. Evaporation contribution anomalies during (**c**) El Niño and (**d**) La Niña. Only significant anomalies are plotted

4.2 The Risks of LULC Change in Critical Precipitationsheds

A watershed-only perspective may ignore crucial LULC changes occurring upwind but outside watershed boundaries, which can alter precipitation patterns through downwind effects (Makarieva et al. 2014; Wang-Erlandsson et al. 2018; Weng et al. 2018; Creed et al. 2019; Posada-Marín et al. 2024). For example, the Amazon forest plays a critical role in sustaining TMR across tropical South America, a function threatened by deforestation (Boers et al. 2017; Zemp et al. 2017; Molina et al. 2019; Makarieva et al. 2023). This can reduce precipitation in distant watersheds such as the Magdalena, Ucayali, and La Plata (Weng et al. 2018; Sierra et al. 2022). Similarly, deforestation in the Guiana Shield has local and downwind impacts reaching the Tropical Andes (Bovolo et al. 2018). Because these forests lie within the Magdalena's precipitationshed, their degradation poses transboundary risks to the watershed hydrology. For example, wetlands covering large areas have been found to be affected in terms of water availability by LULC occurring in upwind areas (Fahrländer et al. 2024). This is the case of also the large coastal wetland located at the confluence of the Magdalena River in the Caribbean Sea. Unlike watershed-based approaches, the precipitationshed framework allows for a broader, risk-informed management strategy.

4.3 Emerging Challenges in Expanding Water Management Boundaries

The traditional focus on watersheds often limits the scope of water management by ignoring moisture sources beyond watershed boundaries. In the Magdalena Watershed, for instance, the energy sector—strongly dependent on an extensive reservoir network (Gómez-Dueñas et al. 2018)—concentrates its efforts within the watershed, neglecting critical upwind areas. Transitioning to a precipitationshed perspective requires challenging entrenched assumptions and overcoming institutional inertia. Our analysis contributes to this shift by offering scientific evidence of atmospheric interdependencies. Given that the terrestrial precipitationshed extends into neighbouring countries, effective governance must consider LULC across both the watershed and the broader precipitationshed.

Unlike watersheds, which are topographically defined and often studied as invariant (Lehner and Grill 2013), precipitationsheds are dynamic, shaped by atmospheric circulation and sensitive to seasonality (Fig. 5), climate variability (Fig. 6), and LULC changes (Makarieva et al. 2023). Consequently, they require flexible, adaptive planning frameworks that account for shifting boundaries and feedbacks with climate change and variability. Moreover, this framework invites a rethinking of evapotranspiration. Traditionally viewed as a net loss under a demand-side paradigm, evapotranspiration can instead be recognised as a supply-side process that contributes to precipitation through local (LMR) and regional (RMR) moisture recycling (Ellison et al. 2012; Staal et al. 2018; Posada-Marín et al. 2024).

The Magdalena Watershed exemplifies this complexity: although it lies entirely within Colombia, it relies heavily on external terrestrial sources vulnerable to socio-political drivers, including peace processes and national elections (Salazar et al. 2018, 2022; Rodrigues-Filho et al. 2015). Our results challenge prevailing notions of national hydrological sovereignty and reveal weak incentives to conserve crucial external source regions, such as the Llanos Orientales and Amazon rainforest. Acknowledging these trans-watersheds and transnational dependencies may require revisiting national and international water law to include atmospheric moisture flows.

Despite the variability of precipitationsheds, some upwind regions contribute consistently across seasons and ENSO phases due to persistent atmospheric patterns—e.g., easterly winds linking the Magdalena to its upwind Orinoco and Amazon watersheds. Identifying these “core” contributors could support targeted LULC planning and forest conservation, aligning scientific insights with policy action. The high dependence on evapotranspiration from neighbouring countries also raises the question of whether this moisture constitutes an unrecognised transboundary ecosystem service. Since approximately 30% of the Magdalena Watershed’s precipitation originates from forests and landscapes beyond the watershed’s and Colombia’s borders, there is an implicit hydrological interdependence through the atmosphere that is not currently accounted for in national water governance. Isotope analyses confirm the role of regions like the Orinoco and northern Amazon in supplying atmospheric moisture to Colombia (Agudelo et al. 2019). Recognising this dependence could open the door to new forms of international cooperation, including compensation schemes or incentives for upstream LULC practices that sustain moisture recycling. These mechanisms, while politically complex, align with emerging discussions on environmental services and shared responsibilities in transboundary hydrological systems (Ellison et al. 2012; Rockström et al. 2023; Keys et al. 2024; Posada-Marín et al. 2024). Acknowledging this service could foster new cooperation mechanisms, including incentives or compensation for upwind conservation practices—an idea increasingly explored in the context of shared environmental responsibilities (Ellison et al. 2012; Keys et al. 2024).

4.4 Limitations and Directions for Future Research

While this study offers novel insights into the transboundary nature of atmospheric moisture flows into the Magdalena Watershed, several limitations must be acknowledged. First, the TMR estimates are subject to uncertainties inherent in moisture-tracking models, including simplifications of atmospheric dynamics, coarse spatiotemporal resolution, and challenges in attributing moisture sources in regions with complex topography and land cover—particularly in tropical mountainous watersheds like the Magdalena, where convective processes and elevation gradients strongly shape precipitation patterns (Posada-Marín et al. 2019; Robledo et al. 2024).

Second, the partitioning of oceanic versus terrestrial moisture sources was not validated using independent observational datasets. Our results also indicate that ENSO phases reduce TMR in the Magdalena Watershed. Future research should integrate reanalysis data, satellite-based evaporation and moisture transport estimates, stable isotopes in precipitation, and surface flux measurements, as these technologies can both validate the partitioning of moisture sources and help describe the mechanisms by which ENSO phases influence TMR. Additionally, the influence of land use and land cover (LULC) change—such as deforestation, urbanization, and agricultural expansion—on atmospheric moisture transport is only implicitly considered in this study and deserves further exploration.

Third, although we highlight the conceptual implications of adopting a precipitationshed perspective, this study does not empirically examine institutional or policy responses. Future research should explore how atmospheric interdependencies can be operationalised within decision-support tools and governance frameworks, particularly in reconciling atmospheric and political boundaries and fostering cooperation across watersheds and national borders (e.g., Meadow et al. 2015).

Advancing this line of inquiry requires modelling approaches that couple high-resolution climate data, land–atmosphere interactions, and socio-institutional scenarios. Our study is a contribution in this direction, aimed at enhancing the understanding of how moisture recycling pathways should be incorporated into water management and may evolve under LULC and climate change. Although our findings align with the behaviour of the SALLJ and OLLJ, we do not assess the model's performance in capturing their full dynamics.

5 Conclusions

This study contributes to a growing body of literature that redefines the spatial paradigms of water governance by introducing the precipitationshed as a critical and complementary framework to the traditional watershed approach. Using the Magdalena Watershed as a case study, we provide empirical evidence that geographically domestic watersheds can be functionally transboundary in atmospheric terms, as they rely significantly on evapotranspiration from upwind land areas located outside their political and hydrological boundaries.

Our analysis shows that nearly one-third of the Magdalena Watershed's precipitation depends on TMR, with substantial contributions from the Amazon and Guiana Shield forests. These findings underscore the vulnerability of downwind water availability to upwind LULC changes in remote source regions—a dynamic that conventional watershed-based strategies generally overlook.

The study also exposes important institutional and conceptual challenges. Existing water management frameworks tend to operate under static, jurisdictional logics, neglecting atmospheric interdependencies that are dynamic, cross-scale, and transboundary. Adopting a precipitationshed perspective thus requires a paradigm shift—from managing water as a locally bounded resource to recognising its dependence on continental-scale ecological processes and regional cooperation.

Importantly, this approach opens new opportunities for integrating climate adaptation, biodiversity conservation, and hydrological resilience under a common framework. It invites rethinking entrenched notions of water sovereignty, particularly in transboundary contexts where upstream LULC decisions in one country affect precipitation and water security in another. This resonates with ongoing efforts such as the Escazú Agreement in Latin America and global initiatives advocating for a "new economics of water as a common good" (Rockström et al. 2023).

In sum, we argue that incorporating TMR into water policy and governance is not only scientifically grounded but also normatively necessary. It provides a pathway toward more just, sustainable, and cooperative forms of water stewardship in a time of intensifying climatic and LULC pressures. In this way, the case of the Magdalena Watershed combines important national water resources, atmospheric dependencies, intensive LULC, and large upwind dependencies converge to offer a case study for transboundary dependencies and their implications for national and transnational water management.

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Author Contributions All authors contributed to the study conception and design. Material preparation, simulations and postprocessing were performed by J.A.P-M. The first draft of the manuscript was written by A.M.R. F.J. and J.F.S who commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability and materials.
The WAM-2layers model code is available through Van der Ent et al. (2014) (https://github.com/ruudvdent/WAM2layersPython). The ERA-Interim reanalysis data (Dee et al. 2011) can be obtained using the download scripts present in the previous github repository from https://apps.ecmwf.int/datasets/data/interim-full-daily/. Data from our simulation are available at a Zenodo repository via https://doi.org/10.5281/zenodo.7797182 with CCA 4.0 license.

Declarations

Competing interests The authors declare no competing interests.

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