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Review article

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Global water resources and the role of groundwater in a resilient water future

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Supporting Information (SI) for

Global water resources and the role of groundwater in a more resilient water future

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Section 1: Acronyms:

ATM: Automated Teller Machine

CSR: Univ. of Texas Center for Space Research

EFR: Environmental Flow Requirements

ENSO: El Nino Southern Oscillation Index

ET: evapotranspiration

GEMS: Global Environment Monitoring System (United Nations)

GRACE: Gravity Recovery and Climate Experiment

GRanD: Global Reservoir and Dam database

JPL: NASA Jet Propulsion Laboratory

M: mascons

NAO: North Atlantic Oscillation

NCP: North China Plain

P: precipitation

PDO: Pacific Decadal Oscillation

SD: standard deviation

SDG: Sustainable Development Goal

TIVR: Trend to Interannual Variability Ratio

TWS: Total Water Storage

TWSA: Total Water Storage Anomaly

UN: United Nations

WHO: World Health Organization

Section 2: Water Storage Variability from GRACE Satellite Data

GRACE satellites are used to monitor water storage at continental to global scales. Variations in the Earth's gravity field monitored by GRACE satellites are controlled primarily by variations in water storage, related to floods, droughts, and groundwater pumpage in aquifer systems globally. GRACE satellites provide data on TWS changes that are mostly aggregated at monthly timescales. TWS anomalies (TWSAs, calculated by subtracting the long-term mean from monthly data from April 2002 to August 2022) in this study were based on GRACE data Release 06 from the Univ. of Texas Center for Space Research mascons (CSR-M) solutions and NASA Jet Propulsion Lab mascons (JPL-M) solutions. The data are based on the original GRACE mission and the GRACE Follow-On mission, extending from April 2002 through August 2022 (~19 years). The CSR-M native resolution is 1˚, resampled at 0.25˚ whereas the JPL-M native resolution is 3˚, downscaled to 1˚ using CLM-4 land surface model and resampled to 0.5˚. CSR-M release 6 divides the hexagonal tiles near the land-ocean interface into two tiles to reduce leakage between the land and the ocean. JPL-M applies a Coastline Resolution Improvement (CRI) filter to minimize land-ocean leakage.[1] TWSA from GRACE includes Snow Water Storage, surface storage (reservoirs, wetlands, lakes etc), soil moisture storage, and groundwater storage.

Section 3: Surface Water-Groundwater Interactions

Because predevelopment rates of recharge and discharge were equal and, by definition, unaffected by development, they can be removed from the balance equation (Fig. 2d). The predevelopment recharge rate has no effect on the ability of the aquifer to achieve a new balance in response to pumping. In humid regions, the occurrence of rejected recharge and extensive surface water make capture by groundwater pumping easier and faster.

During early stages of aquifer development, pumping is balanced by storage depletion; however, over time, pumping is increasingly derived from capture, including decreased discharge to streams and springs and evapotranspiration (ET), and/or increased recharge from surface water caused by declining water tables, and/or capture of formerly rejected potential recharge. If after some time, all pumping becomes balanced by capture, then pumping can be maintained indefinitely with net physically sustainable groundwater development.

Capture is generally not observable in surface water gage data. In affected streams and rivers, the capture (or decrease in flow) typically represents only a small fraction of the flow in a stream or river, and therefore might only might not background noise and stream gaging error except during low-flow periods. In lakes, reservoirs, or other surface water bodies that have large volumes relative to the groundwater flux, the capture typically represents only a very small fraction of the volume of water in that surface water body, hence is very difficult to measure directly. Low flows in streams and rivers are impacted by groundwater pumping, but measurement results are highly variable because of other confounding factors[2-4]. Capture is most likely to be observable in stream gage records during low-flow periods, when the change in flow due to capture represents a larger proportion of the streamflow than during average and high-flow periods.

Section 4: Water Quality Issues

Surface Water Quality: Surface water is generally more susceptible to contamination from pathogens than groundwater. An estimated 1.8 billion people globally rely on drinking water contaminated with feces increasing risks of cholera, dysentery, typhoid, and polio[5]. About 46% of the global population (3.6 billion people) in 2020 lacked access to safely managed sanitation services, with Africa particularly affected[5,6,6]. In the US, agricultural runoff is the leading cause of water quality degradation, with 43–

58% of surface water rated poor for nitrogen and phosphorus, respectively[7,8]. Similar findings are reported in the European Union[8]. Previous analyses indicate that phytoplankton blooms in lakes related to nutrient loading have been increasing globally, with impacts on aquatic ecosystems and drinking water[9]. The Nature Conservancy has linked agricultural expansion in major urban watersheds globally over the past century (1900 -2005) to large increases in pollutant loading (40% for sediment and ~120% for nitrogen) increasing treatment costs for cities by an average of ~30%[10].

Groundwater Quality: Few studies of water scarcity address groundwater quality; however, groundwater is impacted by both anthropogenic and natural contaminants[11]. Biological contamination, including from poor sanitation and animal manure sources, of shallow groundwater wells is a problem in many parts of the world[12]. Elevated groundwater nitrate can be attributed to anthropogenic (e.g., agricultural) or natural sources[13,14]. Naturally occurring contaminants of geologic (geogenic) origin include arsenic and fluoride with hotspots in different regions around the world[15,16]. In Bangladesh, switching from surface water to groundwater in the 1980s to avoid mortality from gastrointestinal disease, resulted in the largest mass poisoning in history from geogenic arsenic contamination[17]. In addition, irrigated food crops grown in arsenic hazard areas may increase overall human exposure locally or through food trade[18]. Additionally, saline groundwater is a critical issue in many regions and can be attributed to different sources of salinity[19,20]. Examples include connate seawater in sediments during deposition (e.g., Pampas, Argentina), evaporation (Tibetan Plateau, Northeastern Australia), salt dissolution (Saudi Arabia, North China), dryland salinity from rising water tables, irrigation related salinity (Northwest India, Aral Sea), and seawater intrusion. Globally, 32% of coastal metropolitan cities (population ≥1 million within 150 km of coast) are threatened by seawater intrusion[21]. The widespread global threat of groundwater contamination emphasizes the need to better incorporate groundwater quality into water scarcity assessments.

Section 5. Water Scarcity

Most physical water scarcity indices quantify the ratio of water demand (or use) to renewable freshwater supply (or availability)[22]. Scarcity indices vary depending on definitions of supply and demand and spatiotemporal resolution of estimates. Early studies focused on water supply from surface water only, including renewable groundwater discharge[23] while later studies incorporate groundwater abstraction[24,25] and green water (soil moisture)[23,26]. Definitions of water demand range from withdrawal (water consumption plus return flows), as used in most assessments[22,27] to water consumption (amount evaporated, transpired, or incorporated into products)[28]. More detailed analyses account for ecosystem water demands (e.g., environmental flow requirements)[29] and additional factors, such as socioeconomic considerations (e.g., access to basic water supply[30-32]), land use change, and water storage management (e.g., reservoirs)[33]. Previous studies suggest that 80% of river flows are required to meet environmental flows[34-36]; however, others suggest this value is too high and varies across river regimes[22]. Including environmental flow requirements potentially shifts the population impacted by water scarcity from mostly moderate (3.2 billion) to severe (~4 billion) water scarcity[37]. Similarly, increasing the spatial resolution of index estimates from country-level[23,38] to finer, gridded analyses (~50 km) increase impacted populations by at least a factor of 3[39]. Increasing temporal resolution from annual to monthly timescales shifted the impacted populations from moderate (3.2 86 billion) to severe (4 billion) [37] (Table S1b). Many people in water insecure areas rely on groundwater storage to meet daily needs; therefore, accounting for groundwater can significantly alter water availability indices[40].

Section 6: Climate Data, Projected Precipitation

A total of 25 Coupled Model Intercomparison Project Phase 6 (CMIP6) models were used to calculate the ensemble hydrological annual precipitation time-series data for the projected period of 2071 to 2100. Annual precipitation was calculated using monthly total within each calendar year. Projected mean (2071 -2100) annual precipitation was subtracted from the baseline (1985 – 2014) annual precipitation and presented in Fig. S2.

The scenarios used in the CMIP6 are the Shared Socioeconomic Pathways (SSP) and target radiative forcing level of SSP5-8.5 by the end of the twenty-first century (2071-2100). Table S5 lists the details of the models used and summarizes their main characteristics. It is important to note that the latest CMIP6 phase model dynamics improvements are added to simulate reasonable climate, including higher horizontal resolution, better representation of synoptic processes, comprehensive scenarios development, and updated forcing data consideration.

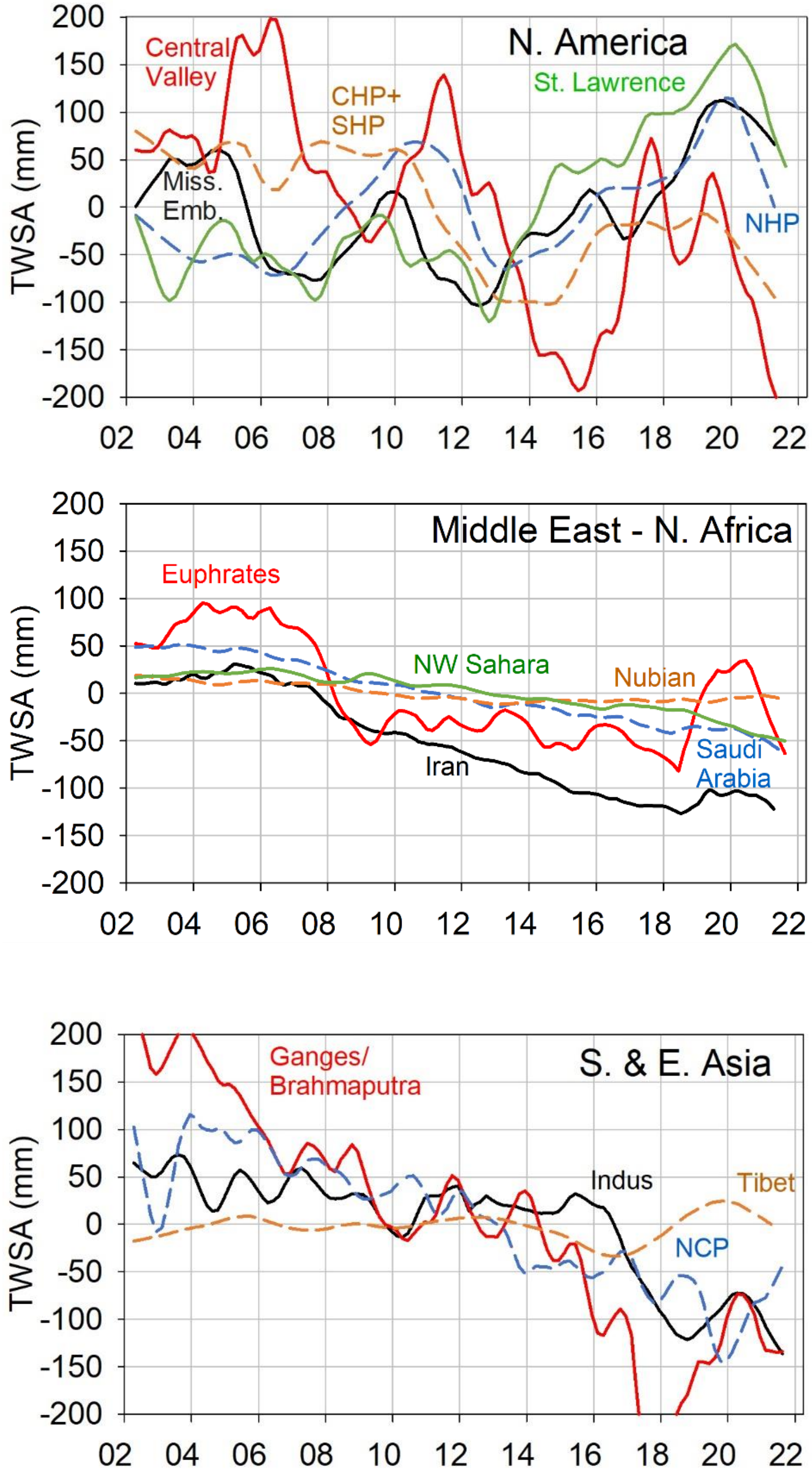

Figure S1a. Time series of GRACE TWSAs for aquifers and river basins in N. America, Middle East – N. Africa, and South and East Asia. These represent large versions of time series that are shown in Fig. 2. Data are provided in Table S3c.

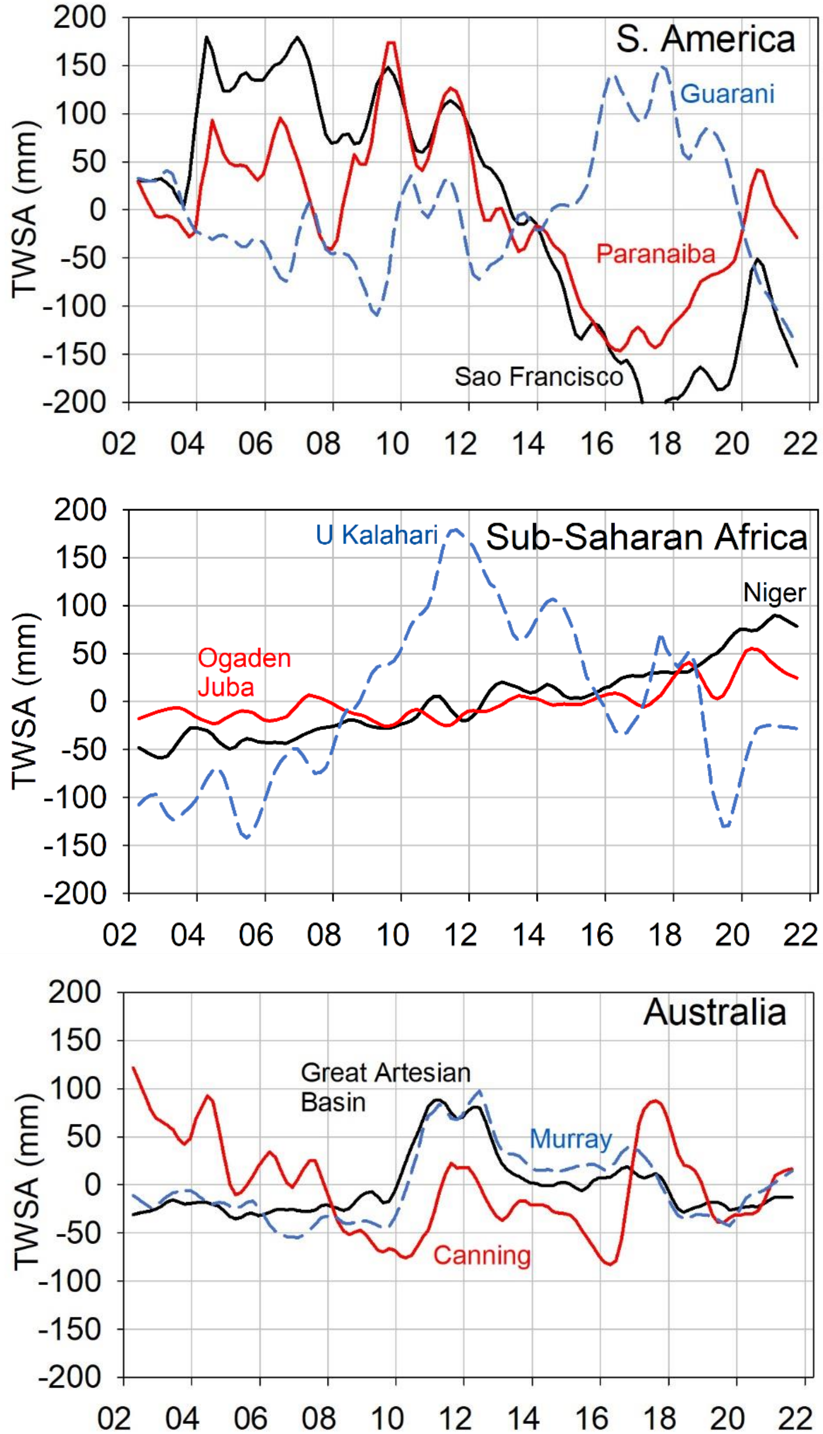

Figure S1b. Time series of GRACE TWSAs for aquifers and river basins in S. America, Sub-Saharan Africa, and Australia. Larger versions of time series than shown in Fig. 3. Data are provided in Table S3c.

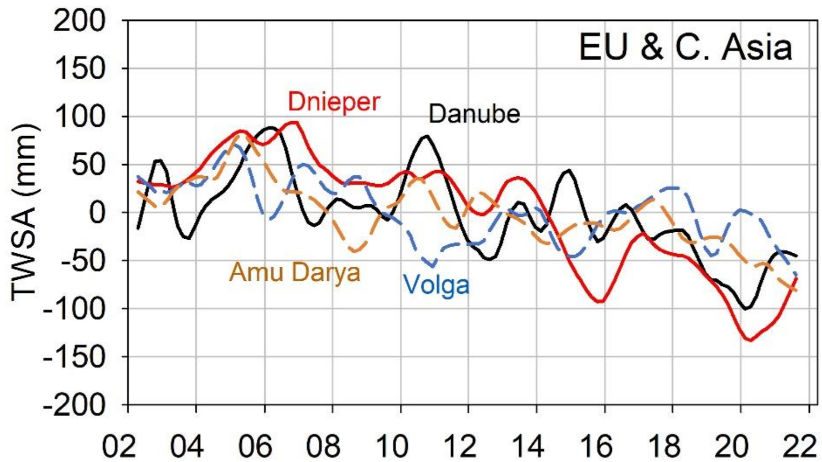

Figure S1c. Time series of GRACE TWSAs for river basins in Europe (EU) and Central Asia. Data are provided in Table S3c.

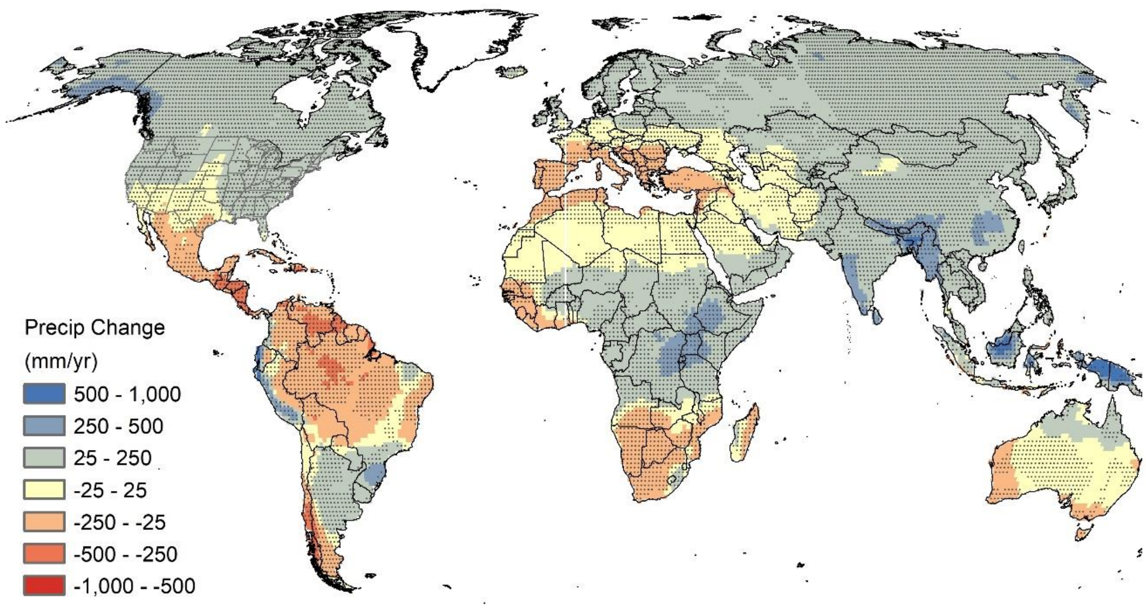

Figure S2. Projected change in annual precipitation (mm/yr) based on precipitation for end of 21[st] century (2071 – 2200) relative to baseline period (1985 - 2014). The projected precipitation was derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6) multi-model ensemble mean (2071 – 2100) monthly precipitation based on Shared Socioeconomic Pathways (SSP) and target radiative forcing level of SSP5-8.5 (SI, Section S2). Stippling reflects areas where more than two thirds of the models agree. The model sources are described in Table S7.

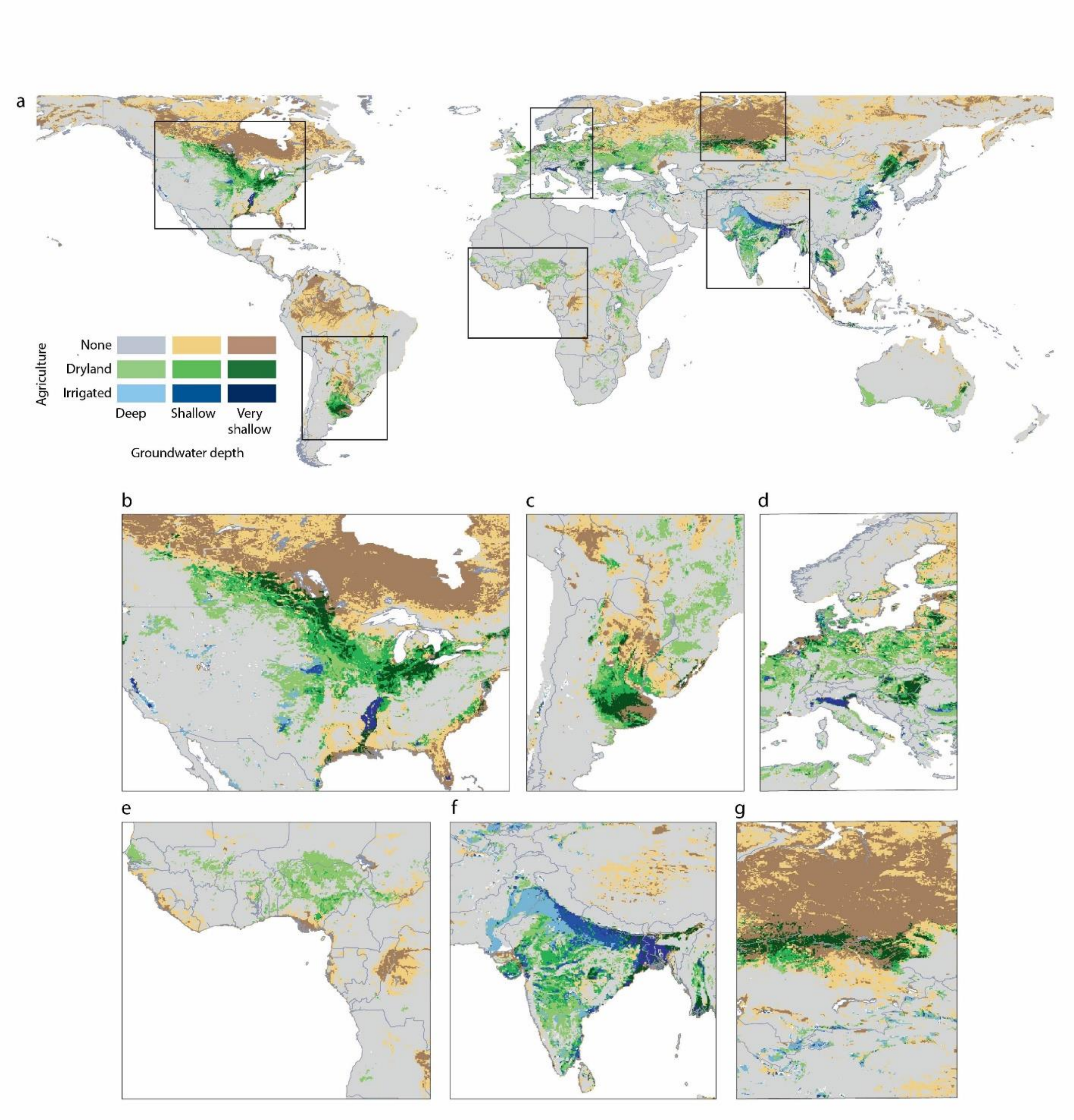

Figure S3. **Relationship between agricultural development and groundwater depth.** a) global map**.** b) the United States and Canada. c) the Pampas and Chaco regions of South America. d) the Po Valley in Western Europe. e) West Africa. f) India and Pakistan. G) border region of Kazakhstan and Russia. Cells are classified as agricultural if cropland areas exceed 30% of a cell's area. Irrigated agriculture is estimated from cell areas with ≥ 30% irrigated area. Groundwater depths of ≤ 3 m, 3 – 10 m, and > 10 m correspond to very shallow, shallow, and deep groundwater, respectively. Data sources include cropland data[41], water table depth[42].

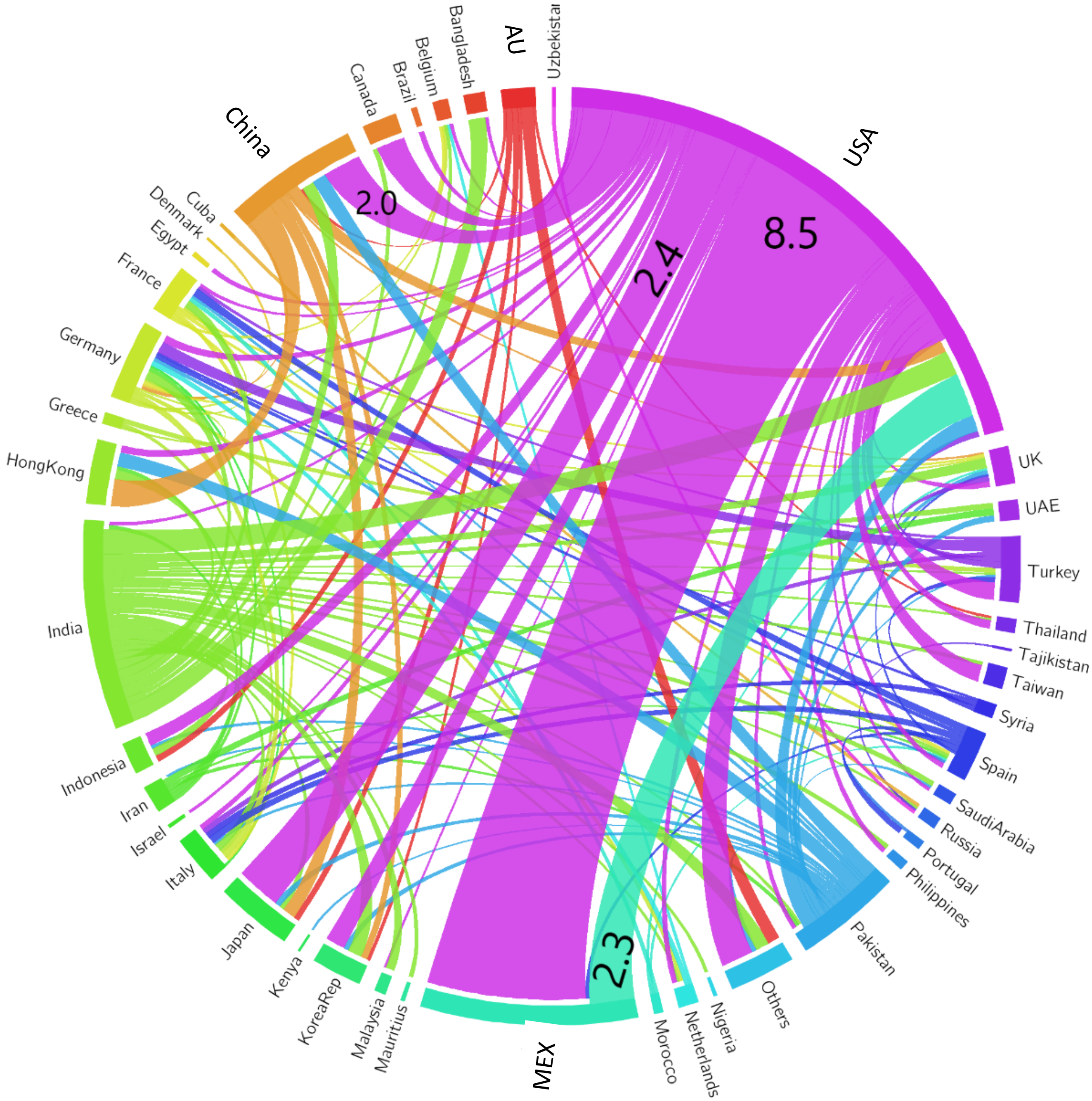

Figure S4a. Virtual groundwater flows between countries based on data from 1996 - 2005. Numbers indicate volumes in km^3 and the colors of the links correspond to the exporting country. Data were derived by combining the blue virtual water flows and the share of irrigated area served by groundwater. Data are provided in Table S8b. For example, virtual groundwater flows associated with USA exports to Mexico is 8.5 km^3/yr and Mexican exports to US is 2.3 km^3/yr.

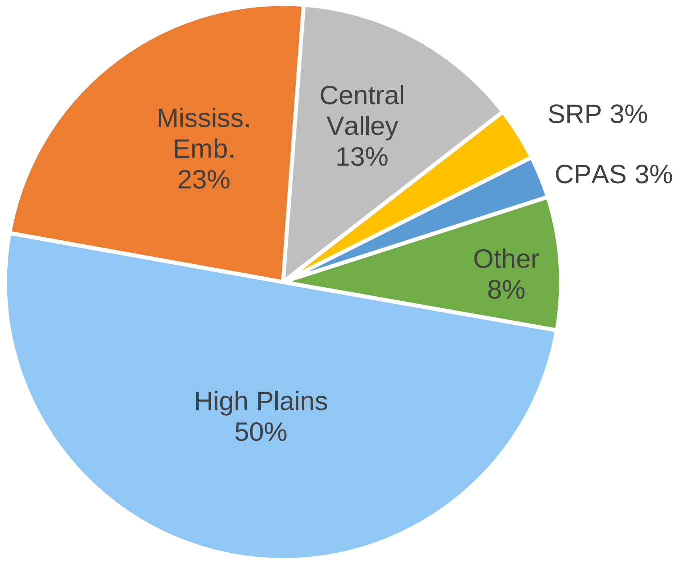

Figure S4b. Virtual groundwater export for major US aquifers. Numbers represent percentages of total volume. The data along with the source are provided in Table S8c. Mississ. Emb.: Mississippi Embayment; SRP: Snake River Plain; CPAS: Columbia Plateau Aquifer System.

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