A Fellow Speaks: What Drives Global Change in Hydrology and Human Freshwater Consumption?

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I am honored and grateful to have been elected AGU Fellow and thank everyone who has supported me in this election. I also thank all friends and colleagues who have worked with me over the years on the research leading to this recognition. An overarching goal of my research has been to link our understanding of water flow and waterborne transport at multiple scales and through various water bodies into a coherent view and representation of the continuous, ever-flowing hydrological system on Earth.

Water and waterborne material fluxes along various pathways connect the world's rivers, lakes, wetlands, and aquifers into a coupled hydrological system (schematized in Figure 1A), which is organized in catchments and drainage basins of different scales that, together, cover Earth's land surface (Figure 1B). Through some water fluxes and flux pathways, the basin-wise organized hydrological system also interacts closely with other major Earth system segments, including the anthroposphere (through the engineered water systems and water impacts of society) and other surface and subsurface features of the landscape, as well as with the atmosphere and the coastal and marine waters. Overall, the coupled water fluxes within and into/from each hydrological basin thus propagate hydrological and environmental change from different change drivers, including regional-global forces of atmospheric climate change as well as landscape-internal change drivers (see main driver types and examples schematized in Figure 1C).

For regional hydrological basins in different parts of the world, recent research has shown landscape-internal drivers as dominant for main hydrological shifts occurring over the past century (see, e.g., the Swedish, Aral Sea, and Mahanadi River basins among those exemplified in Figure 1B [*Destouni et al.*, 2015]). Specifically, the key landscape drivers in these regional basins were human land use and water use changes, including agricultural extension/intensification, and developments of irrigation schemes and hydropower-related flow regulation. These drivers were all found to increase actual evapotranspiration (ET) relative to precipitation (P). In addition, the flow regulation developments decreased the temporal short-term variability of runoff (R), indicating this as a useful effect for distinguishing ET/P increase driven by flow regulation from that by other landscape-internal or atmospheric climate drivers.

Follow-up studies of hydrological change in many basins/catchments of different scales and with total land area coverage and spreading representative of the global scale have further supported the regional findings of dominant landscape-internal drivers [*Jaramillo and Destouni*, 2014, 2015a]. Specifically, in at least 74% of 462 investigated hydrological basins over the world, dominant landscape-internal change drivers of various types (Figure 1C) were needed to explain ET changes occurring in the basins during the period 1901–2008, in addition to the ET change explanation provided by the observed surface temperature and P change drivers in the basins [*Jaramillo and Destouni*, 2014]. Furthermore, consistent and dominant effects of increased ET/P were found also globally for both flow regulation and irrigation developments, accompanied by decreased temporal R variability for flow regulation developments [*Jaramillo and Destouni*, 2015a].

In total, the global ET increase driven by local flow regulation and irrigation developments over the past century implies an increase in the long-term average human consumption of freshwater by around 3563 km^3/yr from 1901–1954 to 1955–2008, with an uncertainty range of ±979 km^3/yr around this mean quantification [*Jaramillo and Destouni*, 2015a]. This increase in global freshwater consumption then accounts for the total increase in freshwater loss from the landscape to the atmosphere due to the total ET increase driven by these local human activities. This global increase also raises a previous estimate [*Hoekstra and Mekonnen*, 2012] of the global water footprint of humanity by 18% to around 10,688 km^3/yr.

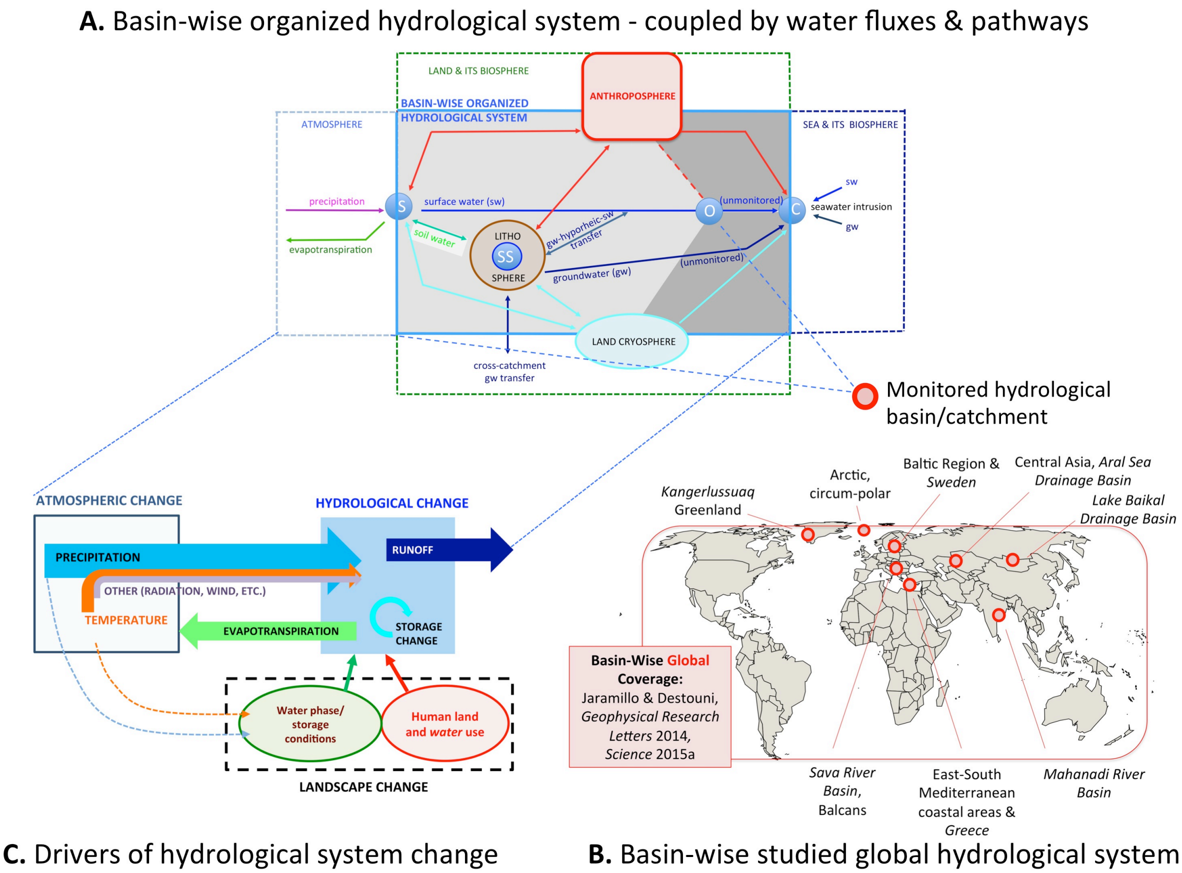

Fig. 1. (A) Schematic representation of the basin-wise organized coupled hydrological system (redrawn and simplified from a similar schematization by *Destouni et al.* [2014]. (B) Examples of hydrological basins around the world that have been in focus for my research on hydroclimatic change and its drivers, and references to some recent papers of multiple basins with total area coverage and spreading that are representative of the global scale [*Jaramillo and Destouni*, 2014, 2015a]. (C) Schematic outline and examples of atmospheric and landscape-internal drivers of hydrological change (redrawn from *Jaramillo and Destouni* [2014]). Fig. 1A shows the pathways of water flow and waterborne transport (arrows) that physically couple the hydrological system and are organized in two types of catchments or basin parts: convergent into an observation point (light gray) and divergent and commonly unmonitored coastal catchment areas draining their water through an extended shoreline (dark gray). The water pathways interact and are partitioned in four main zones of hydrological change, schematized in Figure 1A as blue filled circles, marked with: S, surface; SS, subsurface; C, coast; and O, observation**.**

Moreover, the found global ET increase by local flow regulation and irrigation developments supports previous regionally based estimations [*Destouni et al.*, 2015; *Jaramillo and Destouni*, 2015b] of the total global human water consumption being well above (rather than well below, as suggested in connection with) a proposed planetary boundary of 4000 km^3/yr [*Steffen et al.*, 2015]. Specifically, adding this global ET increase effect to previous estimates of global human freshwater consumption by various other sectors (807 km^3/yr in net total for nonirrigated agriculture, deforestation, industry, and municipalities [*Jaramillo and Destouni*, 2015b]) yields a total global freshwater consumption of 4370 ± 979 km^3/yr.

Regarding total hydroclimatic change on land over the past century, landscape-driven and climate-driven changes in ET have tended to counteract each other globally and in most continents [*Jaramillo and Destouni*, 2014]. This counteraction may have dampened the net total water change so far, compared to only climate-driven or only landscape-driven components of global water change. However, estimates of large-scale change effects are also shown to be highly uncertain for both human-driven [*Jaramillo and Destouni*, 2015a] and climate-driven water changes on land, with the latter considering the relevant hydrological output from the latest generation of Earth system models (ESMs) [*Bring et al.*, 2015]. Common for these recent studies of global and regional water changes on land is their use of a wide range of long-term climatic and hydrological observations, combined with worldwide land use and water use data [*Jaramillo and Destouni*, 2015a], or directly compared with hydrological ESM output data [*Bring et al.*, 2015]. In combination, these data-based results show that worldwide observation data can and should be more widely used to constrain quantifications of long-term global hydrological and freshwater changes, in addition to only attempting to model such changes.

The data-based results have thus expanded both the likely magnitude and the uncertainty range of the global human consumption of freshwater, and should raise awareness of and guide new efforts for reducing both. These results and the direct comparison between observation and ESM output data also stress the importance of considering local water use and hydrological system conditions and constraints (Figure 1A) in addition to larger-scale atmospheric and land use considerations in Earth system studies and modeling that should be of relevance for water resources and their changes on land.

References

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A Fellow Speaks: Emerging Role of Algorithms in HydroComplexity

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Digital water cycle, a characterization of processes participating in Earth's water cycle through widespread measurements and their digital representation, is becoming increasingly more realistic. On the one hand, we have large-scale representation of terrestrial, atmospheric, and oceanic attributes from regular monitoring using satellites, and, on the other hand, emerging low-cost sensing through in situ instruments and UAVs (unmanned autonomous vehicles) promises to provide a pervasive knowledge of the state of our environments almost everywhere and almost all the time. Long-term place-based studies such as LTER (https://www.lternet.edu/), NEON (http://www.neoninc.org/), Fluxnet (http://fluxnet.ornl.gov/), and Critical Zone Observatories (http://criticalzone.org/national/) are creating rich databases that allow exploration of deep linkages. Deeply intertwined in this milieu are the data associated with anthropogenic participation in the water cycle, albeit often fragmented and difficult to obtain, which is impacting the water cycle from the local to global scale with potential to create emergent risks [*Kumar*, 2015]. Such data are complex in that they encompass a heterogeneous collection with many dimensions, local coordinate systems, scales, variables, nomenclature, providers, users, and scientific contexts. Due to the rapidly increasing volume of such data, we have to think of new ways of representing the information such that their complex interdependencies and hierarchies are retrievable. In this regard, the representation and ease of access of information about the data become just as important as the data. This is because the sheer volume and heterogeneity of the data makes direct human consumption difficult, requiring that most of the data be directly consumed by sophisticated tools for analysis, visualization, modeling, decision support, etc., through APIs (application program interfaces).

Emerging semantic web technologies are making such representation and data use a reality. They support