Hydroclimatic vulnerability of wetlands to upwind land use changes

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Abstract

Despite their importance, wetland ecosystems protected through the Ramsar Convention on Wetlands are under pressure from climate change and human activities. These drivers are altering water availability in these wetlands, changing water levels or surface extent, in some cases, beyond historical variability. Attribution of the effects of human and climate activities is usually focused on changes within the wetlands or their upstream surface and groundwater inputs. However, the reliance of wetland water availability on upwind atmospheric moisture supply is less understood. Here, we assess the vulnerability of 40 Ramsar wetland basins to precipitation changes caused by land use and hydroclimatic changes occurring in their upwind moisture-supplying regions. We use moisture flows from a Lagrangian tracking model, atmospheric reanalysis data, and historical land use change data to assess and quantify these changes. Our analyses show that historical land use change decreased precipitation and terrestrial moisture recycling in most wetland hydrological basins, accompanied by decreasing surface water availability (precipitation minus evaporation) in some wetlands. The most substantial effects on wetland water availability occurred in the tropical and subtropical regions of Central Europe and Asia. Overall, we found wetlands in Asia and South America to be especially threatened by a combination of land use change-driven effects on runoff, high terrestrial precipitation recycling, and recently decreasing surface water availability. This study stresses the need to incorporate upwind effects of land use changes in the restoration, management and conservation of the world's wetlands.

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Abstract

Despite their importance, wetland ecosystems protected through the Ramsar Convention on Wetlands are under pressure from climate change and human activities. These drivers are altering water availability in these wetlands, changing water levels or surface extent, in some cases, beyond historical variability. Attribution of the effects of human and climate activities is usually focused on changes within the wetlands or their upstream surface and groundwater inputs. However, the reliance of wetland water availability on upwind atmospheric moisture supply is less understood. Here, we assess the vulnerability of 40 Ramsar wetland basins to precipitation changes caused by land use and hydroclimatic changes occurring in their upwind moisture-supplying regions. We use moisture flows from a Lagrangian tracking model, atmospheric reanalysis data, and historical land use change data to assess and quantify these changes. Our analyses show that historical land use change decreased precipitation and terrestrial moisture recycling in most wetland hydrological basins, accompanied by decreasing surface water availability (precipitation minus evaporation) in some wetlands. The most substantial effects on wetland water availability occurred in the tropical and subtropical regions of Central Europe and Asia. Overall, we found wetlands in Asia and South America to be especially threatened by a combination of land use change-driven effects on runoff, high terrestrial precipitation recycling, and recently decreasing surface water availability. This study stresses the need to incorporate upwind effects of land use changes in the restoration, management and conservation of the world's wetlands.

Key Points:

- Land use changes led to mean annual runoff (*P-E*) decreases in wetland hydrological basins globally.
- The most substantial land use-related *P-E* changes occurred in tropical and subtropical wetlands across Asia, South America and Europe.
- We identify eight wetlands in Asia, South America, and Australia as particularly vulnerable to changes in upwind moisture sources.

Plain Language Summary

Wetlands protected by the Ramsar Convention face threats from climate change and human activities, impacting their water availability and altering wetland functions. While past studies often focused on immediate surroundings, our research looks into the influence of changes in the upwind atmospheric moisture supply of wetlands. We evaluate the vulnerability of 40 Ramsar wetland basins to precipitation shifts caused by land use and hydroclimatic changes in upwind regions, using the output of an atmospheric moisture tracking model and historical data. The results indicate that historical land use changes have reduced precipitation and moisture recycling, leading to a decrease in water availability in some wetlands, notably affecting tropical and subtropical regions of Central Europe and

Asia. We assess that wetlands in Asia and South America face heightened risk due to a combination of land use-induced runoff impacts, high precipitation recycling, and declining surface water availability. This study highlights the need to incorporate upwind effects of land use changes in wetland restoration, management, and conservation efforts globally, recognizing the crucial role of these influences in shaping effective strategies for wetland protection amidst evolving environmental conditions.

1. Introduction

Wetlands are responsible for around 45% of all the value generated by natural biomes globally (Davidson et al., 2019) and are critical to the health and livelihoods of many people globally (Ramsar Convention on Wetlands, 2021). They protect coasts and water quality, maintain and regulate groundwater levels and soil moisture, help mitigate floods, sequester carbon, and support impressive biodiversity (Thorslund et al., 2017). These ecosystems are also critical to sustainable development (Jaramillo et al., 2019). However, the provisioning of these services is compromised by low water availability, as impacted by past, ongoing and future land and water management and anthropogenic climate change.

In particular, agricultural expansion (Kashaigili, 2008), fragmentation by road infrastructure (Jaramillo et al., 2018; Wemple et al., 2018), water impoundment (Grill et al., 2019), and freshwater withdrawals for irrigation (Zaki et al., 2020) significantly alter wetland water availability. In addition, climate change also modifies the evaporation and precipitation of wetland systems, leading to drying or wetting (Xi et al., 2021). Since 1970, approximately 35% of global wetland areas have been lost due to local land use conversions and hydrological modifications, such as drainage for agricultural use (Fluet-Chouinard et al., 2023). Although the loss rate has slowed in regions like Europe and North America, it has increased over large parts of Asia and the tropics (Acreman et al., 2007; Davidson, 2016).

Land use changes occurring upstream of the wetland can alter water availability within the wetland ecosystem; changes in vegetation and land use alter land evaporation (i.e., the total of transpiration, soil moisture evaporation, and interception evaporation), modifying the amount and timing of freshwater flowing into the wetland (Sterling et al., 2013). However, upwind land use-induced changes can also modify precipitation over the wetlands' hydrological basin by altering wind patterns and terrestrial moisture recycling (i.e., the process whereby land evaporation is transferred to the precipitation over land; Tuinenburg & Staal, 2020). The impact can be substantial, as 40 to 50% of terrestrial precipitation comes from evaporation over land and 60 to 70% of evaporation over land results in terrestrial precipitation (Eltahir & Bras, 1996; van der Ent et al., 2010; Tuinenburg & Staal, 2020). Furthermore, around half of this moisture supply to terrestrial precipitation is sustained by vegetation and can be considered an ecosystem service (Keys et al., 2016). In fact, current human land use covers over 40-50% of the Earth's land surface (Ellis & Ramankutty, 2008) and already considerably impact precipitation and downwind river flows through modifications of moisture recycling (Wang-Erlandsson et al., 2018).

The upwind area of the most important moisture supply to these wetlands, termed 'precipitationshed' (Keys et al., 2012), can then help identify transboundary upwind-downwind moisture transport relationships (Keys et al., 2017; Wang-Erlandsson et al., 2018). Hence, it can also be used to determine wetlands' vulnerability to upwind land use change. Although similar upwind vulnerability assessments have been done for megacities (Keys et al., 2018), croplands (Keys et al., 2012), and critical natural assets (Chaplin-Kramer et al., 2022), there is still no assessment of the vulnerability of wetland water availability to upwind changes. Such assessment would provide evidence of the need to incorporate upwind effects of land use changes in the restoration, management and conservation of the world's wetlands and to evaluate their resilience to human and hydroclimatic changes.

Here, we assess the vulnerability of 40 wetland hydrological basins to upwind changes in land use and water use by accounting for their associated impacts on evaporation and precipitation through moisture recycling. The hypothesis is that upwind land use changes can drive considerable changes in long-term water availability in the hydrological basins of wetlands. We use a database of atmospheric flows created with the Lagrangian UTrack atmospheric moisture tracking model, atmospheric reanalysis data and historical land use change data.

2. Methods and Data

2.1 Data

This study uses global land data to describe the characteristics of the selected wetlands of the Ramsar Convention (https://rsis.ramsar.org/?pagetab=1) (Sect. 2.1.1) and hydrometeorological data to describe their moisture flows (Sect. 2.1.2). Information on land includes digital elevation models for basin delineation (see Table 1) and data on current global anthromes to characterize the land use types of moisture sources (Ellis et al., 2013). Hydrometeorological data include moisture flow data for moisture recycling analyses (Tuinenburg et al., 2020), model outputs of evaporation and precipitation for estimating the impact of land use change (Wang-Erlandsson et al., 2018), and precipitation and evaporation data for the moisture recycling and hydroclimatic trend analysis (Hersbach et al., 2020; University of East Anglia Climatic Research Unit et al., 2021).

Since data were accessed from multiple sources with different temporal and spatial scales, resolutions, and metadata, they were pre-processed by transforming, subsetting, and transposing for consistency. This pre-processing of datasets was done using the open-source and Linux-based command line operators of the Geospatial Data Abstraction Library (Rouault et al., 2022) and Climate Data Operators (Schulzweida, 2020). Next, the gridded data were transposed to match the UTrack climatology dataset (Tuinenburg et al., 2020) at 0.5° resolution using the bilinear transposing method and the World Geodetic System (WGS) 1984 (EPSG:4326) was applied to all geospatial datasets. Finally, Raster and shapefiles were converted with the Python packages geopandas and rasterio (Gillies et al., 2013).

2.1.1 Land Data

Wetland location markers and water body delineations were taken from the Ramsar Convention dataset (https://rsis.ramsar.org/) and from (Zhang et al., 2017), who used remote sensing to map and classify wetlands of the Ramsar Convention. For the delineation of the basin boundaries of selected wetlands, the water body delineations and several Digital Elevation Models (DEMs) were used (Table 1). Since some hydrological basins extend beyond the latitude 60° North and global digital elevation models often exclude these areas, we used additional region-specific models to delineate the northernmost basins in Europe, Canada and Russia. For wetlands in the deltas of major river basins (see Table 2 in Sect. 2.2.2), the hydrological basin boundaries were taken from the Global Runoff Data Centre (GRDC, 2020). Furthermore, optical images from the Google Earth engine were also used to validate and, if necessary, manually adjust the wetland's outlet and generate an accurate boundary.

Table 1: Overview of the Digital Elevation Models (DEMs) used for hydrological basin delineation (See more details in Table S1, Supplementary Material); Acronyms: Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Global Digital Elevation Map (GDEM), Shuttle Radar Topography

Mission (SRTM), Canadian Digital Elevation Data (CDED), Canada Centre for Mapping and Earth Observation (CCMEO).

Service	Sources	Resolution	Coverage
EU-DEM	ASTER GDEM, SRTM, Russian Topomap	25 m	Europe > 60N
DEM3	SRTM, ASTER GDEM, Russian 200k and 100k	90 m	Russia > 60N
SRTM 90m	SRTM	90 m	global < 60N
CDED	CCMEO	20 m	Canada

Furthermore, the Anthropogenic Biomes of the World v2 (year 2000 version) dataset (Ellis et al., 2013) was used to determine the contribution to moisture supply by land use type (Sect. 2.2.4). This dataset focuses on anthropogenic alterations by global land use change. The 19 anthromes were aggregated into seven categories (i.e., Dense settlements, rainfed cropland, woodland, rice and irrigated cropland, rangeland, and barrenland), following Keys et al. (2012). In addition, we grouped residential, populated, and remote rangelands into a single category, 'Rangeland', by assuming similar hydrological characteristics. Finally, to distinguish between terrestrial and oceanic evaporation sources, a land-sea mask was accessed through the ERA5-Reanalysis Single Levels Dataset of the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020).

2.1.2 Hydrometeorological Data

We used three hydrometeorological datasets for three different purposes: (1) analyzing hydroclimatic trends (Sect. 2.2.3 and 3.1), (2) establishing moisture sources and sinks relationships (Sect. 2.2.4 and 3.2), and (3) estimating land use change impacts on precipitation (Sect. 2.2.5 and 3.3). Subsequently, the three independent analyses each contributed to estimating one sub-indicator of vulnerability, which were used to obtain a final vulnerability indicator (Sect. 2.2.6 and 3.4).

First, for analyzing hydroclimatic trends (Sect. 2.2.3), we used precipitation and evaporation data from the CRU-TS4.05 monthly dataset from 1980 to 2020 (Harris et al., 2020). The dataset was used to determine water availability in the hydrological basins and their change over time. The CRU-TS version 4 dataset is a global climate dataset derived through interpolating observation data, which are better suited for calculating hydroclimatic trends than reanalysis as they are constructed based on observations (Jaramillo & Destouni, 2014).

Second, for moisture recycling analyses (Sect. 2.2.4), we used the output of the Lagrangian atmospheric moisture tracking model UTrack (Tuinenburg et al. (2020); see also Supplementary Material. This global dataset contains the mean monthly moisture flows from 2008 to 2017 between each pair of moisture source and sink cells. For every grid cell in the world, the dataset provides the fraction of upwind evaporation from each source cell that contributes to its precipitation. The moisture tracking of UTrack was initially performed at 0.25°-resolution and 0.1-hour timesteps using hourly atmospheric reanalysis data from the ECMWF Reanalysis v5 (ERA5) dataset (wind and specific humidity at 25 pressure levels, and surface data of land and ocean evaporation and precipitation) (Hersbach et al., 2020). They then aggregated the UTrack model to a monthly resolution and an output of 0.5° and 1° spatial resolution, of which we used the former. The monthly resolution of the dataset limits understanding of moisture dynamics arising from shorter climatic events, such as those linked with typhoons and hurricanes. Hence, resolving moisture supply to wetlands based on these climatic events is beyond the scope of this study (Wang et al., 2016). Monthly evaporation and precipitation data from ERA5 from 2008 to 2017 was further used to correspond to the mean monthly moisture flows of the UTrack output (Tuinenburg et al. (2020).

Third, for land use impact analyses, we used evaporation and precipitation model outputs for current and potential vegetation scenarios (Sect. 2.2.5). This dataset was taken from the two-way coupled model runs between the hydrological model STEAM and the moisture recycling model WAM-2layers described in Wang-Erlandsson et al. (2018) in 1.5° x 1.5° spatial resolution covering the period from 2000 - 2013.

2.2 Methods

2.2.1. Summary of the Methods

The main workflow of the methods is the following. First, we selected 40 wetlands from the dataset of the Ramsar Convention of Wetlands, attempting to obtain a global coverage of wetlands with large hydrological basins and delineated them (Sect. 2.2.2). We calculated precipitation (P) and water availability (i.e., $P – E$) over the wetland's hydrological basin and their trends in time (Sect. 2.2.3). Second, we estimated the moisture supply to these wetland hydrological basins using moisture flow trajectories from the UTrack model (Tuinenburg et al., 2020) and computed their precipitationsheds (Sect. 2.2.4). Hence, we were able to estimate terrestrial (ρ_{terr}) and basin internal moisture (ρ_{int}) recycling ratios for each wetland hydrological basin. Third, we isolated the impact of vegetation changes on moisture supply in the form of precipitation to the wetland hydrological basins by pairing the moisture tracking with the 1) current land use classification (Ellis et al., 2013; Wang-Erlandsson et al., 2018) and 2) potential vegetation scenarios dataset (Wang-Erlandsson et al., 2018) (Sect. 2.2.5). From here on, we obtained the precipitation and evaporation for both scenarios, P_{cur} and E_{cur} and P_{pv} and E_{pv}, respectively, and calculated their difference (i.e. current minus potential scenario) for P, $P – E$, and ρ_{terr}. Finally, the vulnerability (VI) of the wetlands to upwind moisture supply changes linked to land use change is estimated based on the observed recent hydroclimatic changes, land use change impacts on water availability and terrestrial precipitation recycling (Sect. 2.2.6).

2.2.2 Wetland Selection and Delineation

Forty wetlands of international importance (Table 2) were selected to obtain balanced global coverage and ensure a reliable output from the soil moisture tracking algorithm; we focused on wetlands with an area greater than 2000 km^2. In Europe, where Ramsar wetlands are smaller than elsewhere, the minimum size was set instead to 1000 km^2 to include representative wetlands such as Doñana National Park in Southern Spain and the Sjaunja Wetlands in Northern Sweden. The subset of wetlands meeting these criteria includes ten wetlands in Africa, nine in Asia and South and Central America, five in Europe and North America and two in Australia. The selection comprises different wetland types, including peatlands (e.g., Polar Bear Provincial Park, Queen Maud Gulf), river floodplains (e.g., Grands affluents, Rio Negro), mountainous headwater wetlands (e.g., Sichuan Changshagongma Wetlands), coastal wetlands (e.g., Sian Ka'an, Everglades), and wetlands located around lakes (e.g., Coongie Lakes) and river deltas (e.g., Indus delta, Zambesi delta).

Table 2: List of the 40 selected wetlands with abbreviated names, Ramsar identification number, country, continent and surface area of the wetland according to Ramsar (km^2). Four of the study sites are an aggregate of multiple Ramsar Sites; for example, Wetland Nr. 2 sums three floodplains in Chad, Nr. 5 aggregates the Grands affluents and Ngiri-Tumba-Maindombe wetlands in Congo and the Democratic Republic of the Congo, Nr.40 includes the Pacaya-Samiria wetlands and Complejo de humedales del Abanico in Peru, and Nr. 39 combines the Bolivian and Brazilian sections of the Pantanal wetland.

No	Name	Abbreviation	Ramsar ID	Country	Continent	Area [km^2]
1	Chott Ech Chergui	Chergui	1052	Algeria	Africa	8,555
2	Basse Valée de l'Ouémé	Ouémé	1018	Benin	Africa	6,528
3	Okavango Delta System	Okavango	879	Botswana	Africa	55,374
4	Plaines d'inondation du Chad	Plaines	1839, 1560, 1621	Chad	Africa	104,269
5	Grands affluents & Ngiri-Tumba-Maindombe	Ngiri	1742, 1784	Congo, DRC	Africa	124,777
6	Bassin de la Lufira	Lufira	2318	DRC	Africa	44,710
7	Sankarani-Fié	Sankarani	1167	Guinea	Africa	16,560

8	Delta Intérieur du Niger	Niger	1365	Mali	Africa	41,195
9	Zambesi Delta	Zambesi	1391	Mozambique	Africa	31,712
10	Sudd	Sudd	1622	South Sudan	Africa	57,000
11	Dalai Lake National Nature Reserve, Inner Mongolia	Dalai	1146	China	Asia	7,400
12	Sichuan Changshagongma Wetlands	Sichuan	2348	China	Asia	6,698
13	Tibet Selincuo Wetlands	Tibet	2352	China	Asia	18,936
14	Ili River Delta and South Lake Balkhash	Ili	2020	Kazakhstan	Asia	9,766
15	Indus Delta	Indus	1284	Pakistan	Asia	4,728
16	Volga Delta	Volga	111	Russia	Asia	8,000
17	Tobol-Ishim Forest-steppe	Tobol	679	Russia	Asia	12,170
18	Parapolsky Dol	Parapol	693	Russia	Asia	12,000
19	Brekhovsky Islands in the Yenisei estuary	Yenisei	698	Russia	Asia	14,000
20	Coongie Lakes	Coongie	376	Australia	Australia	21,790
21	Kakadu National Park	Kakadu	204	Australia	Australia	19,798
22	Sian Ka'an	Sian	1329	Mexico	Central America	6,522
23	Rio Sabinas	Sabinas	1769	Mexico	Central America	6,031
24	Lemmenjoki National Park	Lemmen	1521	Finland	Europe	2,860
25	Etangs de la Champagne humide	Etangs	514	France	Europe	2,558
26	Danube Delta	Danube	521	Romania	Europe	6,470
27	Donana National Park	Doñana	234	Spain	Europe	1,116
28	Sjaunja	Sjaunja	32	Sweden	Europe	1,813
29	Whooping Crane Summer Range	Crane	240	Canada	North America	16,895
30	Queen Maud Gulf	Maud	246	Canada	North America	62,782
31	Dewey Soper Migratory Bird Sanctuary	Dewey	249	Canada	North America	8,159
32	Polar Bear Provincial Park	Bear Park	360	Canada	North America	24,087
33	Everglades National Park	Everglade	374	USA	North America	6,105
34	Banados del Río Dulce y Laguna de Mar Chiquita	Dulce	1176	Argentina	South America	9,960
35	Los Lípez	Lipez	489	Bolivia	South America	14,277
36	Río Blanco	Blanco	2092	Bolivia	South America	24,049
37	Ilha do Bananal	Bananal	624	Brazil	South America	5,623
38	Rio Negro	Negro	2335	Brazil	South America	120,016
39	Pantanal	Pantanal	602, 1089	Brazil, Bolivia	South America	33,249
40	Pacaya-Samiria & Complejo de humedales del Abanico	Pacaya	546, 1174	Peru	South America	59,073

The hydrological basins of the 40 wetlands were delineated in ArcMap using the ArcGIS Spatial Analyst Hydrology Toolbox. Since the entire hydrological basin upstream of the wetland contributes to the surface water inputs to each wetland, the hydrological basins were used as sink areas for the moisture tracking process.

2.2.3 Hydroclimatic Trends

The trend in water availability in a given wetland hydrological basin elucidates whether a wetland is historically susceptible to decreasing water influxes. We used mean annual $P- E$ as a proxy for water availability, as it relates to the amount of water that runs on the surface and is potentially stored in ground and surface water bodies and applied the non-parametric Mann-Kendall test for trend analysis (see Supplementary Material).

2.2.4 Establishing Moisture Sources

To ‘backtrack’ the precipitation in the sink (wetland basins) to its sources of evaporation (precipitationsheds), we used the moisture flow database and method created and described by Tuinenburg et al. (2020) (see Sect. 2.1.2). The process is called ‘offline’ tracking because the dataset only supplies monthly averaged atmospheric trajectories, not re-calculating them for every timestep. Although the database shows moisture flows in both directions (source to sink and vice-versa), it is based on forward simulations of evaporation in a source cell to its sink cells. Hence, to extract correct backward flows, forward tracking from each possible source cell for each sink cell in a sink region has to be performed individually and eventually summed up. To avoid the large computational requirements needed to use this method on all the hydrological basins, we used the forward tracking method suggested by Tuinenburg et al. (2020) in the backward direction. We multiplied the resulting normalized evaporation source arrays by the specific precipitation from the sink cells, adding these backward footprints of precipitation up for each sink region. This way, the sink regions tracked precipitation is equal to ERA5 precipitation, while the cellwise contributions of evaporation are still accurately represented. It is worth mentioning that this does not eliminate the up to 5% error introduced in creating the dataset by converting float to integers.

The moisture tracking simulations encompassed four distinct tracking runs (Table 3). The first run (Run 1) employed ERA5 inputs (detailed in Sect. 2.1.2) to generally identify moisture sources for wetland basins. The second run (Run 2) further decomposed the moisture supply to each wetland into their components regarding the land cover at the source (i.e., anthromes).

Table 3: Moisture tracking routines in this study. Runs 1 and 2 are based on ERA5 inputs (Sect. 2.1.2) and are used to identify the moisture sources of the wetland basins. Run 2 is combined with the Anthromes dataset to link moisture sources to a specific land cover classification. Runs 3 and 4 estimate the impact of LUC based on the STEAM-WAM-2layers evaporation and precipitation scenarios for current land use and potential vegetation, respectively (Sect. 2.1.2).

Run number	Run name	Input	Output/Objective
	Establishing moisture sources (Sect. 2.2.4)		
1	Base run	ERA5 evaporation and precipitation	Wetland moisture imports climatologically (Fig. 2, 3)
2	LC classification run	ERA5 evaporation and precipitation + Anthromes	Wetland moisture imports by land use type (Fig. 4)
	LUC impact estimation (Sect. 2.2.5)		
3	STEAM current land use (incl. irrigation)	STEAM current land use evaporation and ERA-I precipitation	Wetland moisture imports under current land use conditions (Fig. 5)
4	STEAM-WAM2layers potential vegetation	STEAM-WAM2layers potential vegetation evaporation and precipitation	Wetland moisture imports under potential vegetation conditions (Fig. 5)

The fraction of precipitation over wetland basins that originate from land evaporation is termed terrestrial precipitation recycling ratio (ρ_{terr}) (Eq. 1) and was calculated as follows (van der Ent et al., 2010):

$$\rho_{\text{terr}}(x, y) = \frac{P_{E_{\text{terr}}}(x,y)}{P_{\text{total}}(x,y)} \qquad (1)$$

where $P_{E\text{terr}}$ denotes the precipitation over a wetland basin (x, y) that originates from land evaporation, and P_{total} denotes the total precipitation over the wetland basin (L T^{-1}).

Next, we calculated the internal precipitation recycling ratio (ρ_{int}) (Eq. 2), which refers to the fraction of precipitation over a wetland basin (x,y) that originates from evaporation in the same basin.

$$\rho_{\text{int}}(x, y) = \frac{P_{E_{(x,y)}}(x,y)}{P_{\text{total}}(x,y)} \qquad (2)$$

For each wetland hydrological basin, we estimated the 70%-precipitationsheds, i.e., the area that contributes 70% of the total precipitation in the sink region (Keys et al., 2012). The precipitationshed is delineated based on grid cells ranked from high to low moisture contribution to the sink region, thereby excluding the areas with the weakest contributions of evaporation. An important difference between the wetland hydrological basins and the precipitationsheds is the non-stationarity and the more probabilistic nature of the latter. For instance, moisture flows and atmospheric transport patterns are mainly defined by wind speeds, atmospheric pressure and other atmospheric parameters with vertical as well as horizontal variability (see modelling approaches by Tuinenburg and Staal (2020) and van der Ent (2014). However, Keys et al. (2014) also state that precipitationsheds can be persistent in the long term, allowing the concept to be used to investigate precipitation sources of specific sink regions.

Next, we overlaid the moisture data with the Anthromes Biome Classification and aggregated the volumetric precipitation per land use type to calculate the moisture contribution per land use type within the precipitationshed to the total precipitation in the hydrological basin. The land-sea mask, the biome classification, and the precipitationshed datasets were transposed to the same geographical coordinates for this task.

2.2.5 Land Use Change Impacts

To analyze the impact of land use change on wetland basins, we rerun the moisture tracking with evaporation and precipitation data under current land and a potential vegetation scenario (Table 3). Run 3 utilizes the STEAM evaporation and precipitation for current land use, including irrigation. In contrast, Run 4 explores potential vegetation conditions (Sect. 2.1.2). The outcomes of these runs provide insights into wetland moisture imports under current and potential future land use scenarios, as illustrated in Figure 5.

To compare the potential vegetation and current land use scenarios, we calculated P, $(P - E)$ and ρ_{terr} for both and subtracted the results of the potential vegetation scenario from the results of the current vegetation scenario. This results in negative values indicating a decrease and positive values indicating an increase of P, $(P - E)$ and ρ_{terr} caused by land use changes.

2.2.6 Wetland Vulnerability Classification

We introduced a vulnerability index (VI) to define the wetland's vulnerability to climate and land use change. The index is only meant to account for water availability impacts, meaning that only a decrease in water availability is considered a problem. The VI is based on the dependence of the wetland hydrological basin on terrestrial evaporation to sustain their precipitation and ranges from 0 to 3, where higher values imply a higher vulnerability. It is calculated as follows.

$$VI = [1 - \Delta(P - E)_n] + \left[1 - \left(\Delta(P_{\text{cur}} - E_{\text{cur}}) - \Delta(P_{\text{pv}} - E_{\text{pv}})\right)_n\right] + \rho_{\text{terr}} \tag{3}$$

where $\Delta(P - E)_n$ is the normalized hydroclimatic trend (Sect. 2.2.3), the term $\left(\Delta(P_{\text{cur}} - E_{\text{cur}}) - \Delta(P_{\text{pv}} - E_{\text{pv}})\right)_n$ is the normalized difference of water availability between the potential vegetation and current land use scenarios (Sect. 2.2.5), and n indicates that the values are normalized to be between 0 and 1. Finally, ρ_{terr} is the terrestrial precipitation recycling ratio over the basins (Sect. 2.2.4).

3. Results

3.1 Hydroclimatic Trends

The hydroclimatic trends analysis indicates that surface water availability, here expressed as $P - E$, has decreased in both the hydrological basins and precipitationsheds in Eurasia and the southern half of South America (Fig. 1). On the other hand, it has increased across Africa and the Amazon hydrological basin. Consistent significant trends across hydrological basins and precipitationsheds occur for the wetlands of Dulce in South America, Etangs in Europe, Dalai in Asia and Niger and Sankarani in Africa. From this perspective, the first two are experiencing the largest decreases in water availability among the selected wetlands. We generally find significant $P - E$ trends (Mann-Kendall, $p<0.05$) in 14 hydrological basins and 11 precipitationsheds. For instance, $P - E$ increases significantly in the Bear Park, Tibet, Plaines, Sudd, Niger, Lufira, Sankarani and Everglades wetland hydrological basins, while it decreases in Dalai, Dewey, Dulce, Bananal, Blanco, and Etangs.

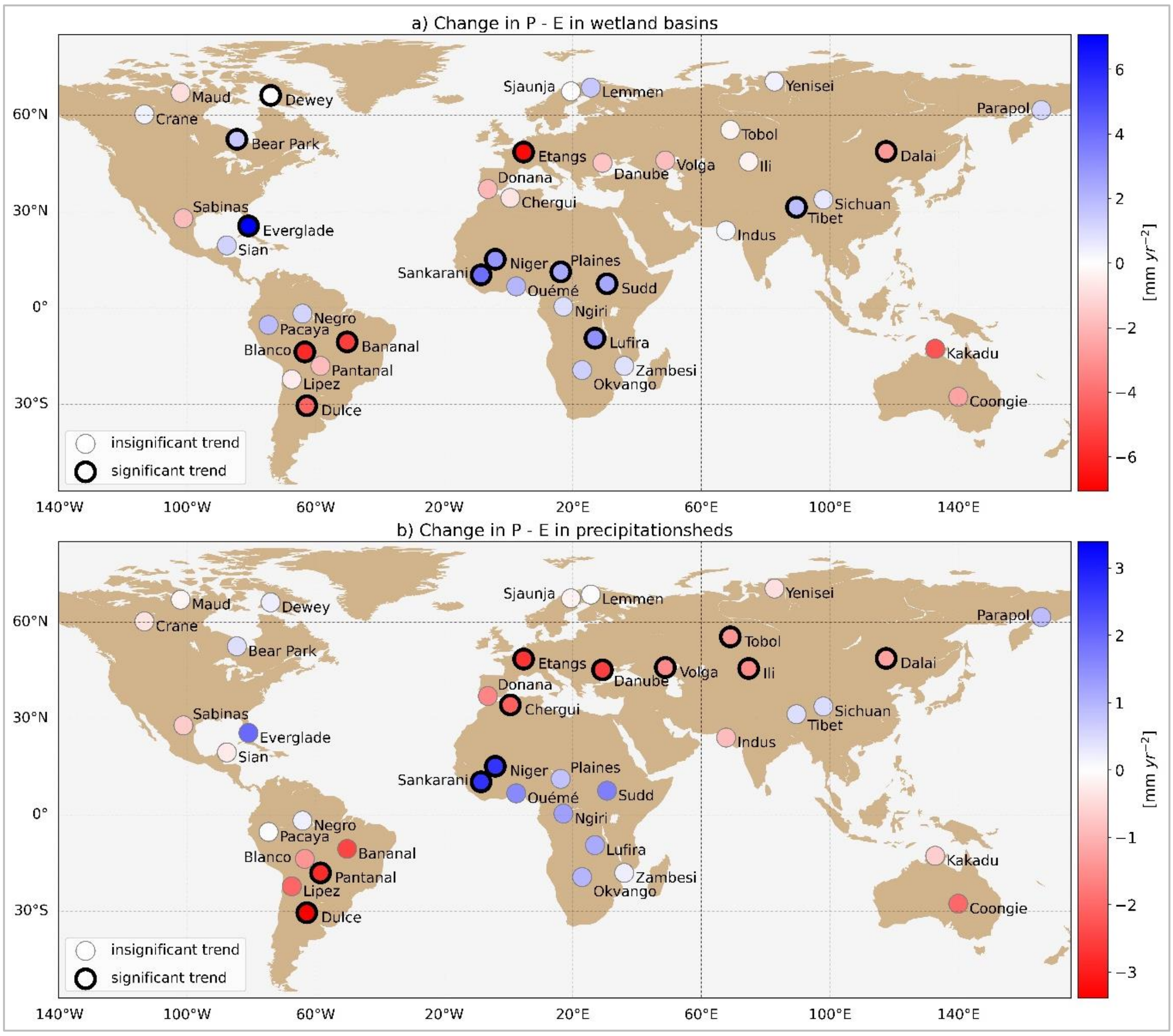

Figure 1: Trends in mean annual precipitation minus evaporation (P-E) in mm/year during the period 1980 – 2020 for the set of ***(a)*** *wetland hydrological basins and* ***(b)*** *their precipitationsheds, calculated from CRU-TSv4.05 precipitation and evaporation using the Mann-Kendall test (Sen-slope). Significant trends (p-value < 0.05) are highlighted with black rings.*

3.2 Upwind Moisture Sources to Precipitation in Wetlands Basins

The upwind areas providing moisture for precipitation in the hydrological basins of the 40 wetlands, termed precipitationsheds, cover a large part of the global terrestrial surface (Fig. 2). Overall, 45% of the area of the precipitationsheds is terrestrial, and 55% oceanic, with their areas often transgressing nation boundaries and covering both oceanic and terrestrial regions. Notably, most of the Northern Atlantic Ocean contributes oceanic evaporation to precipitation in the wetland hydrological basins. For example, while the precipitationshed of the Canadian wetlands covers most of North America, precipitation for the wetlands in Mexico (Sian and Sabinas Nr. 22 and Nr. 23) and the Everglades in Florida (Nr. 33) originate on the Mexican mainland, the coastal Pacific, the Caribbean Sea and the Atlantic Ocean. Furthermore, while the South American wetlands (i.e., Nr. 34 - 40) draw moisture from the South American land surface and the equatorial and subequatorial Atlantic, the African wetlands (e.g., Nr. 2 - 10) receive moisture mainly from Sub-Saharan Africa, the tropical Atlantic Ocean and the oceanic strip along the eastern African coast. Regarding European and West Asian wetlands, there is a considerable overlap of moisture sources, with some depending on moisture from the European land surface and even from parts of the North Atlantic.

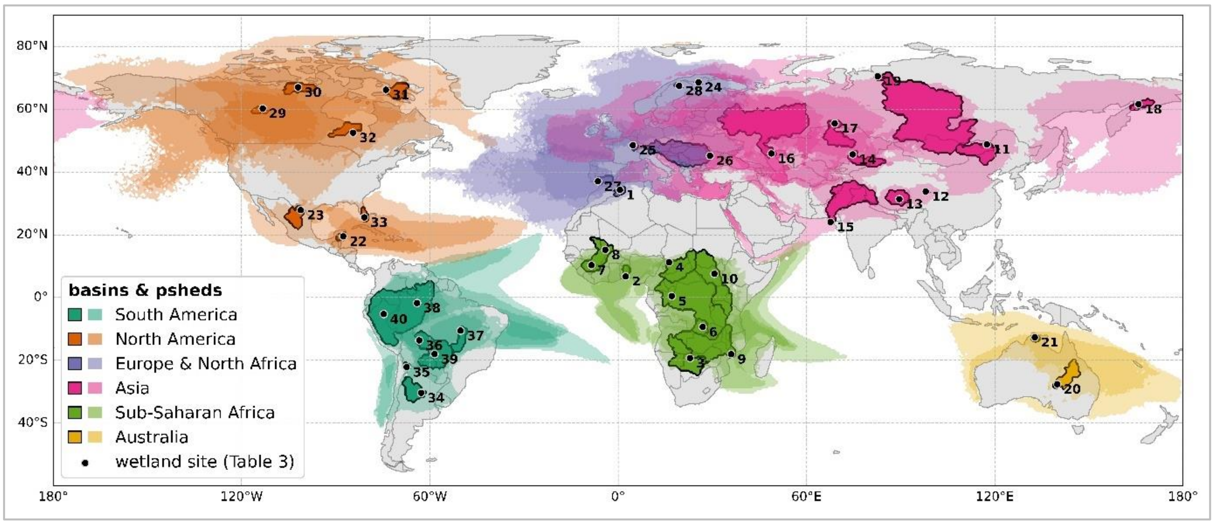

Figure 2: The 70%-precipitationsheds (transparent) and hydrological basins (coloured and black boundaries) of the 40 Ramsar wetlands (black dots), based on the "Base run" using ERA5 reanalysis data (see Table 3). The colour scheme portrays the studied basins and their precipitationsheds in different colours according to their regions to highlight the regionality of the precipitation sources. See Supplementary Materials for a more detailed mapping of hotspot wetlands.

Generally, wetlands with higher terrestrial precipitation recycling ratios are concentrated in Africa, South America, and Asia, ranging from 27% (Chergui) to 98% (Sichuan) (Fig. 3a). For 23 of the 26 studied wetlands in Africa, South America and Asia, more than half of their precipitation originates from land evaporation. Terrestrial precipitation recycling ratios below 50% are only found in the hydrological basins of Chergui in Africa, Parapol in Asia, and Negro in South America. Conversely, low terrestrial precipitation recycling ratios are found in wetland basins around the Caribbean and Mediterranean Seas and Australia. Regarding internal precipitation recycling, most wetland hydrological basins in North America, Australia and Europe have ratios below 5%, except for that of the Sabinas wetland in Mexico and the Danube delta in Romania, with 8% and 17%, respectively (Fig. 3b). The wetland hydrological basins in Asia exhibit ratios ranging from 2% (Sichuan) to 27% (Tibet), suggesting that at most a quarter of the moisture can originate within the wetland hydrological basin. Finally, there appears to be no particular correlation between internal and terrestrial precipitation ratios across the set of wetlands.

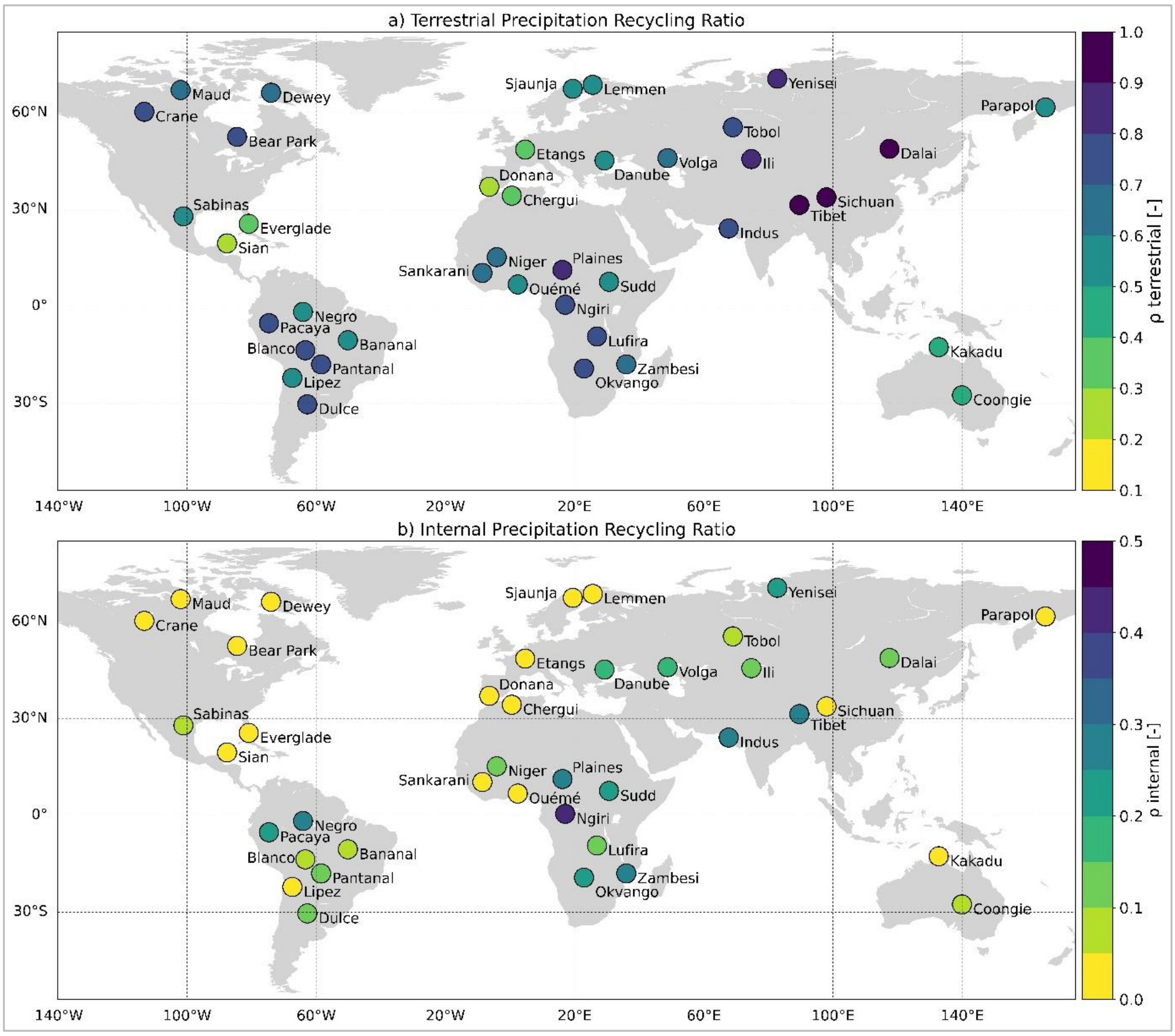

*Figure 3: **a)** Terrestrial (ρ_{terr}) and **b)** internal (ρ_{int}) precipitation recycling ratios for the studied wetland hydrological basins calculated from UTrack backtracking and using Equations 1 and 2, based on the "Base run" using the ERA5 reanalysis data (see Table 3).*

Regarding the source of moisture for the hydrological basins of these Ramsar wetlands, rangelands are the main upwind contributor of moisture (via evaporation) to precipitation across the set of wetland hydrological basins (Fig. 4). Woodlands, rainfed cropland and barren lands follow in their magnitude of contribution. It is also worth noting that for some wetlands, such as those of the Indus, evaporation from rice and irrigated cropland can contribute up to 20% of annual precipitation. On the other hand, the contribution of evaporation from dense settlements is negligible. Interestingly, the wetlands with the largest percentage of woodlands over their precipitationsheds, Pacaya, Negro and Blanco in South America, contribute the largest volumetric moisture supply by evaporation as a percentage of total precipitation per year.

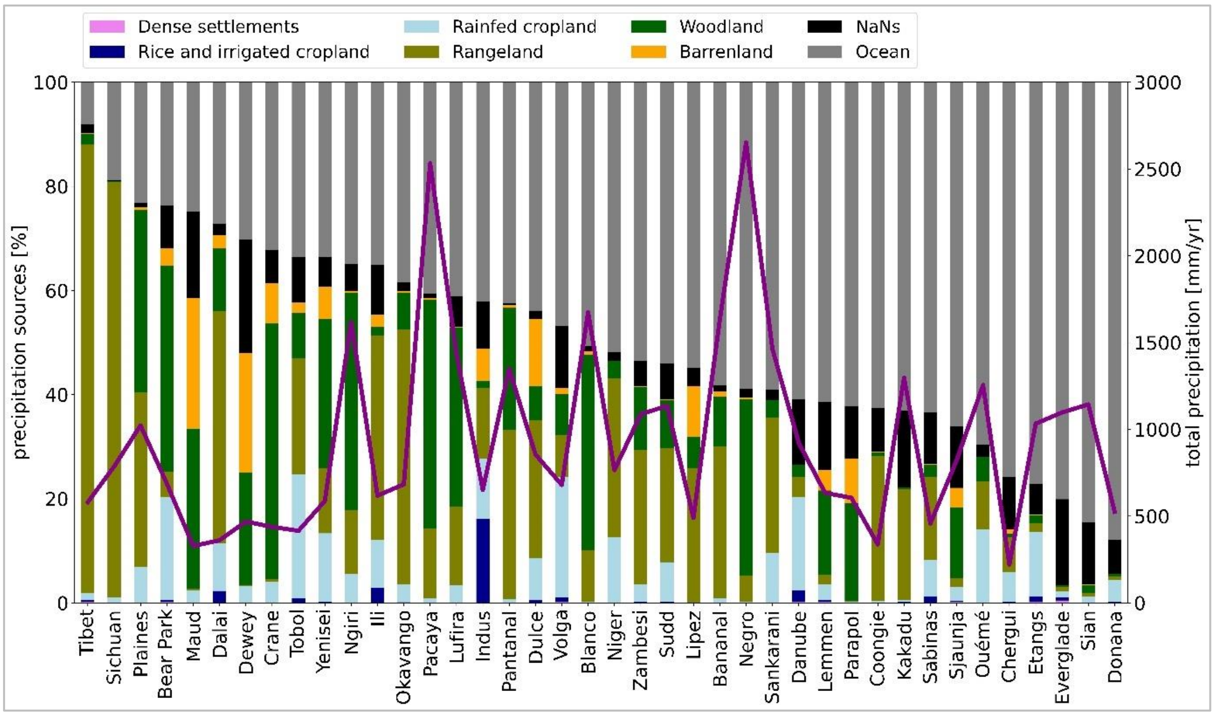

Figure 4: Origin of moisture supply to the wetlands' hydrological basins. Land use contributions of volumetric moisture supply by evaporation, in % of total precipitation per year (left axis and bar plots) and total precipitation to the hydrological basin in mm/yr (right axis and red line). Wetlands are sorted based on the volume of terrestrial precipitation recycling, and the LC classification is run using ERA5 reanalysis data and the Anthromes classification (see Table 3).

3.3 Land Use Change Impacts on Wetland Precipitation and Runoff

The conversion from the potential to the current land cover has resulted in a decrease in precipitation from terrestrial resources (Fig. 5a), accompanied by a similar decrease in terrestrial precipitation recycling ratios (Fig. 5c) for the case of the wetlands in Europe (e.g., Etangs, Danube, Volga), East Asia and South America (e.g., Pantanal, Blanco). The decrease in total precipitation from converting potential vegetation to current land use is more pronounced for Central Africa and Asia wetlands, such as the Indus, Tibet, Niger and Plaines.

Notably, for 18 of the wetlands, the change in precipitation is accompanied by an opposite change in *P-E* (Fig. 5). Change from potential to current land use decreased precipitation and increased *P-E* in most of the hydrological basins (Fig. 5a & b). On the other hand, the largest precipitation increase occurred for the Indus wetland hydrological basin, gaining ~18 mm/yr or a 3% increase in total precipitation. On the other hand, the most significant decrease in *P* occurred in the Danube wetland, the wetland hydrological basin where the most substantial reductions in terrestrial recycling have also occurred (Fig. 5c). The hydrological basins of Sjaunja, Coongie, Lipez, Yenisei, Sian, Lemmen, Negro experienced a decrease in total *P* and *P-E* while Chergui, Sankarani, Niger, Sabinas, Plaines, Ili Tibet and Sichuan present increases in both.

Overall, precipitation over the wetland hydrological basins is affected by land use change, with only six wetlands presenting negligible precipitation changes. However, the relationship between total precipitation and terrestrial changes does not apply to all hydrological basins. Sankarani, for example, shows a decrease in terrestrial precipitation and runoff but a slight increase in the terrestrial precipitation recycling ratio.

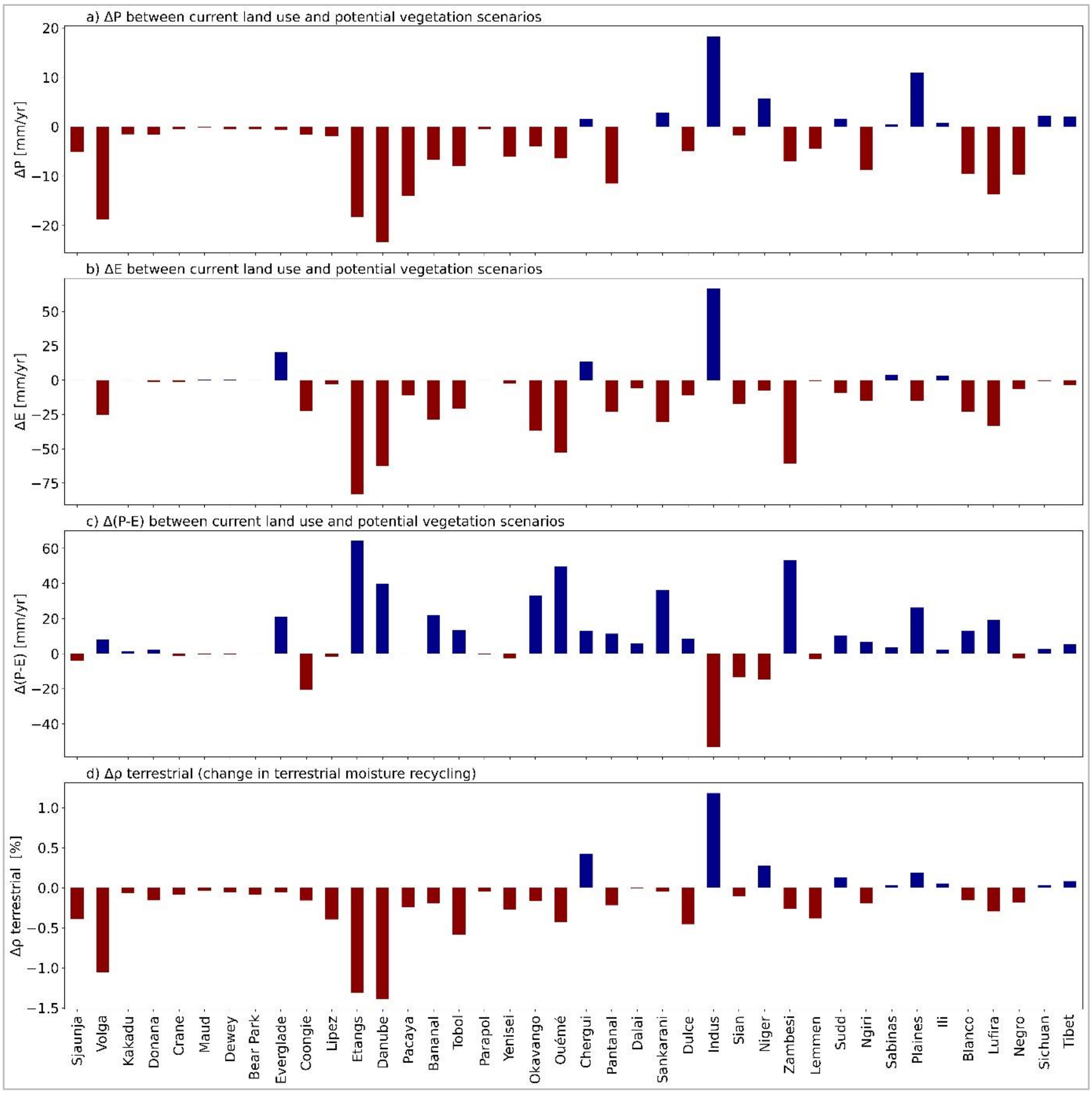

Figure 5: Differences in (a) precipitation (ΔP), (b) evaporation (ΔE), (c) Δ(P-E) and (d) terrestrial recycling ($\Delta\rho_{terr}$) assuming changes from potential vegetation to current land use for each wetland hydrological basin and based on the "STEAM current and potential LC runs" using STEAM evaporation and precipitation based on current and potential land cover (see Table 3).

3.4 Wetland Vulnerability

We assume that the moisture supply of wetlands is vulnerable to upwind land use and water scarcity when: 1) there is a recent decreasing trend in *P-E* in their hydrological basins and precipitationsheds, 2) their hydrological basins have high terrestrial precipitation recycling ratios and when subject to 3) decreasing *P-E* resulting from upwind conversion to current land use. The resulting ranking of vulnerability for all wetlands in Table 4 shows that the most vulnerable wetlands are in Central Asia and South America, with other considerable cases found in Europe (e.g., Danube and Etangs) and Africa (e.g., Ouémé). The moisture supply of many of these relies on evaporation from high-intensity farming lands (e.g., Danube, Volga, Etangs) or high-evaporation tropical ecosystems such as Amazon and Central Africa (Dulce, Pantanal, Ouémé). The precipitationsheds of the first eight 'hotspot' wetlands can be seen in Supplementary Figure S5). On the other hand, the wetlands at the bottom of the table with low *VI* indexes become the most resilient to upwind land use and climatic changes, as they have their terrestrial moisture recycling ratios are low, with most upwind moisture originating in the oceans, have not experienced a recent decrease in $P - E$ and land conversion has not resulted in a large change in $P - E$.

Table 4: Wetland upwind moisture vulnerability index (VI; (min: 0, max: orange)) based on 1980-2020 data. The table includes Sub-indicator 1; the trend in P- E (Sen-slope; min: red, 0:white, max: blue) calculated with CRU-TS v4.05; Sub-indicator 2; the trend of P–E change between the potential vegetation and current land use ($\Delta(P\text{-}E)_{cur-pv}$; min: red, 0:white, max: blue) based on land use scenario outputs of STEAM - WAM-2layers (Wang-Erlandsson et al., 2018); and Sub-indicator 3; the terrestrial precipitation recycling ratio based of base run using ERA5 reanalysis (ρ_{terr}: 0:white, 1:green).

			Sub-indicator 1	***Sub-indicator 2***	***Sub-indicator 3***	***Vulnerability Indicator***
Continent	**Name**	**Ramsar ID**	$(P\text{-}E)_{trend}$ 1980-2020 [mm/yr] (CRU-TS v4.05)	$(P\text{-}E)_{cur} - (P\text{-}E)_{pv}$ [mm/yr] (STEAM – WAM-2layers Output)	ρ_{terr} (ERA5)	***VI***
Africa	Chergui	1052	-2.1	13.1	0.3	1.6
	Plaines	1839	0.8	26.2	0.9	1.5
	Ngiri	1742	1.3	6.6	0.7	1.4
	Lufira	2318	1.1	19.3	0.7	1.4
	Niger	1365	2.7	-14.6	0.6	1.3
	Okavango	879	1.0	33.0	0.7	1.3
	Sudd	1622	1.7	10.5	0.5	1.2
	Zambesi	1391	0.2	53.2	0.6	1.1
	Ouémé	1018	1.6	49.6	0.5	0.9
	Sankarani	1167	2.7	36.3	0.6	0.8
Asia	Indus	1284	-0.9	-53.0	0.8	2.4
	Dalai	1146	-1.2	5.9	1.0	2.1
	Ili	2020	-1.5	2.4	0.9	2.1
	Yenisei	698	-0.4	-2.8	0.8	1.9
	Sichuan	2348	0.5	2.9	1.0	1.9
	Tobol	679	-1.4	13.6	0.8	1.9
	Tibet	2352	0.4	5.4	1.0	1.8
	Volga	111	-1.5	8.2	0.6	1.8
	Parapol	693	0.9	-0.2	0.5	1.3
Australia	Coongie	376	-2.0	-20.5	0.3	1.8
	Kakadu	204	-0.6	1.4	0.3	1.4
Europe	Danube	521	-2.5	39.8	0.5	1.6
	Lemmen	1521	0.1	-3.0	0.5	1.5
	Sjaunja	32	-0.1	-3.9	0.5	1.5
	Doñana	234	-1.6	2.1	0.2	1.4
	Etangs	514	-2.7	64.3	0.3	1.2
North America	Crane	240	-0.4	-1.2	0.7	1.7
	Maud	246	-0.1	-0.3	0.7	1.7
	Bear Park	360	0.4	0.2	0.7	1.7
	Dewey	249	0.2	-0.6	0.7	1.6
	Sabinas	1769	-0.7	3.5	0.4	1.5
	Sian	1329	-0.3	-13.4	0.2	1.3
	Everglade	374	2.0	21.0	0.2	0.7
South America	Dulce	1176	-3.4	8.3	0.7	2.2
	Pantanal	1089	-2.8	11.4	0.8	2.1
	Lipez	489	-2.0	-1.6	0.5	1.8
	Blanco	2092	-1.4	13.2	0.7	1.8
	Bananal	624	-2.5	22.1	0.5	1.7
	Pacaya	546	0.03	0.04	0.7	1.7
	Negro	2335	0.2	-2.6	0.5	1.5

4. Discussion

The subsequent three sections discuss the results with a focus on terrestrial precipitation recycling (Sect. 4.1), land use change and hydroclimatic changes (Sect. 4.2) and lastly, the limitations of this study (Sect. 4.3).

4.1 Terrestrial Precipitation Recycling

Wetland basins with high terrestrial precipitation recycling ratios are mostly found in Central Asia, South America, Sub-Saharan Africa and northern Canada. Part of these clusters can be explained by mountain ranges or general wind patterns. Mountain Ranges like the Andes, the Tibetan Plateau and the Great Rift Valley can trap moisture on continents or shield them from the oceans (van der Ent, 2014). For instance, the orographic effect explains the higher terrestrial precipitation recycling in the hydrological basins closer to the East side of the Andes. Conversely, the hydrological basins further away from the Andes or on its West side have slightly lower terrestrial precipitation recycling ratios. The Tibetan Plateau also keeps moisture over the continent, as seen in the wetland hydrological basins in Tibet and China, which show the highest terrestrial recycling in this study. In Africa, the Great Rift prevents moisture from entering the Indian Ocean in the East (van der Ent, 2014), explaining the high terrestrial recycling in its West. Generally, most tropical continental wetlands also show terrestrial recycling ratios above 50%, since faster water cycles associated with shorter distances of atmospheric transport tend to favour higher moisture recycling rates (van der Ent & Savenije, 2011; van der Ent et al., 2014).

Wetland basins with low recycling ratios are mostly found in dry and coastal hydrological basins around the Gulf of Mexico, Europe, and Australia. In these areas, much of the precipitation stems from evaporation over nearby oceans. For example, the hydrological basins in Florida and Mexico are almost surrounded by oceans and mainly depend on evaporation from the Pacific, Gulf of Mexico, Atlantic and Caribbean to sustain their precipitation. The hydrological basins in Europe and Northern Africa also strongly rely on moisture from the Atlantic Ocean, with precipitationsheds reaching far over the Northern Atlantic. The two Australian hydrological basins are also largely dependent on precipitation from the oceans surrounding the Australian continent.

A combination of a high terrestrial and low internal precipitation recycling ratio implies a higher vulnerability of basin water availability to land use change. High internal precipitation recycling ratios do not make a difference to the vulnerability of mean annual water availability (P - E) to land use changes since any land use-related changes in basin evaporation and the subsequent changes in basin precipitation through internal precipitation recycling are of equal magnitude. For some wetland hydrological basins, there is no correlation between terrestrial precipitation recycling and internal basin recycling (e.g., Sichuan and Crane; Fig. 3). However, the hydrological basin area and the internal recycling ratio are indeed strongly correlated. The largest wetland hydrological basins are usually the hydrological basins of wetlands located in the lower part of major river hydrological basins, such as delta wetlands (e.g. Yenisei, Zambesi and Indus) and floodplain wetlands (e.g. Negro, Ngiri, Plaines), which have the highest internal recycling ratios. This makes them less vulnerable to land use changes in terms of their runoff (P - E) since possible precipitation and evaporation changes coincide when considering the simplest version of the water balance ($Q = P - E$). When E changes, P is assumed to change similarly which would result in little to no change in runoff, respectively. Like the two headwater basins (Sichuan and Lipez), hydrological basins with high terrestrial recycling and low internal recycling strongly depend on terrestrial evaporation from outside their hydrological basin, suggesting that upwind changes in climatic conditions and land use may affect moisture supply to these hydrological basins. Here, the implications of such land-atmosphere feedback may be less direct than those caused by local changes in the hydrological basins.

4.2 Land Use and Hydroclimatic Change

Background climate variation alone can explain wetland water availability to some degree due to the strong influence of Earth's surface air temperatures and precipitation on surface water (Osland et al., 2016; Stagg et al., 2019; Woolway et al., 2020). Nevertheless, the dominant influence of anthropogenic activities cannot be discarded (Wine & Davison, 2019). The current and potential land and vegetation cover in the precipitation areas shed light on the likelihood of potential land use changes and their implications for wetland moisture supply. For instance, if the precipitationshed of a wetland is covered by wooded vegetation that may eventually be converted to cropland or other short vegetation types, then this constitutes a potential vulnerability. In precipitationsheds occupied by croplands and rangelands, negative human impacts on wetland moisture supply have already occurred and part of the vulnerability is realized. However, further degradation to barren landscapes is still possible. To reduce the vulnerability of many of the studied wetlands, prevention of further degradations of human-dominated landscapes is most relevant, since rangelands, woodlands and agricultural lands contribute the most as precipitation sources (in terms of volume of evaporation).

Rangelands are an important precipitation source for the wetland hydrological basins in Australia, Central and East Asia (Tibet, China, Mongolia) and the wetlands whose hydrological basins fall outside of tropical Africa and South America. In addition, the conversion of tall vegetation to rangelands may inflict additional changes in evaporation (Milton & Siegfried, 1994). Hence, areas where rangelands are expanding or degrading run the risk of causing local and downwind precipitation changes (Keys et al., 2012).

Woodlands are critical for the moisture supply to the wetlands of northern Asia, Europe and Canada and some tropical wetlands in Sub-Saharan Africa and South America. The Crane, Maud, Plaines, Yenisei, Nigri, Pacaya and Negro wetlands would be vulnerable to potential vegetation changes as the current moisture supply relies heavily on forests. These forests are now experiencing high deforestation rates, which could jeopardize, to some extent, such moisture supply. On the other hand, although Tibet and Sichuan wetlands have a large volume of precipitation from terrestrial sources, most come from rangelands, which are already transformed by human activities, or at least the corresponding change in evaporation rates would not be as high as when forests are involved (Sterling et al., 2013).

In this sense, deforestation decreases evaporation, leading to positive drought feedbacks downwind (van der Ent, 2014; Staal et al., 2020). For instance, Staal et al. (2020) show the effect of deforestation on precipitation over the Amazon hydrological basin, where deforestation is one of the main pressures on the rainforest. Whereas they have shown a decrease in precipitation, mainly in the West of the hydrological basin, their findings suggest that climate change seems to be the main driver of drying in the Amazon hydrological basin. Our study shows strong precipitation changes in the Amazon wetland basins, Negro and Pacaya but only little to no changes in the runoff in these basins (Sects. 3.3 & 3.4).

This century is projected to see intense population growth and urban and agricultural expansions globally, with the highest increases in tropical regions (Laurance et al., 2014). The expansion of rainfed agriculture can be associated with decreasing (Wang-Erlandsson et al., 2018) or increasing evaporation (Jaramillo et al., 2013), depending on the original land cover and the regional hydroclimate. Our results suggest that rainfed agriculture expansions have already affected moisture supply to wetland hydrological basins in Canada, Africa, Asia and Europe, and conversely, irrigation has affected the Indus wetlands.

4.3 Limitations, opportunities and uncertainty

Wetland water availability is influenced by the drivers, like upwind moisture supply, climate variability and extremes (such as droughts, hurricanes and typhoons), anthropogenic climate change and anthropogenic pressures (e.g. infrastructure development, irrigation, flow regulation for energy, flood control, etc). Differentiating these drivers is daunting due to the many drivers involved and the heterogeneity of wetlands worldwide (Åhlén et al., 2021; Ghajarnia et al., 2020; Thorslund et al., 2017). Several studies have tried to disentangle and separate individual drivers' effects; however, they have remained case-specific due to the reliance on limited data on wetland water availability (e.g., Buytaert & Beven, 2011; Gao et al., 2011; Hattermann et al., 2008)). Therefore, combining our moisture tracking assessment, which considers upwind moisture supply, with these more in-situ effects into an overall vulnerability assessment, although convenient, is not yet possible at the spatial scales and variety of wetlands used in this study.

The two moisture tracking models, UTrack and WAM-2layers, which represent the state of the art, though are known to produce slightly different moisture source estimations. Presumably due to differences in the numerical methods and the vertical and spatial scales of the two models, mean annual terrestrial moisture recycling estimations by WAM2-layers, on average, exceed those estimated by UTrack by 5.4 ± 0.1% across the tropics (Cropper et al., 2021). For example, a comparison of country-scale mean annual terrestrial moisture recycling estimates between Dirmeyer et al. (2009) using the 3D-QIBT method and Link et al. (2020) using WAM-2layers shows, for example, a total difference of 20% for the Central African Republic, 28% for Paraguay and 2% for Portugal. Link et al. (2020) assume these differences could be caused by a false routing assumption in Dirmeyer et al. (2009), where too little land precipitation is routed to runoff and evaporates instead. Fully coupled Earth System Models (ESMs) also inherit such uncertainties, shown by differences in the estimation of precipitation across models (Aloysius et al., 2016) and in the divergence in their predictions of land use change impacts on precipitation (Pitman et al., 2012; Vetter et al., 2015). Studies like Harrington et al. (2023) use the Community Earth System Model (CESM) to study regional moisture contributions to precipitation in North America and acknowledge that land moisture flows can be underestimated due to biases in the model's internal generation of evaporation. The moisture recycling community is now addressing such uncertainties between moisture tracking models, including ESMs, in a model intercomparison project initiated by Benedict et al. (2023) (for further Information, see: https://sites.google.com/view/imrrn/home).

In addition, studies have shown that different data inputs can lead to different moisture source estimations (e.g., Horan et al. (2023), Keys et al. (2014), Yang et al. (2023)). In this study, the moisture source estimations (first two model runs) and the LUC impact could be over- or underestimated in certain basins, depending on the wet or dry bias in the underlying data input of the ERA5 reanalysis data and the STEAM - WAM-2layers coupling performed in Wang-Erlandsson et al. (2018). This could stem from known wet bias in ERA-Interim precipitation across the tropics, especially in Central Africa and a dry bias over the continents in the Northern Hemisphere (Hassler & Lauer, 2021). Additionally, the first two model runs establishing the moisture sources of the wetland basins could include an overestimation in specific precipitation source areas, especially for the tropical basins (e.g. Ngiri, Negro) and those receiving moisture from Central Asia (e.g., Volga, Ili) due to a wet bias in the ERA5 reanalysis data. This is a challenge for many moisture recycling studies. For instance, Yang et al. (2023) studied the moisture sources of the Great Lakes Region in North America using the Dynamic Recycling Model (DRM), where they forced the model with different reanalysis datasets, namely NARR, MERRA-2, NCEP final analysis, and ERA5, compare the results with each other but also to observational precipitation and evaporation datasets. Their analysis shows that results from the forcing with NARR differ greatly from those obtained with the other three reanalysis datasets, leading them to suspect a water imbalance in the NARR dataset. While the other three perform reasonably well, they find MERRA-2 to be the most consistent with observational datasets in the studied area. However, studies like Hassler & Lauer (2021) also find a 4% and 23% smaller bias in estimating precipitation across the tropics for ERA5 compared to MERRA-2 and JRA-55, respectively. The UTrack climatology is generated with ERA5 reanalysis data, and for consistency, we chose to use ERA5 evaporation and precipitation to establish the moisture sources and terrestrial recycling indices in this study. While confidence in ERA5 precipitation appears to be highest outside the tropics, including Central Europe, China, and the South Asian Monsoon region (Hassler & Lauer, 2021; Jiao et al., 2021; Lavers et al., 2022), precipitation in the tropics although improved from ERA-Interim, still shows some errors, such as a wet bias and underestimations of low-intensity events (Gleixner et al., 2020; Lavers et al., 2022). Land evaporation in the ERA5 reanalysis dataset can include overestimations across Central Asia, parts of the Middle East, Australia, and along the West Coast of South America in comparison to two other datasets (GLDAS2, MERRA-2) (Lu et al., 2021).

The contextual relevance of the conclusions may change in the context of climate change, as moisture flows and atmospheric circulation undergo alterations, including an increasing importance of moisture flows from the oceans (Findell et al., 2019). Climate change can be the cause of changes in atmospheric conditions (e.g. circulation changes). For example, the Hadley Circulation expansion has already been studied extensively (Hu et al., 2018), and a shift of the mid-latitude jets towards the poles is predicted under ongoing climate change (Osman et al., 2021). The atmospheric moisture flow dataset used in this study is based on UTrack global computations and hourly atmospheric input data from 2008 to 2017, but is then aggregated to multi-annual monthly means and is also forced with averaged evaporation and precipitation data. Therefore, the potential effects of climate as well as land use change on local land-atmosphere coupling and atmospheric circulation are not addressed in this study. It is important to note that this study specifically considers the influence of land use change on precipitation, taking into consideration the effects of moisture recycling. Since average global annual moisture recycling estimates are predicted to decrease by 2-3% per degree of global warming (Findell et al., 2019), our conclusions are likely to be also relevant under climate change.

The overall implications of downwind LUC on wetland water availability are still relevant, especially for assessing a general vulnerability of wetlands due to core moisture source regions, as Keys et al. (2014) established. Their core precipitationshed concept emphasizes the persistence of sources of evaporation. It reinforces the idea that because of the static moisture flows taken from the UTrack dataset (Tuinenburg et al., 2020), differences in the input data (P, E) are just being translated proportionally to the magnitude of the difference. Therefore, we argue that studies, such as this one, combining static moisture trajectories with evaporation and precipitation data across various land use change (LUC) scenarios, should be viewed as potential LUC impacts within the uncertainties of the applied datasets and scenario estimations. It is essential to recognize that the derived impacts are primarily linked back to downwind moisture recycling effects. We acknowledge that the STEAM – WAM-2layers datasets from Wang-Erlandsson et al. (2018) are generated with ERA-I atmospheric forcing data from 2000 to 2013 and land use classifications from 2005, which are not precisely the period of analysis used for the UTrack dataset (2008 – 2017) and to develop the vulnerability index (1980-2020). However, interannual variability in moisture sources can mainly be traced back to a "pulsating" change in moisture source intensity within a core part of the precipitationshed (Keys et al., 2014), which leads us to contend that such a shift in the timeframe should not influence the results drastically.

5. Conclusion

We have assessed the vulnerability of the selected wetland basins to upwind land use change and accounted for the associated precipitation impacts through moisture recycling. For 30 of the 40 wetland hydrological basins, terrestrial sources contribute to at least half of the total annual precipitation. The lowest terrestrial precipitation recycling ratios are found in coastal wetland basins, where moisture mostly comes from the oceans. Although these wetland basins have a lower dependency on continental evaporation to sustain their precipitation, they still get at least parts (17 – 23%) of their total annual precipitation from land evaporation. Most precipitation in the sink regions comes from evaporation sources close to the sink but does not necessarily overlap with the sink area.

So far, the hydrological basins with the most substantial impact of land use changes on their precipitation and runoff are located in tropical and sub-tropical areas or where much land use has been converted to croplands. Water availability in all of these hydrological basins has been affected by changes in land use. As shown in the hydroclimatic trend analyses, many of the wetland hydrological basins are likely also affected by climatic change.

This study shows that wetlands in South America and Central Asia can be seen as vulnerable to the combined impacts of climatic changes and the effects of land use changes on their precipitation and runoff, here assumed as *P* - *E*. This is presented in the identified 'hotspot' wetlands, where a decrease in runoff and precipitation caused by land use and climatic change can be observed.

This study highlights that land use changes outside basins can impact wetland basins' moisture recycling and precipitation patterns. Differentiating drivers for water availability change in wetlands is also daunting due to the many drivers involved and the heterogeneity of wetlands worldwide (Åhlén et al., 2021; Ghajarnia et al., 2020; Thorslund et al., 2017). Hitherto, driver analyses do not account for the role of upwind land use change for water availability changes in wetlands. Here, we show that precipitationshed analyses have the potential to contribute to a more complete understanding of drivers of wetland threats. However, more in-depth studies of such highlighted vulnerability hotspots using high-resolution time-series data of the source-to-sink moisture flows are needed to understand further wetland moisture recycling dynamics and, more broadly, all water-dependent ecosystems.

Open Research

All data used for this research are publicly available, and their sources are indicated and referenced in the Data section of this study. The wetland delineations can be accessed through the Ramsar Convention on Wetlands (2016) and Zhang et al. (2017). The digital elevation models for the basin delineations can be accessed through EU-DEM (European Environment Agency (EEA), 2015), SRTM (Jarvis et al., 2008), DEM3: (De Ferranti, 2011) and CDED (Canada's Natural Resources, 2015). Anthrome data can be accessed at (Ellis et al., 2013). The hydrometeorological data (evaporation and precipitation) can be accessed through ERA5 Reanalysis (European Centre for Mid-Range Weather Forecasting (ECMWF), 2019; Hersbach et al., 2020), CRU-TSv4.5 (University of East Anglia Climatic Research Unit et al., 2021), UTrack moisture flow database (Tuinenburg et al., 2020). The STEAM evaporation and precipitation data from Wang-Erlandsson et al. (2018) can be accessed through Zenodo (Wang-Erlandsson et al., 2023). The figures and maps were generated using the Matplotlib library (Caswell et al., 2022), including the Basemap Matplotlib Toolkit and Cartopy to create 2D maps. The datasets of the Ramsar wetland basin delineations and the forward and backward atmospheric moisture flows generated in this research are available on Zenodo at Fahrländer et al. (2023). Finally, the Python scripts used for processing the moisture flows are available on GitHub under the MIT licence (https://github.com/sifa4152/utrack_dataset_wetland_processing.git).

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