Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-494
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 25 August 2017

Hydrology and Earth System Sciences
Open Access
Discussions

Remote land use impacts on river flows through atmospheric teleconnections

Lan Wang-Erlandsson[1,4], Ingo Fetzer[1], Patrick W. Keys[2,1], Ruud J. van der Ent[3], Hubert H. G. Savenije[4], and Line J. Gordon[1]

[1]Stockholm Resilience Centre, Stockholm University, Kräftriket 2B, 104 05, Stockholm, Sweden
[2]School of Global Environmental Sustainability, Colorado State University, Fort Collins, CO 80523, USA
[3]Department of Physical Geography, Faculty of Geosciences, Utrecht University, P.O. Box 80.115, 3508 TC Utrecht, The Netherlands
[4]Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, PO box 5048, 2600 GA Delft, The Netherlands

Correspondence to: Lan Wang-Erlandsson (lan.wang@su.se)

Abstract. The effects of land-use change on river flows have usually been explained by changes within a river basin. However, land-atmosphere feedback such as moisture recycling can link local land-use change to modifications of remote precipitation, with further knock-on effects on distant river flows. Here, we look at river flow changes caused by both land-use change and water use within the basin, as well as modifications of imported and exported atmospheric moisture. We show that in some of the world's largest basins, precipitation was influenced stronger by land-use change occurring outside than inside the basin. Moreover, river flows in several non-transboundary basins was considerably regulated by land-use changes in foreign countries. We conclude that regional patterns of land-use change and moisture recycling are important to consider in explaining runoff change, integrating land and water management, and informing water governance.

1 Introduction

River flows (Q) are fundamental for ecosystems, nutrient transport, hydropower, navigation, and human well-being (Oki and Kanae, 2006). Land-use change (LUC) has been suggested to be the most important driver of both past (Piao et al., 2007; Sterling et al., 2012) and future (Betts et al., 2015; Milly et al., 2005) changes in river flows (ΔQ). Central to the analysis of Q is the river basin unit, and estimates of ΔQ from LUC often assume that impacts occur exclusively within a basin (Gerten et al., 2008; Piao et al., 2007; Rost et al., 2008a, b; Sterling et al., 2012). Water governance is strongly focused on frameworks such as the Integrated River Basin Management (IWRM) and largely assumes that there is no land-atmosphere feedback, even in discussions of spatial misfit between institutions and hydrological realities (Hoekstra, 2010; Giordano et al., 2015). In fact, land-atmosphere feedbacks are not incorporated in most recent literature on a wide range of topics of relevance for water management, such as virtual water (Dalin et al., 2017), the freshwater planetary boundary (Rockström et al., 2009; Steffen et al., 2015), water scarcity (Mekonnen and Hoekstra, 2016), relative role of climate and LUC for water flows (Zheng et al., 2016), and land acquisition impacts on water (Johansson et al., 2016; Rulli et al., 2012).

However, studies on land-atmosphere interactions clearly shows that changes in land surface properties can considerably influence precipitation (P) and Q through land-atmosphere feedback, sometimes well beyond the local scale (Badger and Dirmeyer, 2016; Garcia et al., 2016; Avissar and Werth, 2005). For example, general circulation model simulations suggest that complete deforestation of Central Africa may decrease February P by 35 % in the Great Lakes region (Avissar and Werth, 2005), and irrigation in India may support up to 40 % of the P in some arid regions in Eastern Africa (de Vrese et al., 2016). Under a business-as-usual deforestation scenario, Q in the Xingu river basin in the Amazon was found to increase by 10-12 % without land-atmosphere feedback, and decrease by 30-36 % when such feedback was taken into account (Stickler et al., 2013). Furthermore, statistical analyses of observed data suggests that irrigation in the US high plains enhances downwind Q (Kustu et al., 2011) and coupled regional climate modeling shows that irrigation in the California Central Valley can be linked to about 30 % increase in Colorado Q (Lo and Famiglietti, 2013). At the global scale, ΔQ from future climate and LUC scenarios changed from decrease to increase by considering land-atmosphere feedback and by closing the water balance (Arnell and Lloyd-Hughes, 2012; Betts et al., 2015).

Land-atmosphere interactions can influence Q through thermal layer processes, terrestrial moisture recycling (TMR), and circulation perturbation (Goessling and Reick, 2011). First, thermal layer processes refer to the boundary layer and mesoscale circulation perturbation that may lead to a change in total terrestrial evaporation (E) and can locally lead to both positive and negative P responses (Guillod et al., 2015; Seneviratne et al., 2010; Koster et al., 2003). Local forest clearing has for example been shown to enhance P in downwind areas due to turbulence changes (Khanna et al., 2017; Saad et al., 2010). Second, TMR refers to the process of terrestrial E returning to land as P and is underpinned by the mass conservation of water (Brubaker et al., 1993). TMR is often the dominating land-atmosphere process at the regional to continental scale (D'Almeida et al., 2007; Spracklen et al., 2012; Lawrence and Vandecar, 2014; Tuinenburg, 2013). About 40 % of global terrestrial P (van der Ent et al., 2014) originates from terrestrial E and the average distance traveled in the atmosphere is 500-5000 km (van der Ent and Savenije, 2011) – a distance likely to exceed the size of most river basins. Lastly, large-scale atmospheric circulation perturbation allow extreme LUC (e.g., complete tropical deforestation) to impact P in geographically remote regions and continents in unexpected ways (Avissar and Werth, 2005; Badger and Dirmeyer, 2016; Garcia et al., 2016; Lawrence and Vandecar, 2014). Monsoon regions are particularly sensitive to circulation perturbation, and irrigation may for example reduce P by weakening the monsoon onset (Tuinenburg, 2013).

The previous studies that illustrated the importance of remote LUC for basin P and Q, did not systematically assess global effects of LUC on Q, or explore the interplay between LUC within and outside the river basin. These effects are important to disentangle since they can have profound water governance implications (for e.g., riparian water rights and transboundary river basin treaties). While there has been discussions of governance implications of land-atmosphere interactions purely based on atmospheric moisture fluxes between nation states (Keys et al., 2017; Dirmeyer et al., 2009; Ellison et al., 2017), no studies have quantified the magnitude of LUC impacts on P or Q, despite its high relevance for international water law and governance. Thus, there is a missing interdisciplinary bridge between understanding the role of land-atmosphere feedback over large distances and its importance for water governance at the basin scale.

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This study aims to (*i*) investigate the potential impacts of human LUC on Q worldwide accounting for TMR, (*ii*) disentangle the relative influence on Q from within- and extra-basin LUC, (*iii*) attribute potential human LUC impacts on Q to nation states, and (*iv*) discuss the potential implications for water governance. We focus on the TMR effect because it is transparent, closes the water balance, and explicitly links changes in land and water geographically. Given these advantages, similar TMR approaches have in recent years been used to analyze unexplored relations, e.g., LUC impacts of crop yields (Bagley et al., 2012), self-amplifying forest die-back from TMR changes (Zemp et al., 2017), and vulnerability to LUC induced reductions in P (Keys et al., 2016; Miralles et al., 2016). For a comparison of different methods for analyzing LUC impacts on Q, see Table S1.

2 Methods

2.1 Modeling

We used the process-based hydrological model Simple Terrestrial Evaporation to Atmosphere Model (STEAM) (Wang-Erlandsson et al., 2014) to simulate water fluxes based on land cover and land use. STEAM partitions evaporation into five fluxes: vegetation interception, floor interception, transpiration, soil moisture evaporation, and open-water evaporation. STEAM operates at 1.5° x 1.5° and a 3 hour resolution. Based on the long term water balance, mean annual river flow is assumed to approximately equal the difference between mean annual precipitation and evaporation. Minor modifications in land parametrization for this study and comparison against observed runoff data is shown in Supplementary Information.

Atmospheric moisture is tracked using the Eulerian moisture tracking scheme Water Accounting Model-2 layers (WAM-2layers) (van der Ent, 2014; van der Ent et al., 2014). WAM-2layers tracks atmospheric moisture from zero pressure to surface pressure in two layers. Within the layers, atmosphere is assumed to be well-mixed. WAM-2layers tracks vapor flows by applying the water balance. The spatial resolution of WAM-2layers is 1.5° and input data are linearly interpolated to the 15 minute time step to maintain numerical stability.

P under potential land cover is obtained through a coupled model simulation. We use E output from STEAM in WAM-2layers, and iteratively adjust the current day P forcing to STEAM with the changes in P with terrestrial origin obtained by forward tracking continental moisture in WAM-2layers (SI Materials and Methods). P differences between model iterations converges after about four simulations.

2.2 Data

Land use and land cover data input to STEAM are based on the Ramankutty potential land-cover (Ramankutty and Foley, 1999) and current land-use scenarios (Ramankutty et al., 2008) for consistency. We further added permanent wetlands, permanent snow or ice, and urban or built-up areas from the Land Cover Type Climate Modeling Grid (CMG) MCD12C1 International Geosphere Biosphere Program (IGBP) land classification created from Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) data (Friedl et al., 2010) for the year 2005. Monthly irrigated rice and irrigation non-rice crops were obtained from the data set of Monthly Irrigated and Rainfed Crop Areas around the year 2000 (MIRCA2000) V1.1. (Portmann et al., 2010) (SI Materials and Methods).

Meteorological data used in WAM-2layers and STEAM, except for land precipitation, were taken from the Earth Retrospective Analysis Interim (ERA-I) from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al., 2011). ERA-I meteorological forcing to STEAM are: snowmelt, temperature at 2 m height, dew point temperature at 2m height, wind speed (meridional and zonal vectors) at 10 m height, incoming shortwave radiation, and net longwave radiation. In addition, ERA-I evaporation data were used to downscale calculated daily potential evaporation in STEAM to the 3 hour time step. ERA-I model level forcings used in the WAM-2layers are specific humidity, and wind speed at 6 hourly resolution, spanning from zero to surface pressure. Moreover, 3 hourly ocean evaporation is taken from ERA-I. Precipitation forcing for WAM-2layers and STEAM both come from the state-of-the-art product Multi-Source Weighted-Ensemble Precipitation (MSWEP) (Beck et al., 2017) that was specifically created for hydrological modeling. The use of MSWEP as forcing for STEAM resulted in runoff estimates that compare well to observed runoff data (Figure S8). All meteorological data cover temporally 1995–2014, whereas runoff data represent long term average. The years 1995-1999 were used as spin-up for STEAM, 1999 is used as spin-up in forward tracking in WAM-2layers, and 2014 is used as spin-up for backward tracking in WAM-2layers. The spatial coverage of all data used is 57°S-79.5°N latitudes at 1.5° x 1.5° resolution. MSWEP originally at 0.25° and GRDC runoff at 0.5° were aggregated to 1.5° resolution by simple averaging.

2.3 Analyses

2.3.1 Changes in hydrological flows

River flow change without TMR (ΔQ_{noTMR}) is

$$\Delta Q_{\text{noTMR}} = (P_{\text{cur}} - E_{\text{cur}}) - (P_{\text{cur}} - E_{\text{pot,1}}) \tag{1}$$

where P_{cur} is current day precipitation data from MSWEP, E_{cur} is current day evaporation based on STEAM simulation, and $E_{\text{pot,1}}$ results from STEAM simulation in the potential vegetation scenario and forced with current day precipitation (Fig. S8). River flow change after accounting for TMR (ΔQ) is

$$\Delta Q = (P_{\text{cur}} - E_{\text{cur}}) - (P_{\text{pot,4}} - E_{\text{pot,5}}) \tag{2}$$

where $P_{\text{pot,4}}$ is the converged precipitation (i.e., meeting the convergence requirement of mean annual precipitation change < 1 % and monthly precipitation change < 5 mm/month in every grid cell) achieved at the fourth iterative coupling between STEAM and WAM-2layers, and $E_{\text{pot,5}}$ is the evaporation under the potential vegetation scenario simulated in STEAM with precipitation forcing $P_{\text{pot,4}}$.

Precipitation change in a basin that originates from extra-basin evaporation (ΔP_{import}) is defined as the change in tracked basin precipitation ($\Delta P_{\text{tracked,basin}}$) occurring outside the river basin boundaries, whereas change in internally recycled precipitation ($\Delta P_{\text{basin-recycling}}$) is defined as $\Delta P_{\text{tracked,basin}}$ originating from within the basin boundary. Internally recycled evaporation ($\Delta E_{\text{basin-recycling}}$) corresponds to $\Delta P_{\text{basin-recycling}}$ and all other basin evaporation change is considered exported ($\Delta E_{\text{basin,recycling}}$).

2.3.2 Country influence on changes in river flows

The influence on river flow change in river basin b from country c without considering TMR ($I_{\text{b,c,noTMR}}$) is:

$$I_{\text{b,c,noTMR}} = |\Delta E_{\text{b,c}}|. \tag{3}$$

where $\Delta E_{\text{b,c}}$ is evaporation change in the part of river basin b located in country c. The influence on river flow change in basin b from country c with consideration of TMR ($I_{\text{b,c,TMR}}$) is:

$$I_{\text{b,c,TMR}} = |\Delta E_{\text{b,c,export}}| + |\Delta P_{\text{b,c,import}}|) \tag{4}$$

where $\Delta E_{\text{b,c,export}}$ is the evaporation change exported from the part of basin b located in country c, and $\Delta P_{\text{b,c,import}}$ is the precipitation change imported to basin b from country c.

Influences from countries below 5 % of total influences in a specific basin ($I_{\text{b,c,noTMR}} < 0.05 \times \sum I_{\text{b,c,TMR}}$) were lumped into the category "Other".

3 Results

3.1 LUC impacts on global water flows

Our results show that human LUC (from potential land cover to current land use) (Fig. 1a) has led to reductions in E and P, and to increases in Q, in most regions (Fig. 1b-d). E has decreased primarily in Southwest China, Europe, West Africa, south of Congo, and southeast South America resulting from substantial pasture and agricultural expansion (Ramankutty et al., 2008). Following prevailing wind directions (Fig. S1e), subsequent P has decreased in all tropical regions, in South Central China, eastern US, and Europe.

Nevertheless, in some areas, E increased due to incremental irrigation – notably in India, the US, Northeast China, and in the Middle East (Fig. 1b). Due to the combination of heavy irrigation in India and orography, P has increased substantially along the Himalaya mountain ridge (Fig. 1c). Weak increases in P are observed in other downwind regions: the Sahel (i.e., downwind irrigation areas along the Nile) and in the Western US. ΔQ are seen in the La Plata basin in South America, the Zambezi in Southern Africa, the Yangtze in China, and the Indus in North India (Fig. 1d). Figure S1 shows the corresponding relative changes in hydrological flows.

3.2 The role of TMR for ΔQ

In aggregate (Fig. 2), when accounting for TMR, LUC changed global terrestrial E by -1251 km^3 yr^{-1} (-1.8 % from 69,211 km^3 yr^{-1}), P by -586 km^3 yr^{-1} (-0.5 % from 107,800 km^3 yr^{-1}), and Q by 664 km^3 yr^{-1} (+1.7 % from 38,589 km^3 yr^{-1}). The estimated changes to Q fall in the conservative end of previous estimates (Sterling et al., 2012) (Fig. 2). ΔQ with TMR corresponds to the difference between ΔE and ΔP change including TMR (Fig. 2, solid bars), whereas ΔQ without accounting for TMR simply corresponds to ΔE without TMR (Fig. 2, hollow bars).

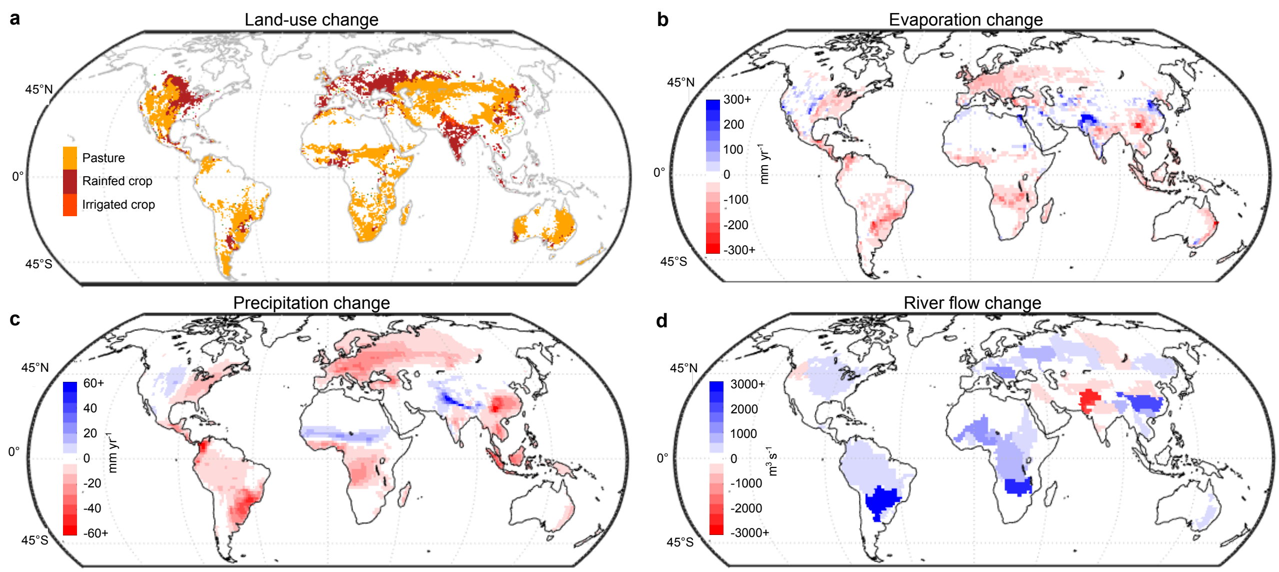

Figure 1. Differences between the current land-use and the potential land cover scenario. Changes in **a**, land use (only shifts in grid cell dominant land-use types are shown), **b**, mean annual evaporation (changes < ± 20 mm yr^{-1} are in white), **c**, mean annual precipitation (changes < ± 4 mm yr^{-1} are in white), and **d**, mean annual river flow (changes < ± 200 m^3 yr−1 are in white). Note that changes in river flows are aggregated to river basin level and shown in m^3 s^{-1}. Changes in hydrological flows are based on model simulations with meteorological input data covering the years 2000-2013.

Including TMR nearly halves the global ΔQ estimate. This is because E returns as P over land and thus compensates for the initial water "loss" from the basin. This suggests that previous studies without TMR (e.g., Gerten et al., 2008; Piao et al., 2007; Sterling et al., 2012) may have substantially overestimated the net LUC impacts on Q. Our estimate of LUC impact on Q is comparable to some of the estimates of CO_2 fertilization and consumptive water use (i.e., net withdrawal) impacts, but smaller than climate change and overall human impact (Fig. 2).

Our river basin analysis shows that accounting for TMR considerably alters estimates of ΔQ (Fig. 3a): in the Congo, Volga, and Ob basins, ΔQ are reduced by more than half; in the Amazon, ΔQ drops from 1630 to 270 m^3 s^{-1}; and in the Yenisei, the sign of ΔQ is reversed from an increase (150 m^3 s^{-1}) to a decrease (-220 m^3 s^{-1}).

3.3 The interplay between internal and external LUC

Furthermore, atmospheric moisture does not respect river basin boundaries (Fig 3a., and spatial maps in Fig. S2, S3, S4, and S5). In fact, P over the basins has been modified more significantly by external than by internal LUC (change in imported precipitation $\Delta P_{\mathrm{import}}$ > change in internally recycled precipitation $\Delta P_{\mathrm{basin-recycling}}$) in some of the largest basins (Fig. 3a). Likewise, internally recycled evaporation changes ($E_{\mathrm{basin-recycling}}$) (Fig., 3b, II) are substantially smaller than ΔE affecting P elsewhere ($\Delta E_{\mathrm{basin-recycling}}$ < change in exported evaporation $\Delta E_{\mathrm{export}}$) for all selected river basins (Fig. 3a).

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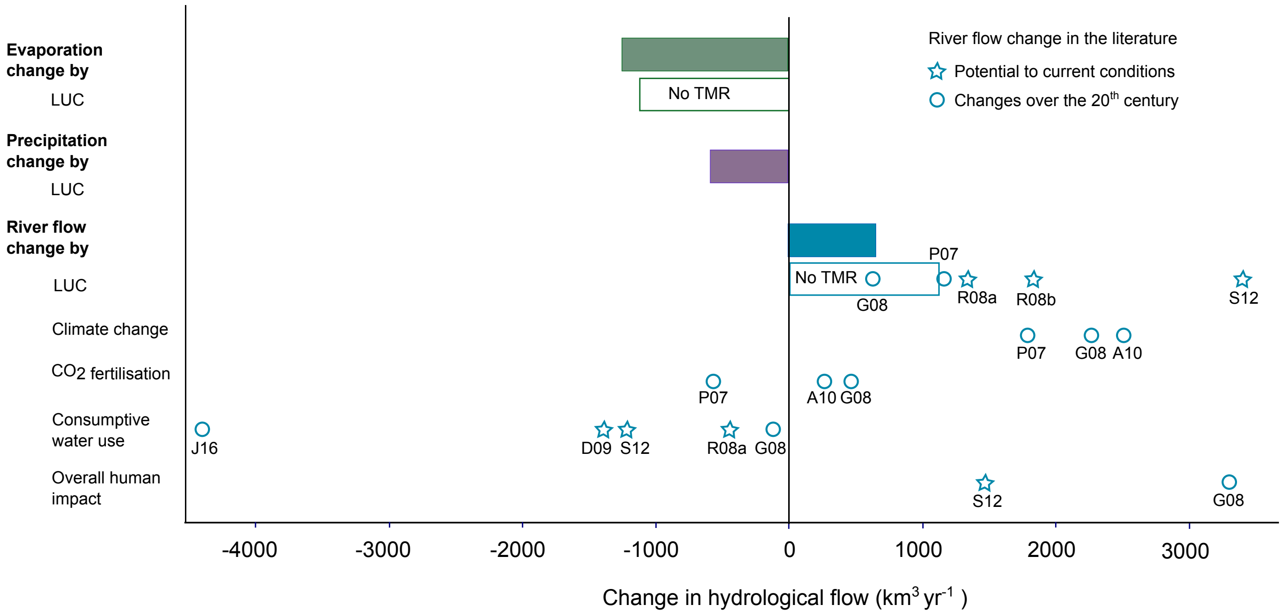

Figure 2. Human impact on global hydrological flows. The solid bars show our estimated net change (terrestrial area 131.7 106 km^2 and time period 2000-2013) in evaporation, precipitation and river flows including consideration of terrestrial moisture recycling (TMR). Hollow bars show flow changes without TMR. Circles and stars indicate river flow change estimates from other studies (Table S2), where land-use change (LUC) implicitly accounts for consumptive water use. Note that while consumptive water use alone always reduces river flows, other human impacts have both positive and negative influences that are concealed by the global aggregate.

Internal moisture recycling (Fig. 3b, II) does not affect ΔQ directly, only indirectly if $\Delta P_{\mathrm{basin-recycling}}$ affects subsequent $\Delta E_{\mathrm{export}}$ under transient change (Fig. 3b and Methods). Thus, provided steady-state, ΔQ simply corresponds to the difference between $\Delta E_{\mathrm{export}}$ and $\Delta P_{\mathrm{import}}$ (Fig. 3a). For example, ΔQ in the Amazon is very small because the reduced $\Delta P_{\mathrm{import}}$ is almost entirely offset by reduced $\Delta E_{\mathrm{export}}$. In Congo, about half of the within-basin LUC induced Q increase is counteracted by extra-basin LUC (i.e., $\Delta P_{\mathrm{import}} \approx 0.5 \Delta E_{\mathrm{export}}$). The effect of TMR on ΔQ ($\Delta Q_{\mathrm{noTMR}} - \Delta Q$, where subscript $_{\mathrm{noTMR}}$ denotes simulation without TMR) corresponds to total ΔP (i.e., $\Delta P_{\mathrm{import}} + \Delta P_{\mathrm{basin-recycling}}$) and any indirect ΔE (i.e., $\Delta E_{\mathrm{noTMR}} - \Delta E$, not shown). In Yangtze, the ΔQ is mitigated mostly by $\Delta P_{\mathrm{basin-recycling}}$. The strong flow reduction in the heavily irrigated Indus, however, is only mildly compensated by TMR (i.e., $\Delta P_{\mathrm{import}} \ll \Delta E_{\mathrm{export}}$).

3.4 Attributing influence on ΔQ to nations

Typically, TMR attributes LUC influence on Q to a larger number of nations than when only basin boundaries are considered (Fig. 4 and Fig. S6). For example, in the Amazon, ΔQ originates from as far away as Africa if considering TMR (Fig. 4b-c). Because of the large LUC-induced E reductions, the African influence on Amazon ΔQ is comparable to within-basin influence

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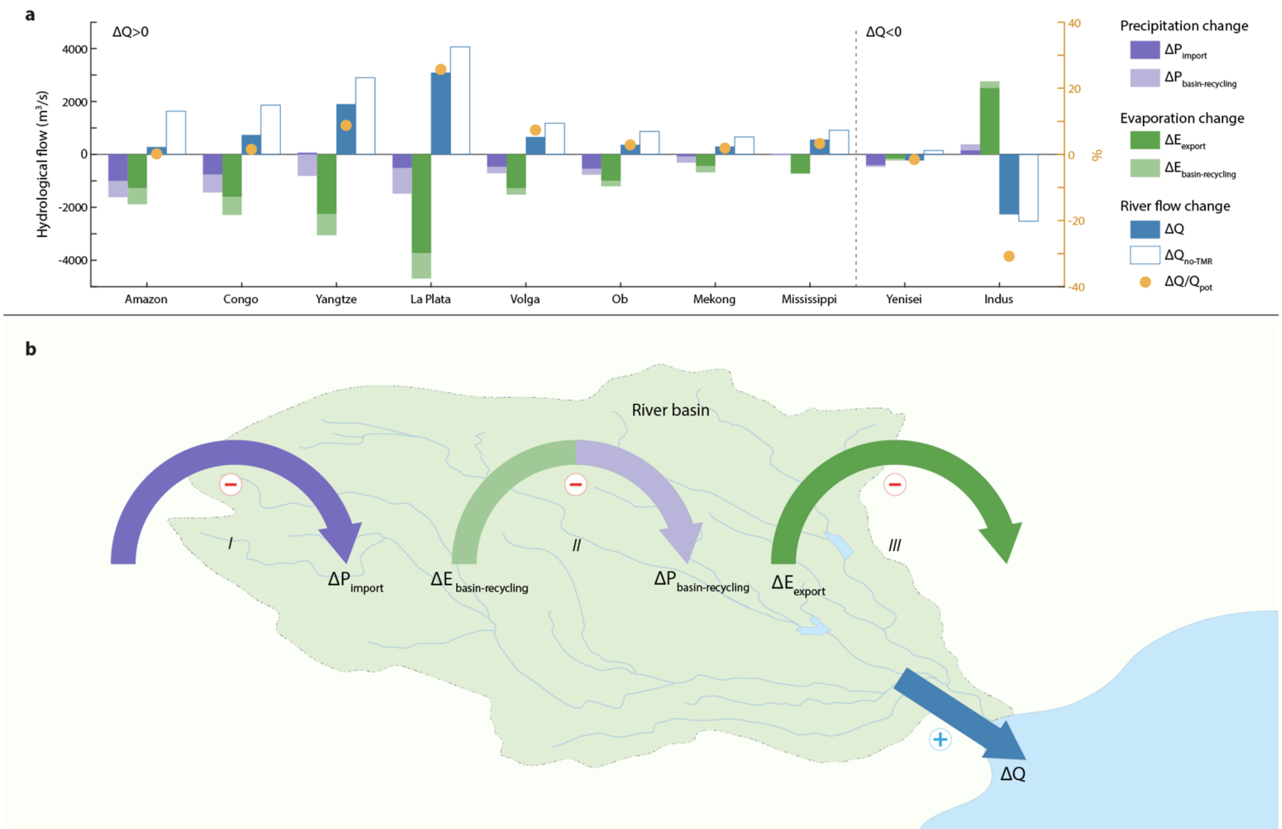

Figure 3. Changes in hydrological flows at river basin scale. **a**, Changes in hydrological flows by ten basins with the largest terrestrial moisture recycling (TMR) effect on river flows (Q): eight basins with increased and two with decreased Q. Basins are ordered by maximum absolute TMR effect on Q, i.e., the difference between Q with or without TMR ($\Delta Q - \Delta Q_{\mathrm{noTMR}}$). **b**, Conceptual figure of hydrological flow changes in a basin. The (-) and (+) as displayed here are e.g. seen in Amazon, Congo, Volga derived from results shown in a. In Indus and Yenisei, the (-) and (+) are reversed.

(SI Methods). Notably, basins geographically confined within one nation can be influenced by LUC taking place in foreign nations. This is for example the case in Yangtze, where simulated irrigation in India increases the basin's P (Fig. 4g).

4 Discussions

4.1 Interplay between TMR and LUC

At the global scale, ΔQ as a response to LUC can be almost halved by taking TMR into account (Fig. 2). However, these effects vary widely by regions. While the TMR effects are negligible in some basins, remote LUC can compensate the majority of the impact on Q from local LUC in other basins (e.g., Amazon, Fig. 3a) and even propose new transboundary relationships

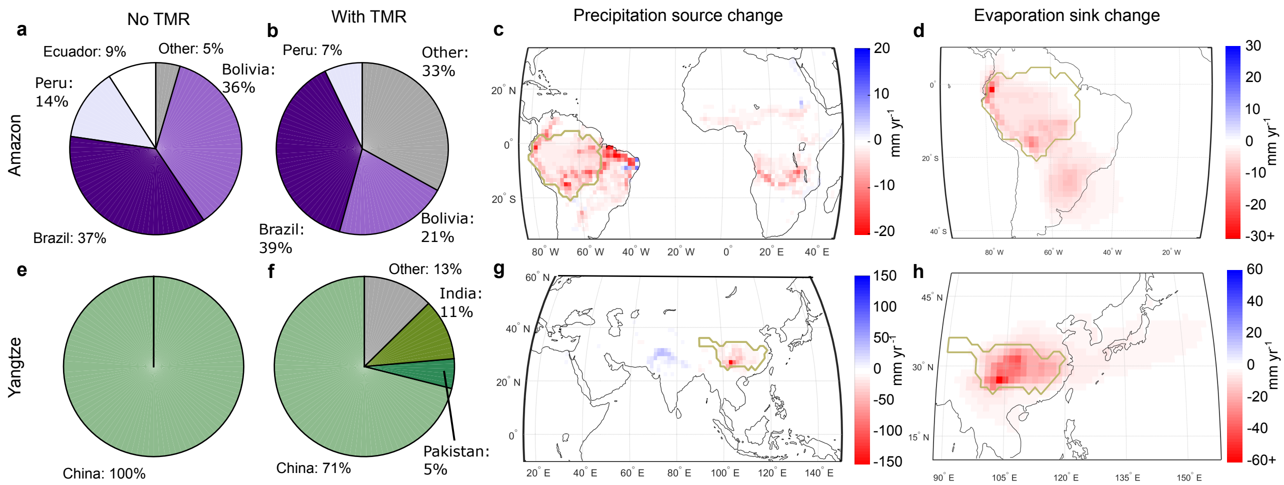

Figure 4. Nation influence of river flow change depending on consideration of terrestrial moisture recycling (TMR) in **a-b**, Amazon and **e-f**, Yangtze. Without TMR, the nation influence on river flow change originates entirely from within-basin country-wise evaporation change (**a**, **e**). By considering TMR, the nation influence **b**, **f** is the sum of absolute imported precipitation change (precipitation source outside encircled basin boundaries in **c** and **g**) and of absolute exported evaporation change (evaporation sink outside encircled basin boundaries in **d** and **h**) (Methods). Precipitation sources (**c**, **g**) and evaporation sinks (**d**, **h**) within basin boundaries are recycled.

(e.g., Yangtze, Fig. 4e). From a TMR perspective, the impact on Q from within-basin LUC depends on the ΔE exported from the basin as much as the ΔP imported to the basin.

Our analysis shows the importance of considering LUC on par with TMR to identify anthropogenic influence on water resources, beyond analyses of pure moisture exchanges (Dirmeyer et al., 2009; Keys et al., 2017). While Africa does not constitute a major moisture source of Amazonian P (7 % of all Amazon P, 13 % of Amazon P with continental origin, see also Fig. S2a), the spatial extent of ΔE from LUC was sufficient to elevate the relative importance of African LUC for Amazonian ΔQ (28 % of Amazon ΔP, see also Fig. 4c). Similarly, India is not identified as a major moisture source of Yangtze (see Fig. S2c and Wei et al. (2012), but has about 10 % influence on Yangtze ΔQ (Fig. 4f and 4g).

4.2 Potential governance relevance

Our results indicate that both precipitation- and evaporationsheds of river basins are relevant governance units. Previous studies of TMR for water management (Berger et al., 2014; Keys et al., 2017) have emphasized the importance of considering the P source region, i.e., the precipitationshed (Keys et al., 2012), which was introduced as a concept analogue to watershed for water resources management. This study finds that the evaporationshed (van der Ent and Savenije, 2013), i.e., the E sink region, is just as important when considering changes to Q.

LUC impacts Q through TMR in different ways depending on how precipitationshed, river basin, and evaporationshed are aligned. For example, where an evaporationshed has a limited overlap with river basin boundaries, reforesting a river basin may lead to unexpectedly large reductions in Q, if considerable deforestation simultaneously occurs in the precipitationshed outside the river basin.

The magnitude of TMR effects from remote LUC on Q can be comparable to managed water flows. For example, Yangtze River provides 36 % of the country's surface water resources, and is subject to two of the world's most ambitious water engineering projects: the Three Gorges Dam and the South-to-North Water Diversion (CWRC, 2017). The overall TMR effect on mean annual LUC-induced ΔQ is here estimated at 980 m^3 s^{-1} in the Yangtze basin, and the mean annual moisture change imported to the basin from foreign countries is estimated at 1,110 m^3 s^{-1} (Fig. 4g). As comparison, the Q difference between a normal and a dry year is about 300 m^3 s^{-1} and the total amount of water to be transferred from the Yangtze through the South-to-North Water Diversion is aimed to be 1420 m^3 s^{-1} (NSBD, 2011). Seasonal and interannual flow variability is a major challenge facing the Yangtze, and future research in the seasonal LUC influence and interaction with the monsoon system is needed. Note, however, that our estimates are associated with parameter sensitivity (see Fig. S7) and large uncertainties as discussed in the Limitations.

We note that the relevance of considering TMR governance depends on future LUC. The simulated ΔQ in this paper follows from a rather extreme LUC scenario (from potential to current land-use). The current LUC in this study is 15 million km^2 cropland and 28 million km^2 pasture conversion (Ramankutty et al., 2008). As comparison, models used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) estimated cropland changes from -1.2 to +12 million km^2 between 2000 and 2050 (IPCC, 2007). A more recent multi-model comparison range cropland conversion until 2050 from -1 to + 8.5 million km^2 across different scenarios (Schmitz et al., 2014). In total, the potential land for agricultural conversion has been estimated at 17 million km^2 (Schmitz et al., 2014). Thus, future LUC can be considerable, and potential TMR impacts on Q will be dependent on the type and geographical distribution of LUC.

4.3 Limitations

Our TMR analyses should be seen as an inquiry to better understand the relative importance of local and remote LUC effects on Q from a water balance perspective, rather than an exact prediction. Our approach only accounts for the TMR effects. The frequency or intensity of P (Medvigy et al., 2011) are assumed to remain unaffected by thermal layer processes or circulation perturbation, which may introduce a bias in the quantitative estimates of hydrological flows under water limited conditions (i.e., semi-arid regions and temperate region during summertime). Furthermore, vegetation response to ΔP is not simulated, such as forest dieback from increased fire risk under drying conditions. Our analyses concern mean annual ΔQ, and can be considered conservative in the sense that seasonal signals are expected to be much stronger. Human modification of Q through dams and climate change (Haddeland et al., 2014) are not considered in this study. The magnitude of our estimated ΔP (Fig. 2) and ΔQ from LUC is also conservative in comparison to the literature (Spracklen and Garcia-Carreras, 2015). Thus, despite the uncertainties of the magnitude of change, we are confident that upwind extra-basin LUC can be essential for Q.

4.4 Future research outlook

A key challenge for considering TMR effects in water governance is the modeling uncertainties and inherent variabilities associated with land-atmosphere feedback processes. The most complex modeling approaches account for the highest number of feedback processes. However, the sign, magnitude, and location of impacts vary widely even among state-of-the-art climate models (Pitman et al., 2009; Aloysius et al., 2016). Key future improvements in climate models' ability to simulate ΔP from LUC will contribute to the governability of TMR. In-depth examination of differences in model simulation of P (e.g., the ongoing Precipitation Driver Response Model Intercomparison Project (Myhre et al., 2017)) is one step in this direction. Tracking moisture in coupled climate models could further help identify causes for simulated differences in atmospheric and hydrological outputs. Key elements missing in current research on LUC effects on hydrological flows include socio-economic dynamics and landscape resilience, which are complex issues currently explored in experimental model settings (Nitzbon et al., 2017; Reyer et al., 2015). In the meantime, "no-regret" policies in river basin management, where TMR objectives align with other aims can potentially be explored in conjunction with LUC scenarios that include TMR effects.

5 Conclusions

We analyzed the potential impact of human LUC on Q worldwide through TMR, and separately looked at the remote and local LUC effects of relevance to water governance. Despite the river basin being the standard unit in water governance and water resources management, we find that ΔQ are ultimately dependent on the modifications in both incoming P and outflowing E. For example, where extra-basin LUC affects basin P more strongly than within-basin LUC, reforesting a river basin may lead to unexpectedly large reductions in Q if deforestation simultaneously occurs in P source regions outside the river basin. Therefore, we emphasize the necessity of considering both the origin of basin P as well as the fate of basin E for management of local water resources. Further, we suggest the potential need for transboundary governance of river basins where extra-basin LUC is important for ΔQ. International governance arrangements of teleconnnected LUC influence could be needed, even for river basins that today are not considered transboundary. We conclude that consideration of TMR is essential for understanding Q modifications and managing water resources in a rapidly changing and tele-coupled world (Liu et al., 2013) facing increasing pressure on both land (Schmitz et al., 2014) and water (Mekonnen and Hoekstra, 2016). Further research in both climate modeling and water governance strategies is needed to internalize land-atmosphere interactions in future water resources considerations.

Code and data availability. The moisture tracking scheme Water Accounting Model-2 layers (WAM-2layers) in Python code can be obtained from GitHub (https://github.com/ruudvdent/WAM2layersPython). Earth Retrospective Analysis Interim (ERA-I) meteorological data can be obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/). The Ramankutty potential land-cover can be obtained from the website (https://nelson.wisc.edu/sage/data-and-models/global-potential-vegetation/index.php) and current cropland and pasture map can be obtained from EarthStat (http://www.earthstat.org/datadownload/). Land Cover Type Climate Modeling Grid (CMG) MCD12C1 International Geosphere Biosphere Program (IGBP) land classification created from Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) data for the year 2005 can be downloaded at https://modis.gsfc.nasa.gov/data/dataprod/mod12.php. Monthly irrigated rice and irrigation non-rice crops were obtained from the data set of Monthly Irrigated and Rainfed Crop Areas around the year 2000 (MIRCA2000) V1.1. and can be downloaded at http://www.uni-frankfurt.de/45218031.

Author contributions. Research was conceived by L.W-E., R.J.v.d.E., P.W.K., H.H.G.S., and L.J.G.. I.F. contributed ideas for analyses. L.W-E. carried out the model simulations, analyzed the data, and wrote the paper with input from all authors.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. We thank Victor Galaz for providing feedback on the manuscript. L.W-E., P.W.K, and L.J.G, are funded by The Swedish Research Council Formas (grant number 1364115). R.J.v.d.E. received funding from the European Union Seventh Framework Programme (FP7/2007–2013, grant agreement no. 603608). I.F. receives financial support from The Stordalen Foundation. I.F. and L.J.G. are also supported by The Swedish foundation for strategic environmental research (MISTRA).

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