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Supplement of

GCAM–GLORY v1.0: representing global reservoir water storage in a multi-sector human–Earth system model

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1. Review of Reservoir Storage Representation in Global Multi-Sector Dynamics (MSD) Models

Table S1 provides an overview of the representation of reservoir storage across a representative sample of global multi-sector dynamic (MSD) models designed to explore the interactions among climate, land, energy, water, and socioeconomic (CLEWS) systems from regional to global scales. MSD is an emerging transdisciplinary field that models complex systems of systems that deliver services, amenities, and products to society (Reed et al., 2022). A small subset of MSD models maintain full global coverage (i.e., model the entire world), and contain a diverse set of multi-sectoral CLEWS interactions that differ across models. The GCAM model is the focus of this paper. Table S1 is a representative, rather than exhaustive, list of models intended only to provide a broader context regarding the class of global MSD models that GCAM resides within. While we classify all of the models in Table S1 as global MSD models, a separate but long-standing body of literature also refers to many of these models as "Integrated Assessment Models" (or IAMs; Weyant, 2017; Fisher-Vanden and Weyant, 2020). We use the label "global MSD model" here for multiple reasons, including to denote that models such as GCAM have substantially evolved with regard to spatiotemporal and sectoral process resolution, and have placed increasing focus on impacts, adaptation and vulnerability, and have thus evolved substantially enough from the original simple climate-energy "IAMs" to warrant a new clarifying label (global MSD model). It is also worth noting that each "model" may actually include a whole suite of models designed to interact with one another.

As shown in Table S1, the models share similarities along the "water availability" and "water supply" dimension (see definitions below Table 1). Reservoirs appear most prominently in the water supply category. The models are similar in the sense that they all include (often as part of a broader multi-model framework) a hydrology model (e.g., LPJmL), which in turn may (or may not) represent reservoir storage. While the hydrology models may represent reservoir storage, we find that they often do not represent "reservoir storage expansion", including GCAM. Thus, we believe the current study is a novel contribution to considering global reservoir storage expansion. While not the focus here, the global MSD models differ significantly along the water demand dimension, including whether the process is handled exogenously or endogenously to the core global MSD model, as well as with regard to the approaches (e.g., economic versus physical) for allocating scarce water resources to different demand sectors.

Table S1. Review of reservoir storage representation in selected global MSD models that incorporate concepts of water resources.

Model	Hydrologic Model	Water Availability[1]	Water Supply[2]	Water Demand[3]	Reservoir Storage Representation	Reservoir Classification	Reservoir Expansion	Citation
AIM-Hub	H08	Exogenous	Exogenous	Endogenous	Yes	Yes	No	(Masui et al., 2011)
ANEMI3	None	Endogenous	Endogenous	Endogenous	No	No	No	(Breach and Simonovic, 2021)
GCAM	Xanthos	Exogenous	Endogenous	Endogenous	No	No	No	(Calvin et al., 2019; Kim et al., 2016)
REMIND-MAgPIE	LPJmL	Exogenous	Endogenous	Exogenous	No	No	No	(Baumstark et al., 2021; Mouratiadou et al., 2016)
IGSM-WRS	CLM	Endogenous	Endogenous	Endogenous	Yes	No	No	(Strzepek et al., 2013)
IMAGE-LPJmL	LPJmL	Endogenous	Endogenous	Endogenous	Yes	Yes	No	(Stehfest et al., 2014)
MESSAGEix-GLOBIOM	CWatM	Exogenous	Endogenous	Endogenous	No	No	No	(Krey et al., 2020; Fricko et al., 2016)

[1]water availability is the maximum available renewable and non-renewable water for human related activities.

[2]water supply is the amount of water supplied to the demand sectors from the available water.

[3]water demand is the amount of water demanded from the demand sectors.

2. Cost – Slope Relationship

Table S2. Estimated normalized unit cost – mean slope relationships for various size classes of storage capacity (Wiberg and Strzepek, 2005).

Size Class	Storage Capacity (million m³)	Normalized Unit Cost Equation (function of mean slope) (Cost per m³)
I	0 – 25	$y = 0.0197x^2 + 0.0538x + 0.5818$
II	25 – 49	$y = 0.0295x^2 - 0.0044x + 0.4456$
III	49 – 74	$y = 0.0340x^2 - 0.0310x + 0.3982$
IV	74 – 123	$y = 0.0370x^2 - 0.0521x + 0.3655$
V	123 – 247	$y = 0.0372x^2 - 0.0607x + 0.3094$
VI	247 – 493	$y = 0.0368x^2 - 0.0671x + 0.2633$
VII	493 – 1,233	$y = 0.0372x^2 - 0.0607x + 0.3094$
VIII	1,233 – 2,467	$y = 0.0362x^2 - 0.0824x + 0.1895$
IX	2,467 – 4,934	$y = 0.0368x^2 - 0.0671x + 0.2633$
X	4,934 – 12,335	$y = 0.0334x^2 - 0.0868x + 0.1427$
XI	> 12,335	$y = 0.0314x^2 - 0.0896x + 0.1111$

3. Runoff and Demand Patterns

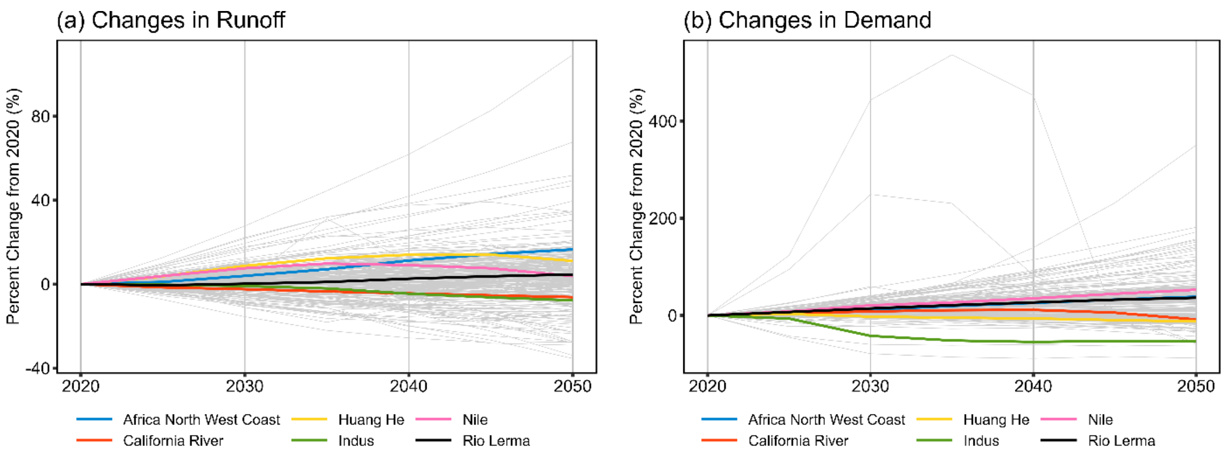


Figure S1. Percent change of (a) annual runoff and (b) annual demand (with feedback) from 2020 for global 235 basins under the selected climate change forcing. Six example basins are highlighted.

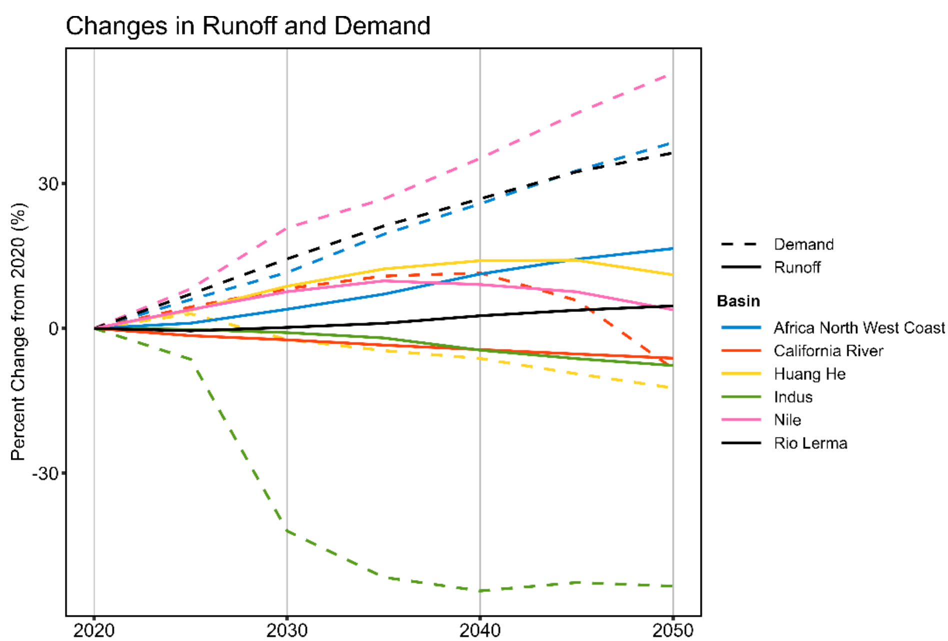
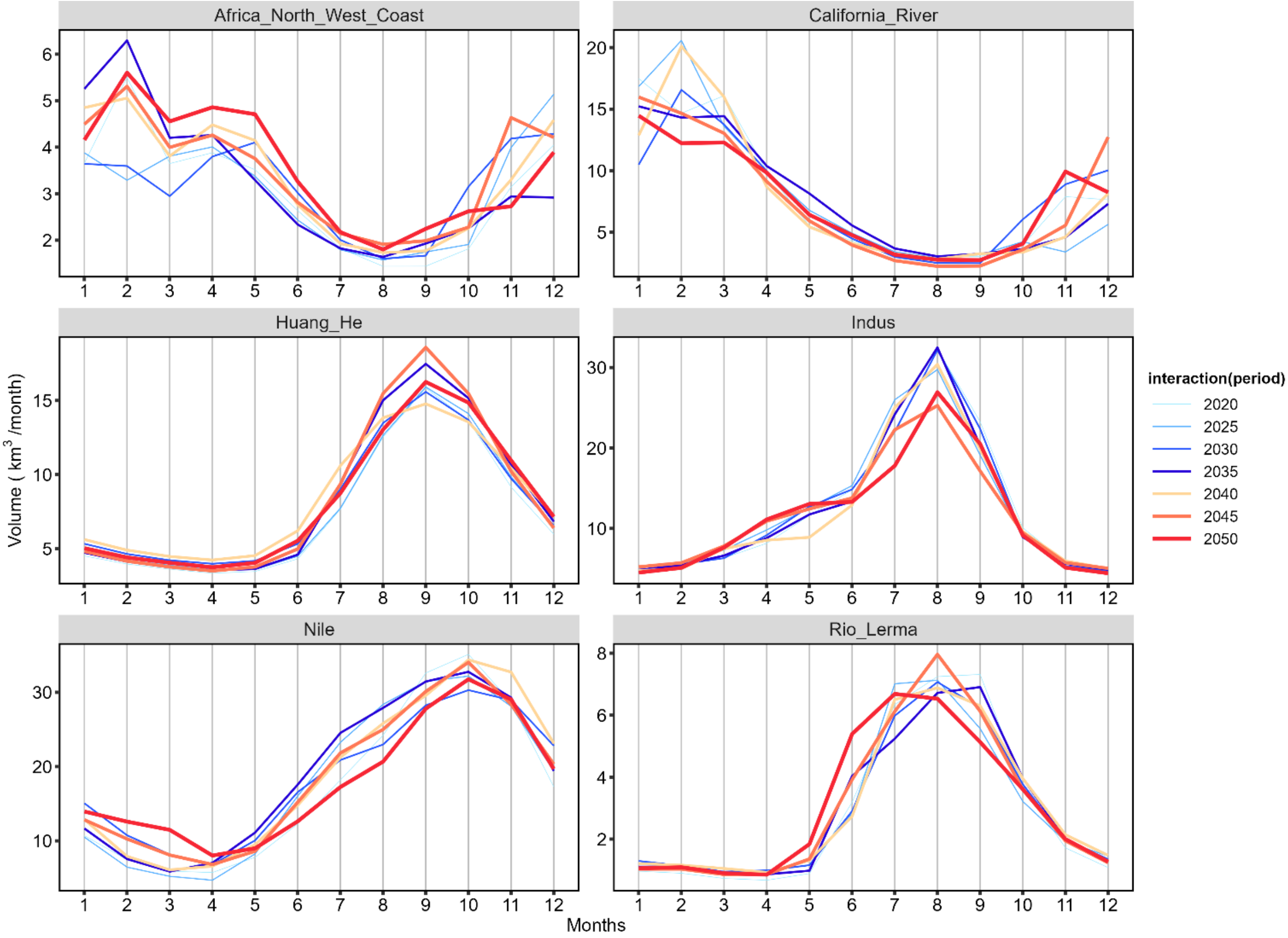


Figure S2. Relative change in both annual natural runoff (solid lines) and demand (dashed lines) in the Feedbacks scenario from 2020.



45 **Figure S3. Monthly runoff from 2020 to 2050 for selected basins.**

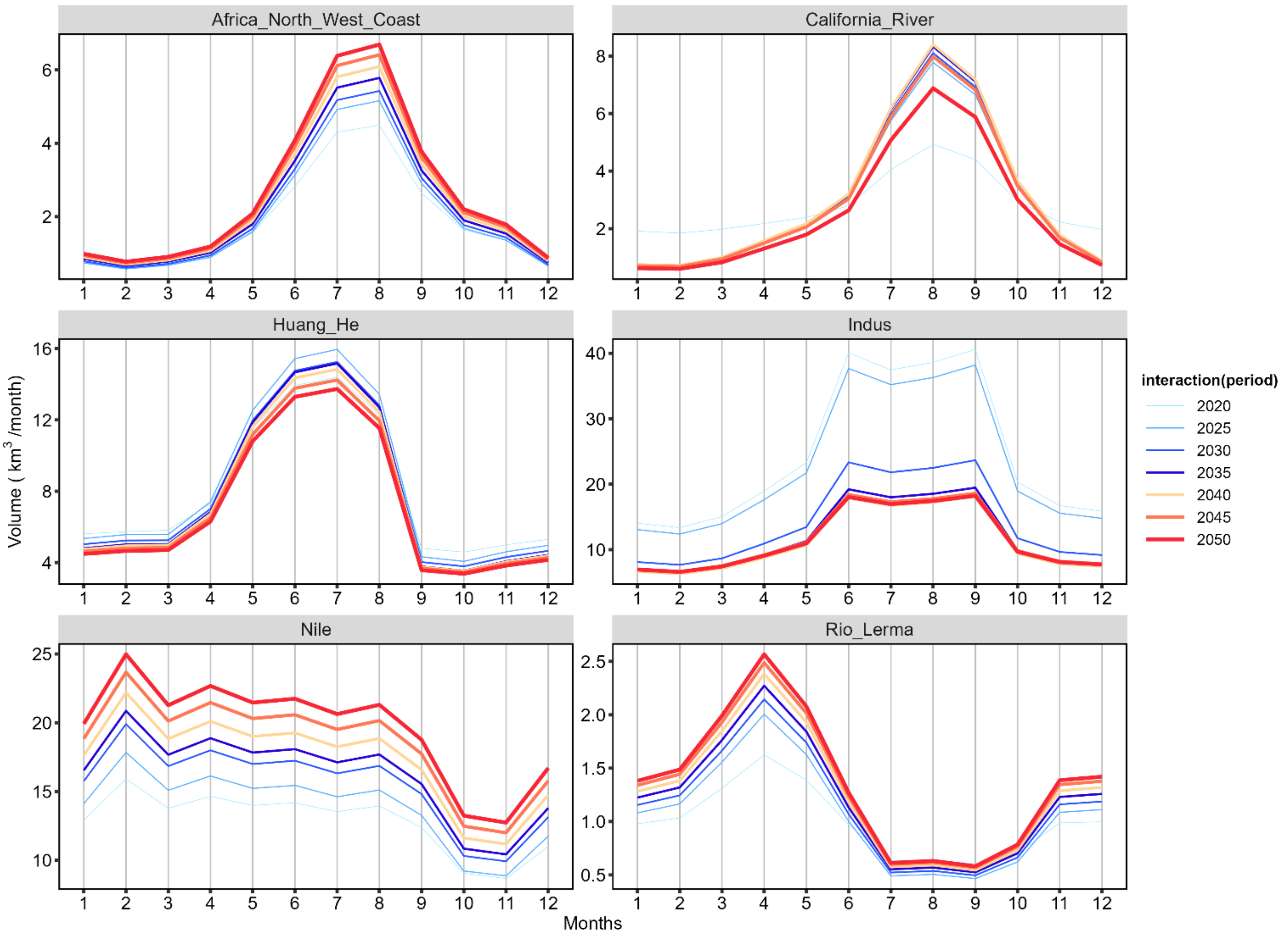


Figure S4. Monthly demand shifts from 2020 to 2050 under *Feedbacks* scenario for selected basins. For *No Feedbacks* scenario, monthly demand for all periods is the same with the monthly demand in 2020.

50

4. Excluded Grid Cells for Reservoir Expansion

To standardize disparate data formats and resolutions, we homogenized population, protected areas, irrigated croplands, and water bodies data. Employing techniques like rasterization, aggregation, and geo-referencing, we unified all layers to a consistent 0.5-degree resolution. The initial population data, at 0.125-degree resolution, underwent density calculations within grid cells, followed by mean-based aggregation to achieve the 0.5-degree resolution. Bilinear resampling was then applied to align population density with the target coordinate system. Similarly, protected area data, initially in shapefile format, was rasterized to 0.125-degree resolution. Utilizing a binary representation for presence, grid cells were labeled as 1 if any protected land existed, employing the "nearest neighbour" method during resampling. Irrigated cropland data, already at 0.5-degree resolution and within the target coordinate system, required no additional adjustments. Global lakes and wetlands data, originally at 30 arcsecond (~0.00833 degree) resolution, designated different water body types as numerical labels. Focusing on types 1, 2, and 3 (lakes, reservoirs, and rivers), corresponding grid cells were marked as binary 1. The raster was then aggregated to 0.5-degree targeted coordinate system using max values.

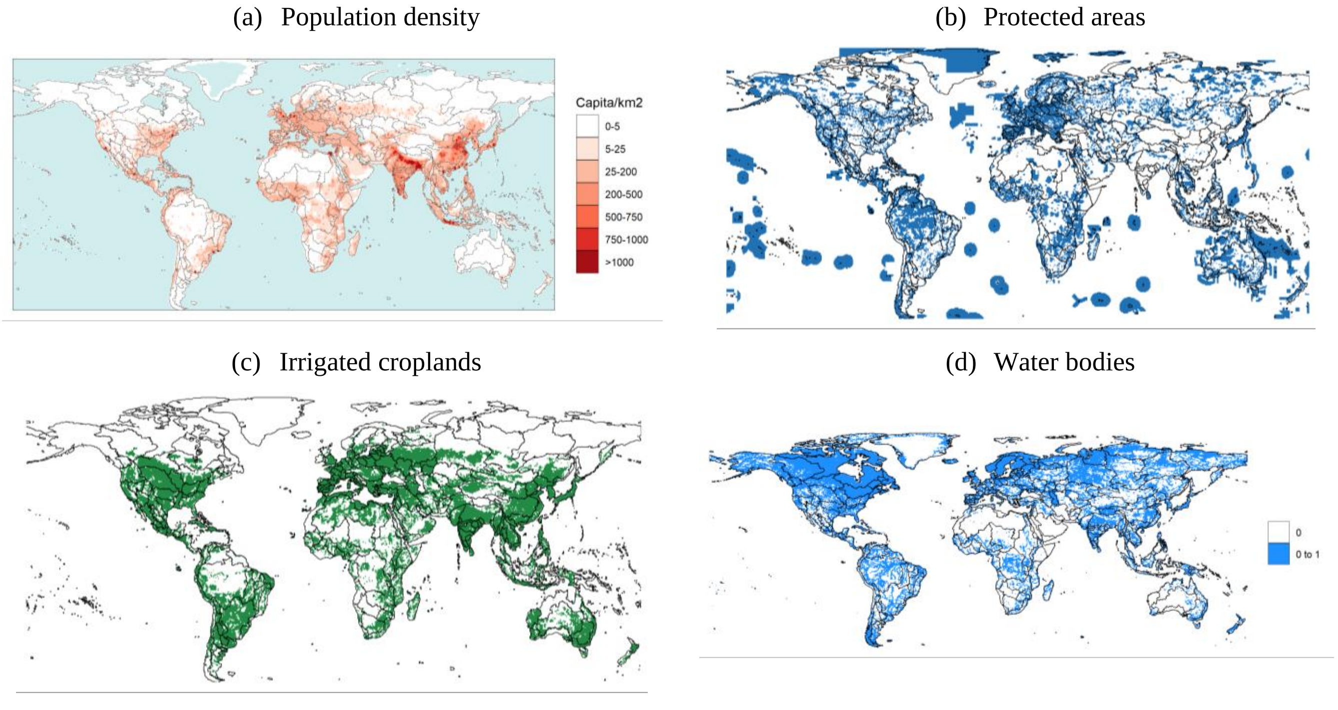


Figure S5. Exclusion layers using four criteria: (a) population density for the grid cell is higher than 1,244 capita per km^2; (b) the grid cell has protected land; (c) more than 10% of the land cover within the grid cell is crop land; and (d) no water bodies exist in the grid cell.

5. Capacity – Yield Curves

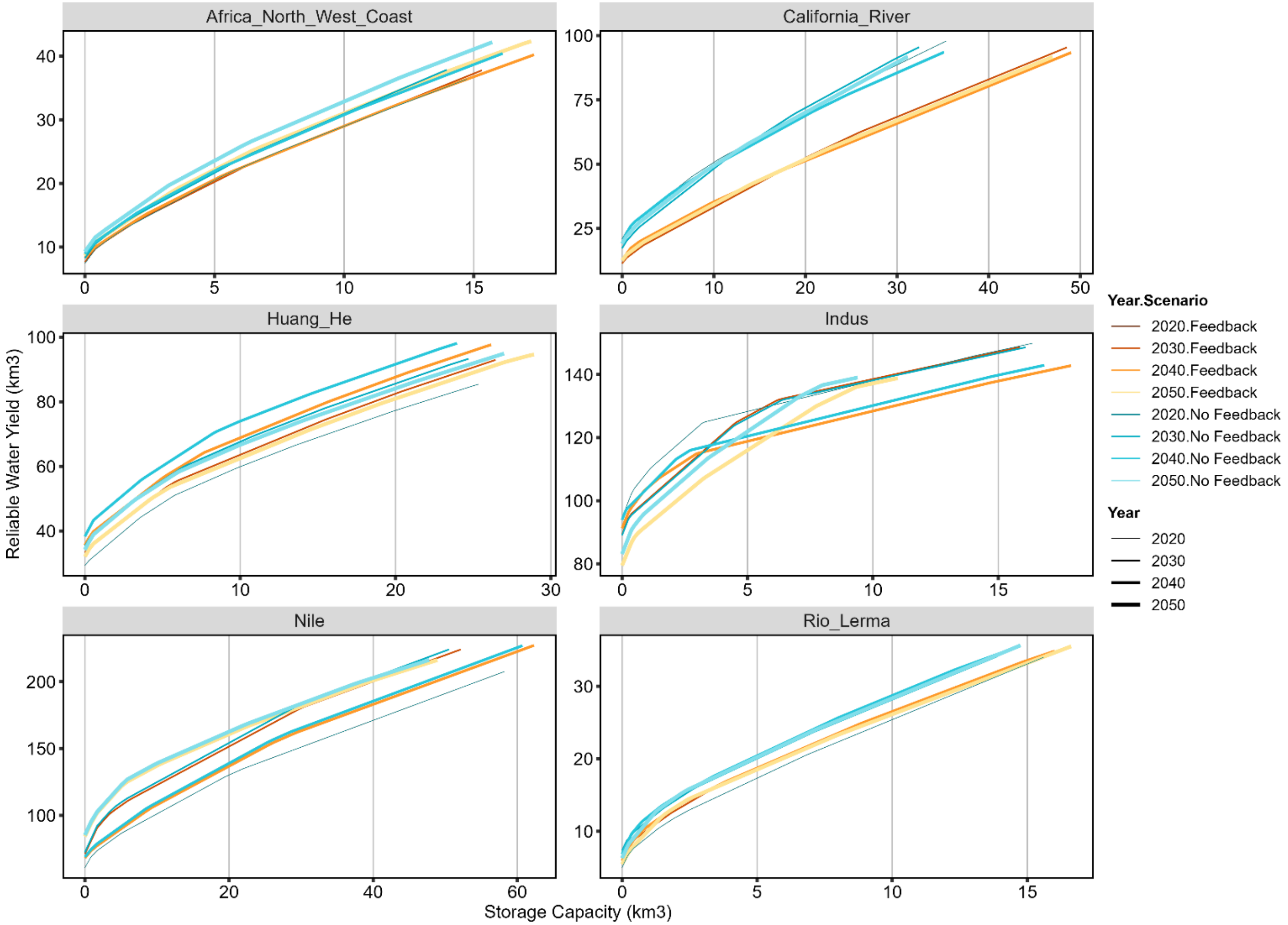


Figure S6. Capacity – Yield curves for 2020 – 2050 at 10-year interval for selected basins for *Feedback* and *No Feedback* scenarios.

6. Reservoir Storage – Surface Area Relationship

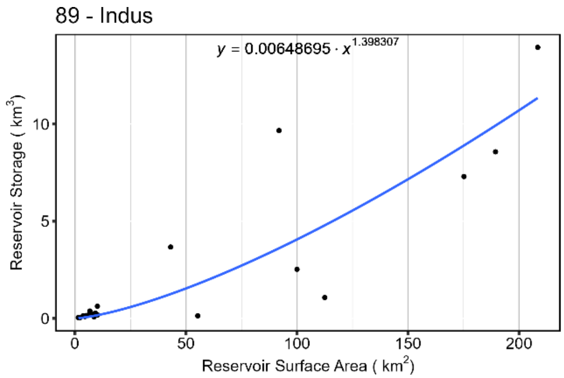


Figure S7. Example of non-linear relationship between storage capacity and reservoir surface area in Indus.

7. Cause and Effect

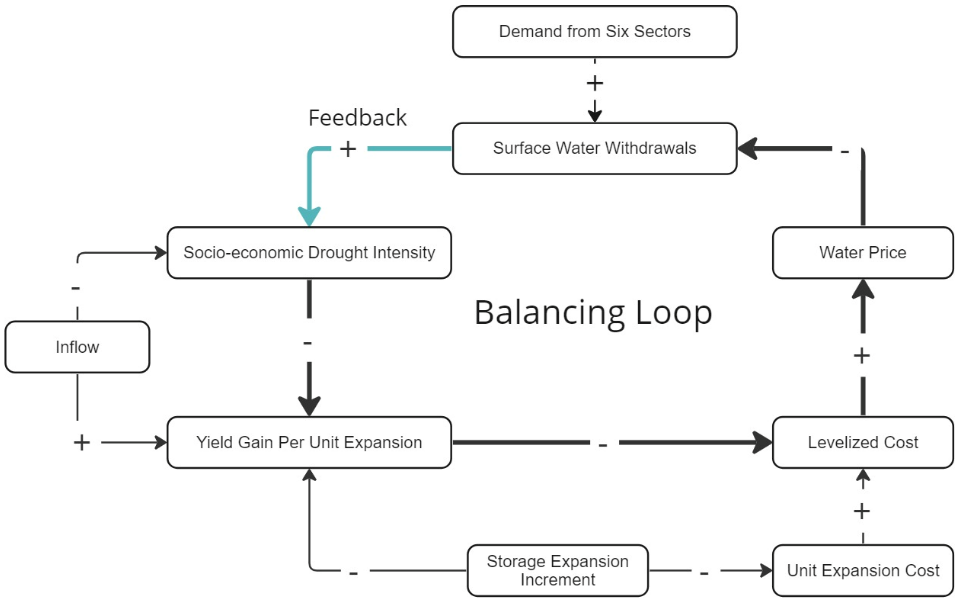


Figure S8. Causal loop diagram of metrics and drivers. The "+" sign means the two variables are positively related, and the "-" sign means the two variables are negatively related. The thick arrows are part of the balancing loop. A balancing loop is formed when there are odd numbers of "-" signs in a loop.

8. Reservoir Expansion Pathway

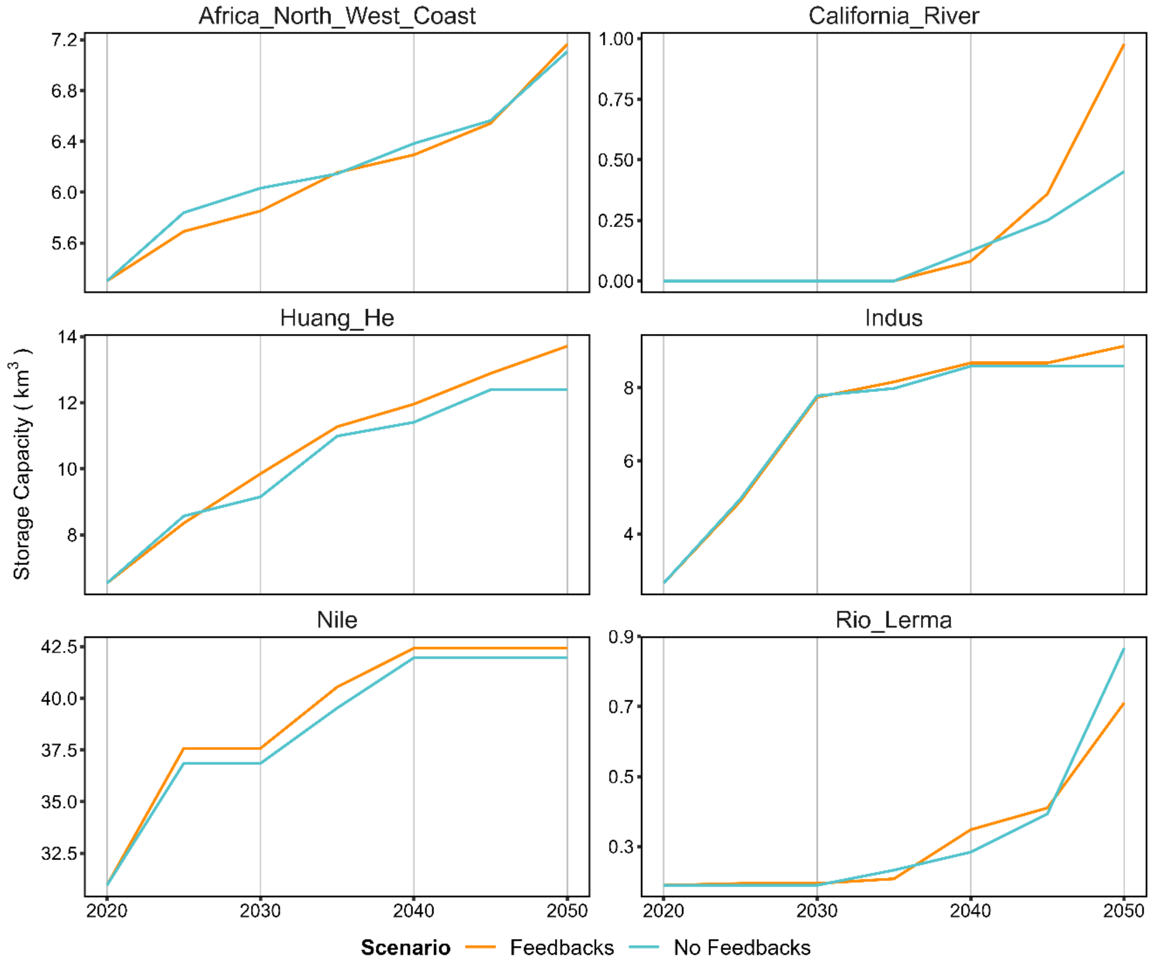


Figure S9. Minimum reservoir storage capacity expansion pathways for example basins. This storage capacity is back-calculated using GCAM solved withdrawal and capacity-yield curve for each GCAM period. The corresponding storage capacity indicated the minimum value required to supply the amount of demand. However, this value can be smaller than existing non-hydropower reservoir storage capacity.

9. Model Validation

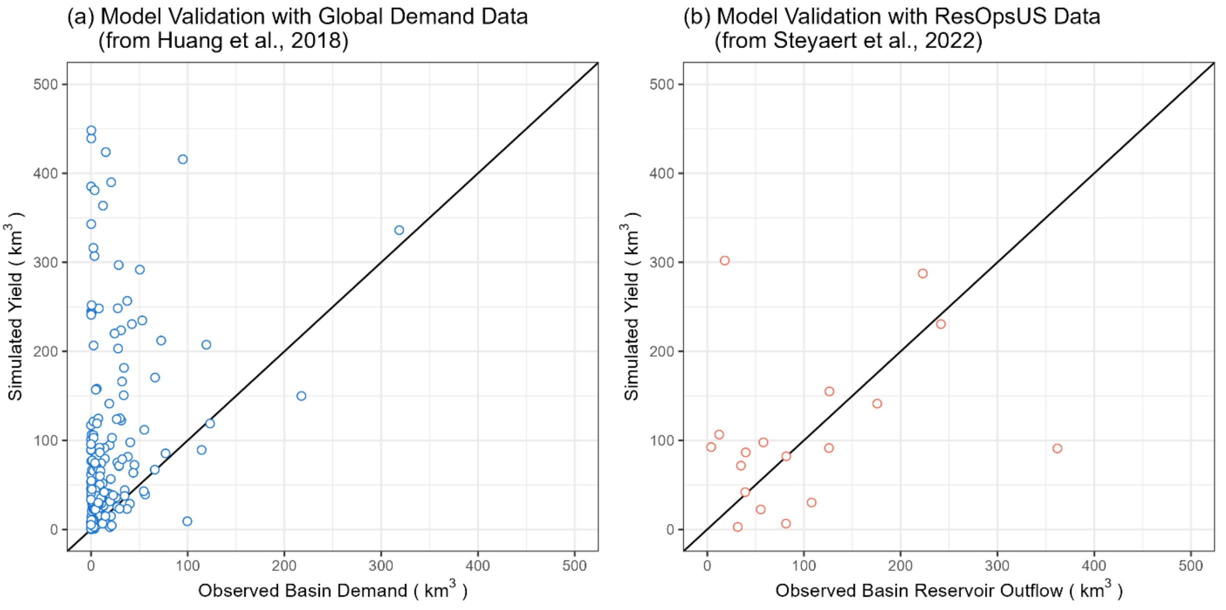


Figure S10. (a) Historical annual water demand in 2010 (Huang et al., 2018) vs. simulated water yield at basin level; the simulated basin yield from reservoirs are mostly above the observed demand indicating the fact that the firm yield served as an upper bound of water demand. (b) historical reservoir outflow in 2010 (Steyaert et al., 2022) vs. simulated water yield at basin level within the U.S. The simulated yield is expected to be similar to outflow of reservoirs.

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