Supplementary Information

SupplementaryTable 1

Conditions where SPS could be used for energy and water storage.

Challenges	Benefits of deploying seasonal pumped-storage
	Energy storage benefits
Highly seasonal hydropower generation[24,29,30]	- Increase water and energy storage in water basins to regulate the river flow and increase hydropower generation. - Store excess water during periods of high hydropower generation and reduce spillage.
Goal for CO_2 emissions reduction[31–33]	- Hydropower, solar and wind generation usually do not have the same seasonal generation profile as the demand for electricity. Natural Gas is an option for flexible electricity generation, however, it is a fossil fuel based source of energy and emits CO_2. A seasonal storage option should be considered by countries that intend to considerably reduce CO_2 emissions.
Increase in solar power generation in countries at high latitudes[34]	- Countries in high latitudes have a strong seasonal solar power generation profile. Seasonal storage allows using the energy stored in the summer during the winter, when there is lower solar generation.
Seasonal demand variations	- Countries in mid and high latitudes tend to have a seasonal electricity demand profile, consuming more electricity summer for cooling and during the winter for heating purposes, respectively. Typically, the peak national grid demand can be two to three times as high as the minimum demand[35].
Electrification of the heating sector	- With the electrification of the heating sector in countries at high latitude, the demand of electricity during the winter will increase even further.
Low energy security[36,37]	- Reduction in fluctuation of electricity prices with fossil fuel prices and supply. - Reduction in fluctuation of electricity prices with renewable energy availability, especially hydropower. - Reduction in fluctuation of electricity prices with the demand for electricity.
Low power plant capacity factor	- Large part of the generation capacity of a country is at stand-by for energy security reasons. The number of stand-by plants would reduce it seasonal pumped-storage is implemented.
Island electricity generation[38,39]	- Costs of oil and diesel based electricity generation might be higher than the combination of renewable sources and energy storage.
	Water storage benefits
Inappropriate topography	- SPS plants can store water on higher ground away from the river, in cases where along the river is infeasible
High evaporation rates	- Water storage in reservoirs with high level variation considerably reduces evaporation rates due to higher volume to area ratio.
High storage reservoir sedimentation	- SPS projects have much smaller sedimentation rates than conventional dams due to the small catchment area.
Lower environmental and social impacts[40]	- Damming a major river for storage would result in higher environmental and social impact than damming a small tributary river. SPS allows water storage without fragmenting the ecosystem of a main river.
Better water quality control	- Storing the water parallel to the river, allows for a better control of the water quality in the reservoir. As it would not be directly affected by the fluctuations in water quality in the main river.
Flood control	- SPS plants can be used in combination with conventional flood control mechanisms to improve their efficacy.

Transport with waterways	- SPS plant channels could be also used for transport in waterways, combining the transport of water and goods. Additionally, the improvement in water management resulted from a SPS plant would reduce the changes that a waterway runs out of water.
Interbasin Transfer	- SPS projects can be combined with an interbasin transfer project to increase the water security of a region or provide balancing between watersheds.
Water security	- Increase the water storage capacity in regions where conventional storage reservoirs are not appropriate.

Supplementary Table 2
Description of the data and methods applied in the model.

Data and methods description	Available resolution	Utilized resolution	Comments	Links in the paper	Reference
Topographical data (SRTM)	3 sec 90 x 90 m*	15 sec 450 x 450 m*	The reduction in resolution assumes the central point of the 5x5 data	Fig. 2a	[19]
River Network, Strahler data (GRIN)	15 sec 450 x 450 m*	15 sec 450 x 450 m*	This data is derived from the same topographical data above. This is used to give a better estimate of the tunnel length connecting the river and the reservoir.	Fig. 2b	[20]
Hydrological data (PCR-GLOBWB)	6 mins 10.8 x 10.8 km*	6 mins 10.8 x 10.8 km*	The annual discharge, seasonality and inter annual variation are derived from this data.	Fig. 2g	[21]
Pumped Storage Costs	-	-	This reference gives very detailed data on pumped-storage costs.	Estimate Project Cost Stage	[26]
Engineering Design	-	-	The methodology used in this reference was used to design the pumped-storage projects.	Estimate Project Cost Stage	[25]

* Distance at the equator, which is corrected with changes in latitude.

Supplementary Table 3
Seasonal-pumped storage world potential model stages description.

Model stages	Description	Links in the paper
Select Point Under Analysis (PUA)	This section consists of combining topographic and the river Strahler data and going through each land grid square around the world looking for SPS projects considering the limitations presented in this paper.	Supplementary Table 2
River Screening	This stage looks if the location was a river with a reasonable amount of water to store. It makes sure that the SPS upper reservoir is not in the same river as the lower reservoir, i.e. it is a parallel river. If finds rivers with Strahler higher than 7 at a distance from 3 to 30 km distance from the Point Under Analysis (PUA) and the model continues. If there are rivers with different river Strahler of 7 to 12 at less than 30 km from the upper reservoir the model will create a different SPS project for each river.	Fig. 2a
Dam Screening	This stage creates four different dams in the given orientations: W to E, N to S, NE to SW, NW to SE. The dam height varies from 50 to 250 m, at 50 m intervals. Each grid square can have projects with five different dam heights.	Fig. 2b

Dam Lowest Point	In order to reduce the number of interactions, this stage checks if the pixel under analysis is the lowest point of the proposed dams. If it is the lowest point of the proposed dams, the model continues developing the SPS project. This grid cell usually coincides with a tributary river.	Fig. 2c
Reservoir Side and Flooding	This stage checks, which side of the dam, should be flooded to build the reservoir. If the reservoir floods an area larger than 1,620 km^2, then the model floods the other side of the dam. If both flooded areas are larger than 1,620 km^2, then the project is discarded.	Fig. 2d
Reservoir Storage Capacity	Once the storage reservoir is flooded, the level of the reservoir varies to find the flooded area vs level and storage volume vs level curves. This is done by subtracting the volume of land and water with the reservoir at a given level by the volume of land and water with the reservoir at its minimum level. In the model the minimum level of the reservoir is assumed to be zero.	-
Estimate Project Cost	This section calculated the project costs, which are divided in dam, tunnel, powerhouse excavation, pump-turbine, electro-technical equipment and land costs.	Supplementary Tables 3, 4 and 7
Hydrological Analysis	The hydrology is included in the analysis to limit the water and energy storage capacity of the SPS projects according to the availability of water in the main river. The maximum water storage capacity is limited to 11% of the river flow. If the storage capacity is much higher than the amount of water available, the estimated cost of storage tends to zero, as the reservoir will never fill up.	Equation 1 Equation 2 Equation 3
Estimate Storage Cost	The project costs are compared with the hydrology of the river to find the water and energy storage costs.	Equation 4 Equation 5

Supplementary Table 4
SPS project parameters analysed and average value of selected projects.

	Minimum possible	Intermediate steps	Maximum possible	Minimum observed	Maximum observed	Average for water storage projects	Average for energy storage projects
Dam height (m)	50	50	250	50	250	140.7	151.7
Dam length (km)	0.32	0.32	7.20	0.32	7.20	1.70	1.65
Tunnel length (km)	2	3	30	3	30	22.2	22.7
Land requirement (km^2)	0.2	0.2	1,625	3.3	1366.4	34.2	36.4
River Strahler	7	1	12	7	11	7.48	7.44
Minimum head (m)	25	-	1200	134.5		478.3	602.0
Level variation (m)	-	-	-	50	250	140.6	151.7
Storage volume (km^3)	-	-	-	0.20	56.89	1.89	-
Energy storage (TWh)	-	-	-	0.93	495.52	-	8.33
Land use / water storage (km^2/km^3)	-	-	-	5.6	68.2	19.7	-
Land use / energy storage (km^2/TWh)	-	-	-	0.40	209.4	-	6.31
River discharge (m^3/s)	-	-	-	47.8	50604.0	1344.9	1149.8
Seasonality variation	-	-	-	0.04	2.22	0.76	0.80
Inter annual variability variation	-	-	-	0.03	5.80	0.57	0.56
Pumping flow (m^3/s)	-	-	-	94.5	842.1	267.5	213.2
Dam cost (B $)	-	-	-	0.044	6.749	0.653	0.655

Tunnel cost (B $)	-	-	-	0.100	39.606	0.881	0.696
Excavation cost (B $)	-	-	-	0.051	0.073	0.059	0.059
Pump-turbine cost (B $)	-	-	-	0.081	0.125	0.090	0.088
Electrotechnical equipment cost (B $)	-	-	-	0.168	0.201	0.171	0.170
Land cost (B $)	-	-	-	0.0151	6.181	0.155	0.165
Water storage cost ($/m^3)	-	-	-	0.007	0.2	0.104	-
Energy storage cost without cascade ($/MWh)	-	-	-	4.606	50.0	-	30.139
Energy storage cost with cascade ($/MWh)	-	-	-	1.832	50.0	-	24.841
Energy storage costs ($/GW)	-	-	-	0.372	0.6	-	0.459

Supplementary Table 5
Selected project parameters change with dam height.

Dam height (m)	Dam length (km)	Land req. (km^2)	Water storage ($/km^3)	Water Storage volume (km^3)	Energy storage without cascade ($/MWh)	Energy Storage without cascade (TWh)	Energy storage with cascade ($/MWh)	Energy Storage with cascade (TWh)
50	0.40	13.0	0.069	0.60	34.8	1.19	11.66	3.56
100	1.21	15.8	0.037	1.31	18.0	2.68	6.16	7.86
150	1.21	16.7	0.034	2.12	16.3	4.46	5.66	12.80
200	1.21	19.5	0.036	3.02	16.8	6.53	5.96	18.42
250	1.21	22.1	0.046	4.03	20.8	8.97	7.52	24.85

Supplementary Table 6
Selected project parameters that do not change with dam height.

Coordinates (lat./lon.)	Min. head (m)	Tunnel length (km)	River Strahler	River discharge (m^3/s)	Pumping flow (m^3/s)	River seasonality	River Inter Annual Var.	Short-term Energy storage (B $/GW)
N 28º43'43" E 97º02'44"	782	18	7	526	145	0.88	0.24	0.65

Supplementary Table 7
Assumptions, uncertainties, limitations and possible improvement of the model.

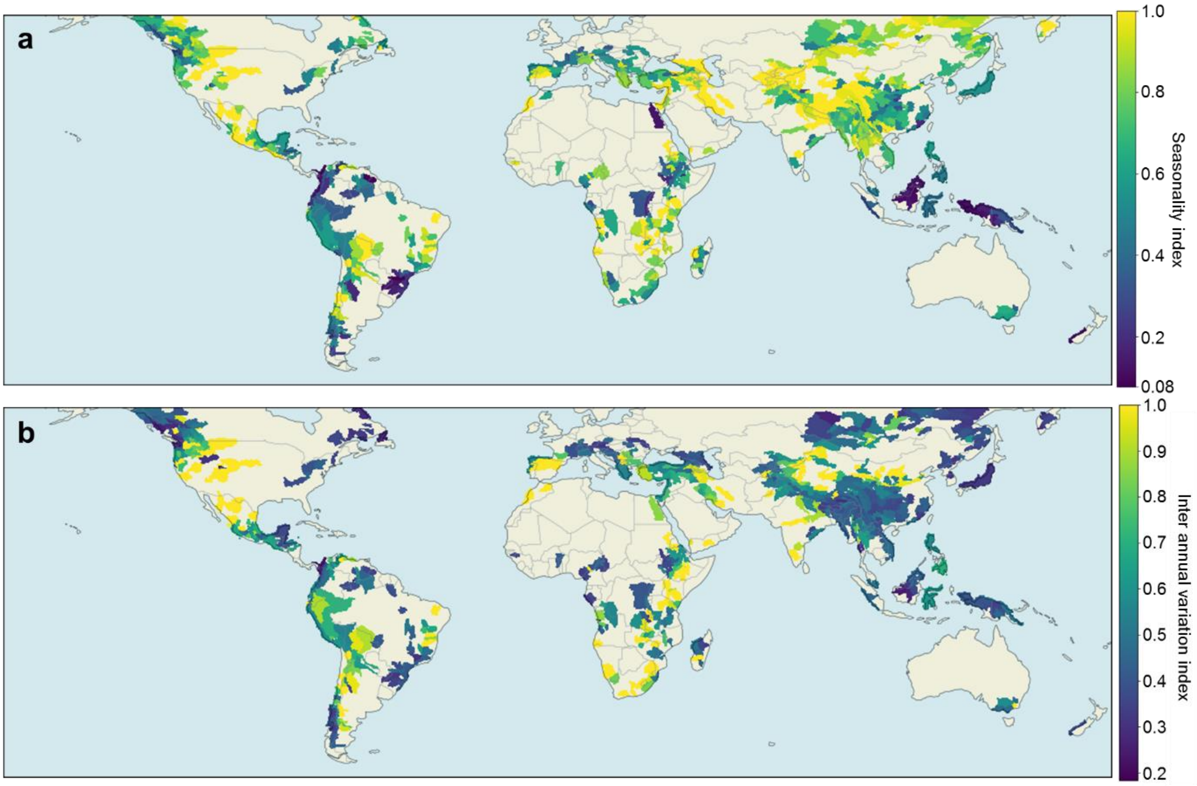
Title	Definition
Assumptions	
Dams in cascade	The model assumes that the energy storage potential is not only limited to the upper and lower reservoirs of the SPS project. It also includes the energy generated at the dams in cascade downstream the SPS plant. It is assumed that 60% of the hydropower head downstream of the SPS plant is developed.
Land costs	The model assumes that the land cost required for the reservoir is equal to 41,000 $/ha. This very high cost of land was assumed with the intention of reducing the flooded area of the selected projects as much as possible.

Latitude corrections	The model corrects the variation of the resolution of the gridded data according to the latitude. This correction is done in steps of 5° of latitude, according to the segmentation of the topographic data.
Uncertainties	
Segmented topography	The topography utilized in the study was divided into 5° sections. Dams, reservoir and tunnels that reach the borders of one topography file and another are discontinued and developed.
Hydrology data	The hydrological data is in 0.5° resolution, which is much lower than the topography resolution 15 sec resolution. Thus, there are sections of the river where the hydrology data give a much lower value. In these cases, it assumes the average value of the particular river Strahler flow in a 5° resolution.
Cost estimation	The cost estimates in this paper intend to give a rough estimate for project costs of the main components such as dam, tunnel, penstocks, generators, turbine, powerhouse excavations and land requirement. Some cost aspects are not included in these estimates, for example, builder costs (which mainly affect dam costs), access tunnels, transport facilities, substations, transmission lines, shafts, surge chambers, gates and valves. Some of these costs vary considerably with the country and local characteristics. The costs for tunnel excavation assumes an average value and does not include the type of rock or earth being excavated. The number and diameter of the tunnels are optimized with the minimization of the capital and operation costs, assuming a capacity factor of 70% for the utilization of the tunnel and an electricity price of $ 65/MWh.
Limitations	
Tunnel design	The tunnel design in the model is limited to the connection of the river with the middle of the dam. Even though this is usually the best design for the tunnels, this might not be always the design of the tunnel. The tunnel could connect to the river, leaving from any point below the minimum reservoir level.
Unique dam	The SPS projects in this model are limited to a single dam. This design covers the majority of the potential. However, there are locations where two or more dams would be required to build a reservoir or to increase its storage capacity.
Minimum reservoir level	The minimum reservoir level in this model assumes that all the reservoir volume would be used. This practice is not appropriate and a minimum reservoir level should be left in the reservoir due to environmental restrictions. These restrictions changes with the country.
Single SPS project	The model only creates one SPS project in parallel to the main river. A cascade of two or more SPS projects could be created to increase the potential energy of the water and increase the energy and water storage potential.
Closed-Loop SPS	Only open-loop SPS plants are considered in this model, which involve the extraction of water from a river. The river can have a small reservoir, however, the operation of the SPS has a substantial impact on the main river. Closed-loop SPS requires two large reservoirs, do not have a substantial impact on the river and are only used for energy storage. The inclusion of closed-loop SPS would considerably increase the world potential of SPS. However, two large reservoirs would be required, increasing the costs of the project. Additionally, there will be no hydropower plants in cascade to increase energy storage without additional costs.
Hydropower potential	The model does not attempt to estimate the additional hydropower generation from the tributary rivers where the upper reservoir of the SPS is built. In some cases, the tributary river flow is able to fill up the reservoir without the need for pumping water from the main river.
Energy and water complementarity	The needs for energy and water storage with SPS plants should be complementary. This is because during the dry season there will be low volumes of water available to be used for energy storage. This complementarity is usually the case in high latitude countries, where during the summer river flow is higher due to ice melting and energy demand is lower compared to the winter. Inter-tropical regions with abundant hydropower generation also have complementarity, where during the wet season there is high water availability and hydropower generation. However, there are regions and countries where the need for energy and water storage is not complementary, for example, in the inter-tropical regions without hydropower generation, where the summer and wet season is the period with highest electricity demand due to air conditioning. In cases where energy and water storage need are not complementary, SPS should not be

	considered as an energy and water storage alternative. Exceptions can be made to SPS projects that have heads higher than 800 meters, in which low volumes of water can store large volumes of energy.
Energy and water needs	The needs for energy and water storage needs are not included in this paper and are an important aspect when planning a SPS plant.
Restriction zones	Biodiversity exclusion zones, population density and relocation costs, costs for the connection of the SPS plant to existing transmission lines, variable costs of land and labour, taxes are not included in this paper.
Lakes	Existing lakes are not included as possible lower reservoir possibilities. The advantage of using a lake as the lower reservoir is because there are much smaller restrictions from pumping water from a lake, when compared to a river. The inclusion of lakes to the models would considerably increase the world potential of SPS.
Possible improvement	
Conservative water storage potential	In very dry locations, availability of water is restricted to a few weeks or months. In these cases, it might be advisable to store up to 50% of the river flow, so that the resource can be appropriately managed.

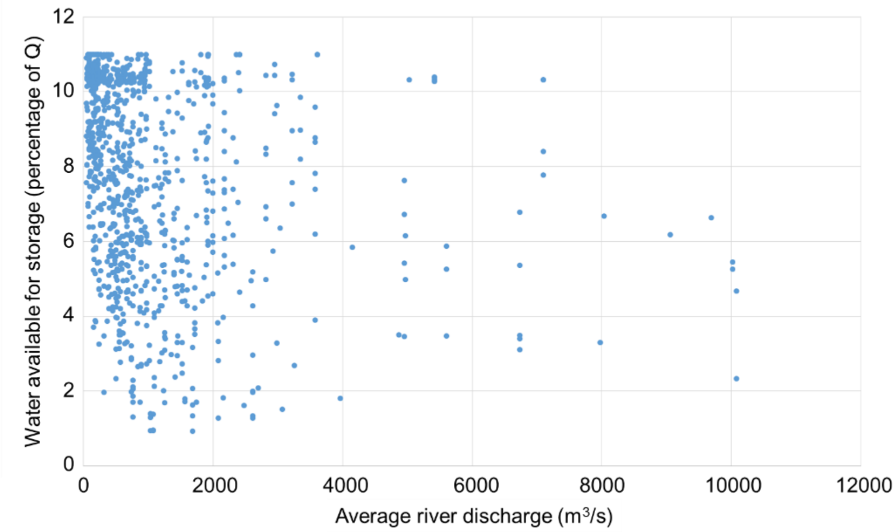
Supplementary Fig. 1

Seasonal and inter annual variation. a, accounts for all SPS projects in each basin and calculates the average seasonal variation of the rivers connected to the SPS reservoir. **b,** Average inter-annual variation.



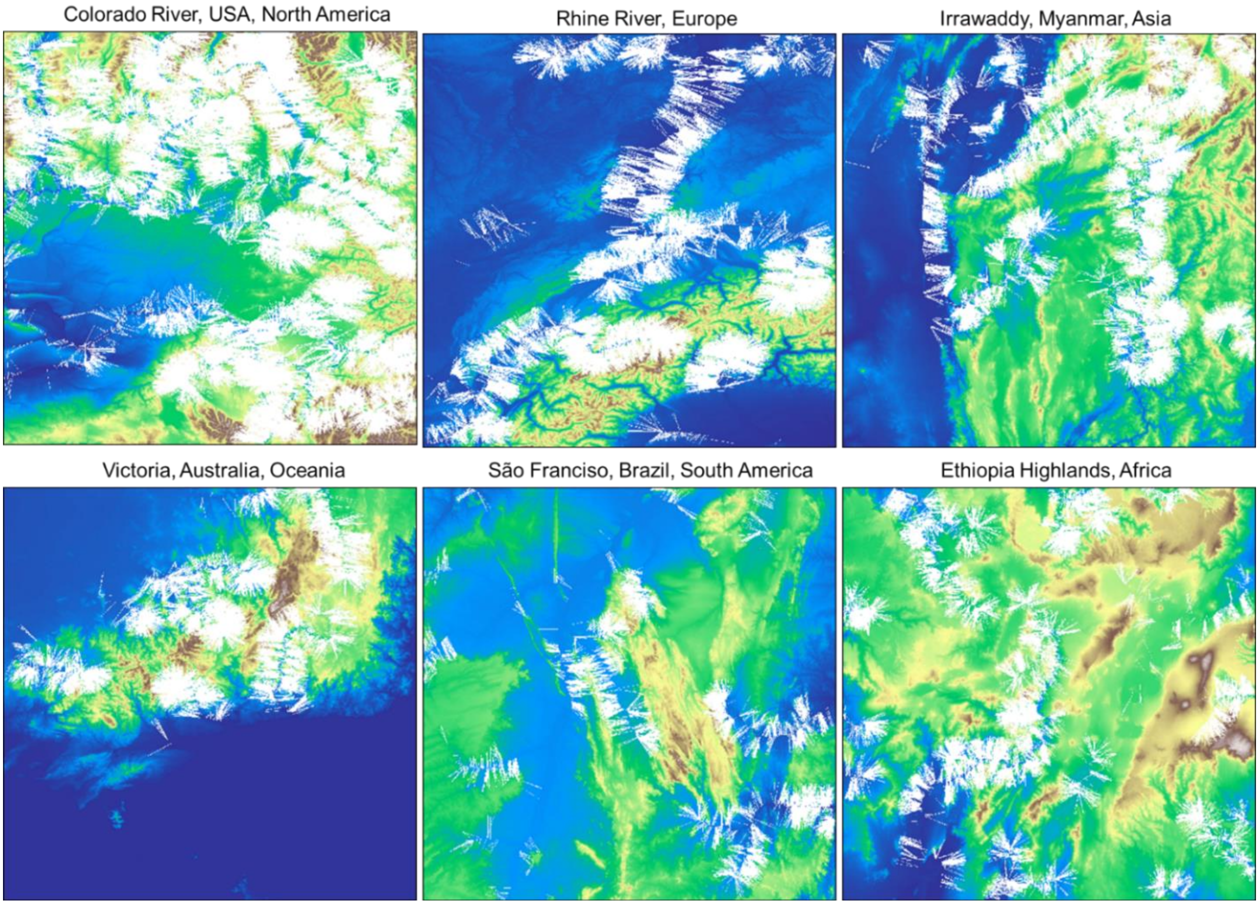
Supplementary Fig. 2

Water used for storage in SPS projects. The blue dots represent the proportion of water that each of the SPS projects extract from the river. As can be seen the withdrawal is constrained to 11% of the total flow of the river, although for many larger rivers the withdrawls can be significantly less.

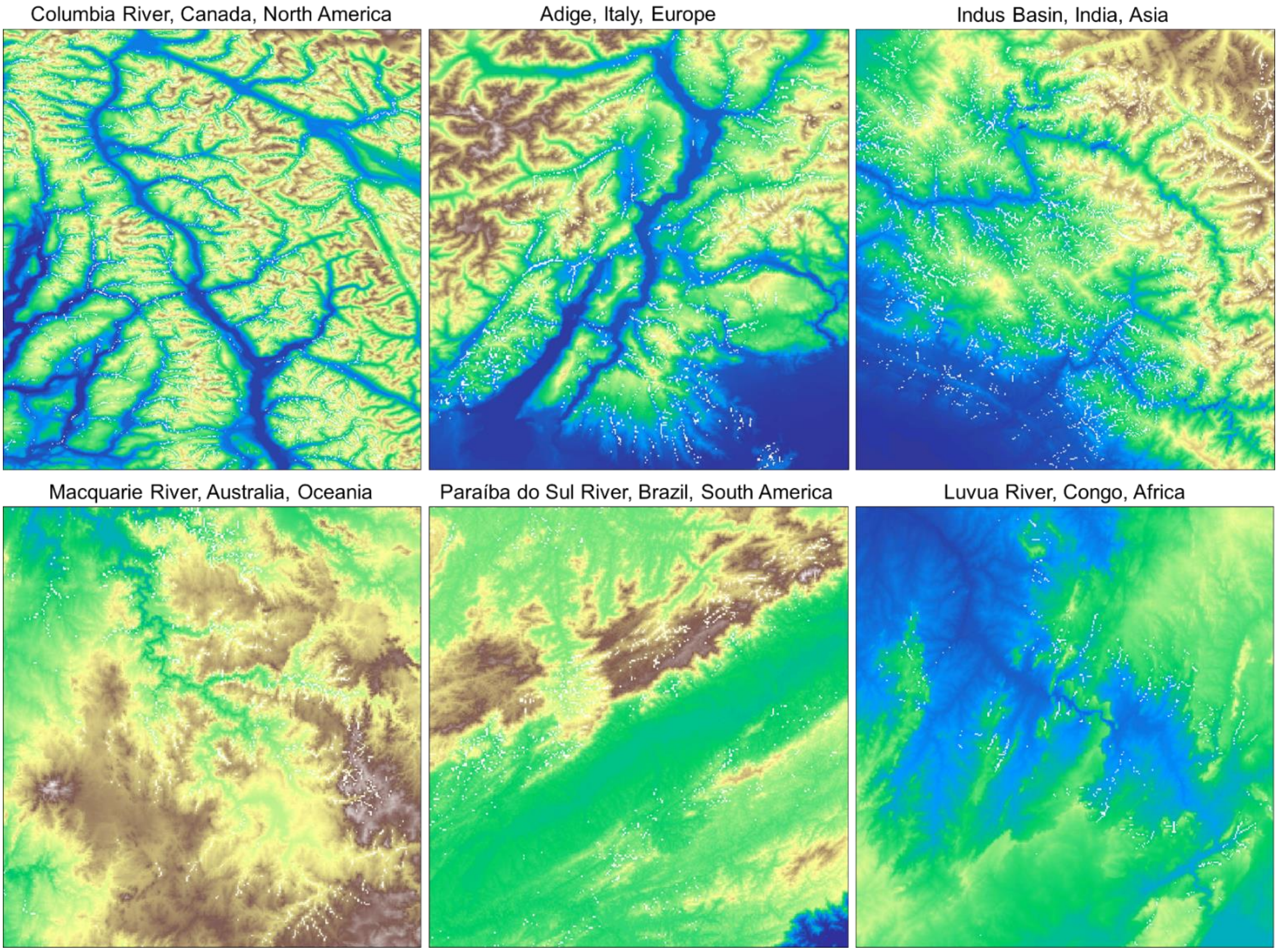


Supplementary Fig. 3

Proposed SPS pipelines. The white lines correspond to the pipelines proposed in the SPS world potential model in different locations. Note that from these projects only the cheapest in 1 degree resolution are considered in the paper.



Supplementary Fig. 4
Proposed SPS dams. The white dots represent the proposed dams in the SPS world potential model in different locations. The pixels marked are the lowest points (altitude) of each dam.


Columbia River, Canada, North America
Adige, Italy, Europe
Indus Basin, India, Asia
Macquarie River, Australia, Oceania
Paraíba do Sul River, Brazil, South America
Luvua River, Congo, Africa