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Hydropower and seasonal pumped hydropower storage in the Indus basin: pros and cons

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ABSTRACT

The Indus basin has a large hydropower untapped potential for electricity generation and to regulate the Indus river flow, which could reduce flooding events and provide water supply during drought periods. In this paper, a computational module is developed to localize potential sites for hydropower generation and seasonal pumped hydropower storage (SPHS). The levelized costs for hydropower generation in the basin with conventional dams are as low as 12 USD/MWh, the cost of energy storage is 1 USD/MWh. In case of SPHS plants, the cost of energy storage is 2 USD/MWh. It can be concluded that the conventional hydropower potential is, for the moment, less expensive than SPHS, but its potential in the Indus basin is limited to 26 GW with hydropower costs below 50 USD/MWh and its reservoirs have a short lifetime due to the high sedimentation rates of the basin. SPHS would be an interesting alternative to complement the hydropower potential adding long-term water and energy storage with fewer sediments, social and environmental impacts. Given that the region has the highest potential and lowest costs for SPHS in the world, it could become a major player on seasonal and pluri-annual energy storage in Asia and globally.

Introduction

Over the last decades, the world has been undergoing a boom in hydropower dam construction. Currently, at least 3,700 major dams, each with an installed hydropower capacity of more than 1 MW are either planned or under construction, primarily in countries with emerging economies. For example, in Europe 8,507 dams are planned to be built, and 278 are under construction, especially in the Balkan region. A total of 2,396 planned, and 77 currently under construction are located in protected areas [1]. The new dams installed worldwide are forecasted to increase the global hydroelectricity capacity from the current 1,200 GW to about 1,700 GW [2]. These dams often contribute to fulfilling broader socio-economic objectives: Pakistan and Ethiopia are examples for which the expansion of hydropower could close the gap for electricity access in the future [2,3].

The Indus basin still has a large hydropower potential to be

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Table 1
Description of the data and methods applied in the model.

Data and methods description	Available resolution	Utilized resolution	Reference
Topographical data (SRTM)	3 sec 90 x 90 m*	15 sec 450 x 450 m*	[43]
River Network, Strahler data (GRIN)	15 sec 450 x 450 m*	15 sec 450 x 450 m*	[44]
Hydrological data (PCR-GLOBWB)	6 mins 10.8 x 10.8 km*	6 mins 10.8 x 10.8 km*	[47]
Pumped Storage Costs	-	-	[46]
Tunnelling Design	-	-	[45]

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

developed due to its high altitudes in the upper Indus region and large water availability. It is very demanding to use water efficiently because the region still faces one of the biggest water management challenges worldwide. This is due to population growth and rapid urbanization, industrialization, and environmental degradation, lack of water storage infrastructure, or inefficient water use due to water losses in outmoded irrigation systems and poverty [4–7]. Groundwater is highly extracted, which reduces the groundwater level and further increases electricity demand for irrigation [4,8]. In addition, water scarcity and flooding also are aggravated by climate change [3]. Another issue that has been brought forward is the high volume of sedimentation in the upper Indus Basin, which increases the challenges for building dams in the region because they will rapidly fill up the reservoir with sediments. This was one of the main reasons why the Tarbela dam has already undergone three height extensions since its construction [4,9,10].

From a hydrological point of view, the Indus river is subject to highly seasonal inflows. This is because the snow and ice masses stored in the mountains of the upper Indus basin during the winter period melt during the summer, which considerably increases the flow of the river and its tributaries. Additionally, the thaw period coincides with the monsoon rainfalls, which also considerably increases the water flow in the rivers. This consequently leads to very seasonal river discharge patterns, regular flooding events during the summer and droughts during the winter.

Research has been carried out to better describe the basin and to analyze the availability of water resources, climate change impacts and possible water management solutions. Charles et al. [11] developed a methodology for forecasting seasonal streamflow in the upper Indus basin of Pakistan. Latif et al. [12] analyzed the precipitation time series over the Upper Indus basin. Ali et al. [13] assessed the runoff in two catchments of the upper Indus Basin by using a semi distributed hydro-glacial model. Faiz et al. [14] assessed the impact of precipitation variability in the stream flow of the Hindu Kush, Himalayan and Karakoram River basins of Pakistan. Immerzeel et al. [15] analyzed the precipitation in the upper Indus basin, taking into account glacier mass balances and runoff analysis. Nepal et al. [16] reviewed the impact of climate change on the hydrological regime of the Indus. Anjum et al. [17] analyzed spatial, temporal variability of snow cover. Hasson et al. [18] prevailed climatic trends and runoff response from the upper Indus Basin.

In addition, several studies have been carried out with the objective of estimating the hydropower and energy storage potential of the Indus basin. For instance, Zhou et al. [19] presented an exploitable potential for hydropower in Pakistan of 108 TWh per year, mainly located in the Indus Basin. Other studies estimate a feasible hydropower potential of about 60 GW [20–25]. This is significantly higher than the estimated hydropower installed capacity of 17 GW expected by 2040, to supply a yearly demand of 64,728 GWh in Pakistan [26]. The levelized costs of electricity (LCOE) estimated for hydropower in Pakistan range from 24 USD MWh^{-1} to 84 USD MWh^{-1} [23]. Hagler Bailly Pakistan investigated technical design, hydrology, climate, sedimentation management, environmental impact and the impacts on fisheries of medium size hydropower projects in Pakistan [27]. Hunt et al. show that the Indus basin is the world region with the largest and cheapest potential for seasonal and pluri-annual energy storage [28].

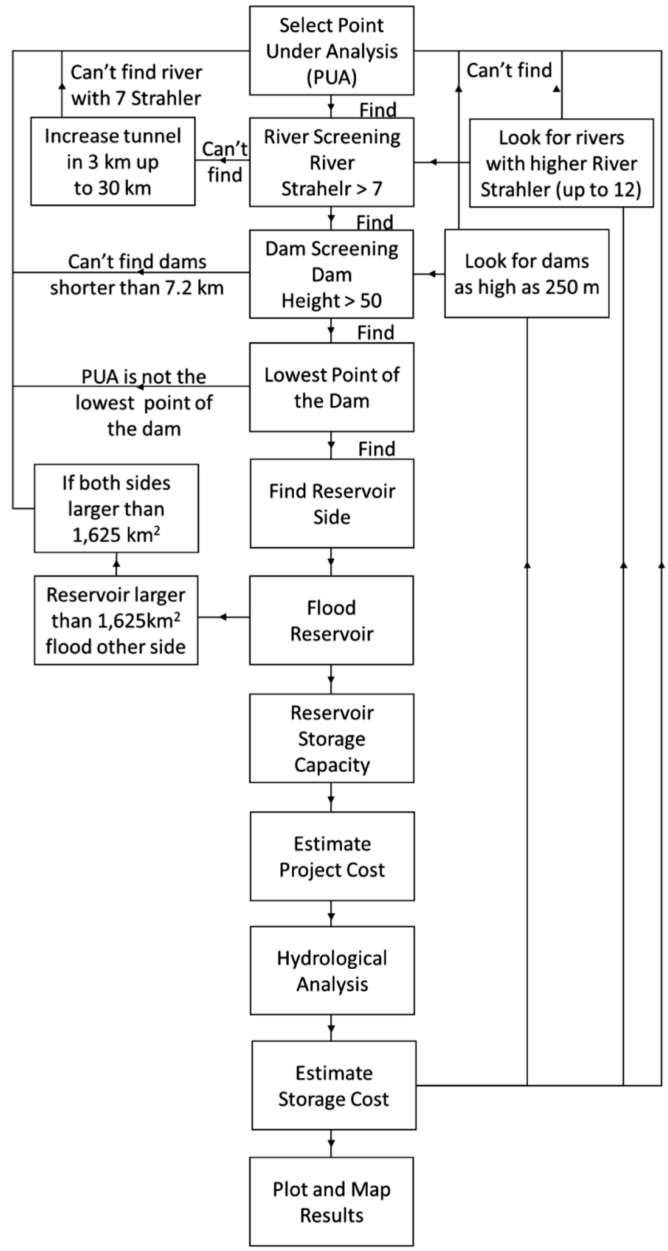

Figure 1. Global siting of hydropower and SPHS projects model framework implemented on the Indus basin.

The research gap that the paper covered is to estimate the costs and potential for hydropower, water storage, long-term and short-term energy storage in the Indus Basin. The key innovation and contribution of the paper lies in the comparing the hydropower and the SPHS potential of a region, focusing particularly on water and energy storage of the reservoirs. It calculates the costs of conventional hydropower dams and SPHS plants for the Indus basin with the intention of finding the most suitable technologies for the development of the hydropower potential and water management solutions for the Indus Basin.

Methodology

The methodology implemented in this paper is based on a Global Model for Seasonal Pumped Storage Analysis presented in [28]. This model has been upgraded to include hydropower plants and is now called "Global siting of hydropower and SPHS projects model". Other methods used for estimating global hydropower potential are [19,

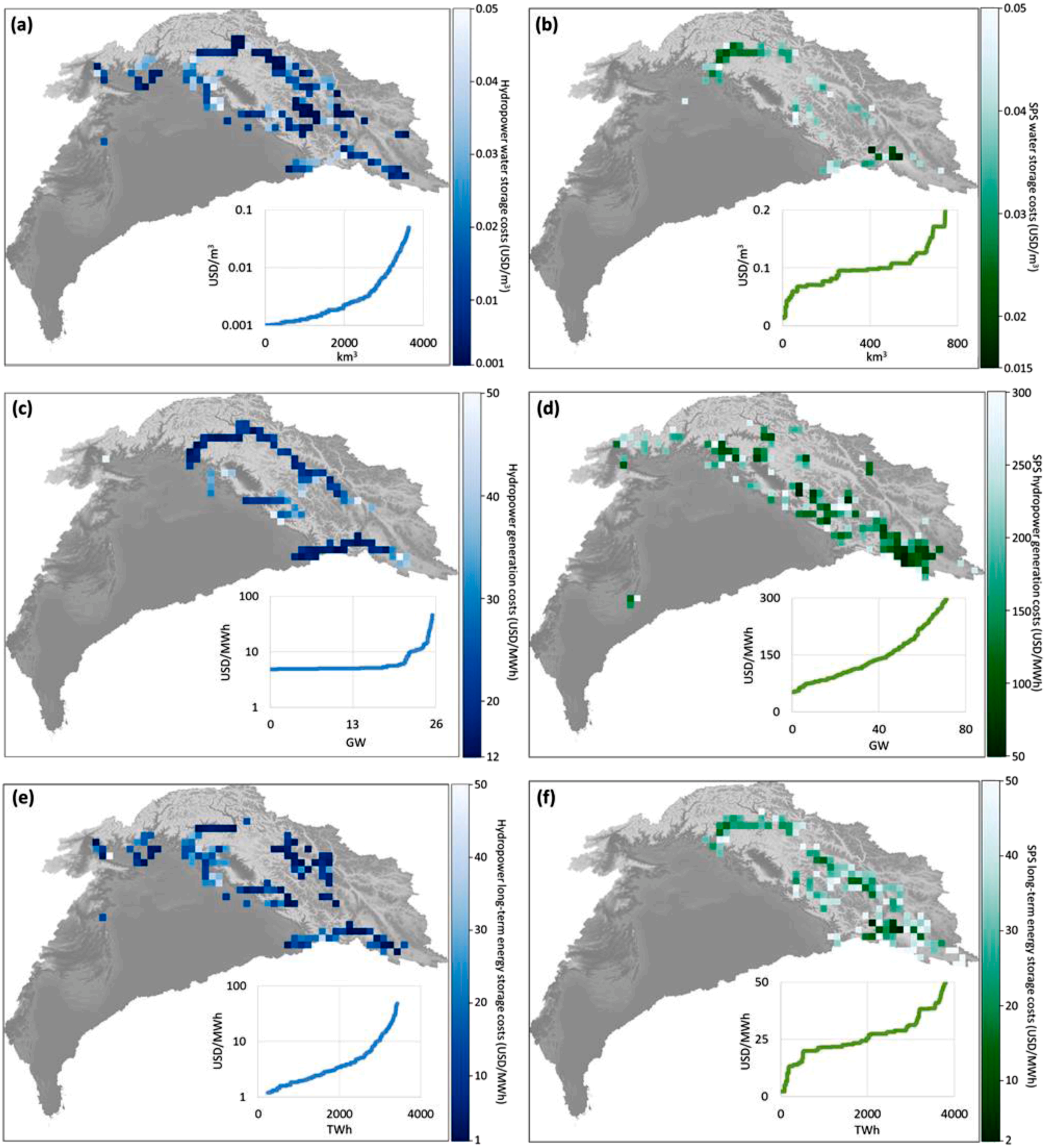

Figure 2. Water storage costs with (a) hydropower plants and (b) SPHS plants; hydropower generation costs with (c) hydropower plants and (d) SPHS plants; long-term energy storage costs (e) hydropower plants and (f) SPHS plants.

29–33], however these methods assume that the plants are run-off-the-river and do not estimate their water and energy storage capacity. One recent study investigates the global potential for PHS and assumes the construction of two reservoirs in a closed loop for daily and weekly operation. They found a global potential of 23×10^6 GWh in more than 600,000 plants, but the project sizes appear to be impractical or infeasible for seasonal storage or water storage and do not include detailed cost analysis or water availability [34,35]. We have not included these closed loop sites because they are designed to store only energy and we are looking at energy and water storage solutions in this paper. Other studies have been developed to find the potential for PHS projects in Europe [33,36,37], and Iran [38], however, these are regional models also do not include costs. GIS models have been created to find daily and weekly pumped hydropower storage plants [34, 38–42], there is only one model that looks at SPHS [28]. Given that the water and energy storage volume for daily and weekly PHS plants is not so large, these models do not estimate the benefits that the SPHS plants would have on the operation of the hydrological basin. Refer to the

Table 2
Cost range description of each main affluent of the Indus basin.

River	Water Storage (USD m^{-3})	Hydropower		
(USD MWh^{-1})	Long-term energy storage (USD MWh^{-1})	Short-term energy storage (USD MWh^{-1})		
Hydropower				
Indus	0.001 - 0.03	12 - 47	1 - 42	-
Jhelam	0.01 - 0.05	29 - 46	7 - 40	-
Chenab	0.005 - 0.04	19 - 35	2 - 18	-
Sutlej	0.005 - 0.05	12 - 50	1 - 39	-
Kabul	0.001 - 0.04	47	1 - 50	-
Kunar	0.001 - 0.02	-	1.2 - 22	-
Seasonal Pumped Hydropower Storage				
Indus	0.021 - 0.05	75 - 300	14 - 50	0.24 - 0.6
Jhelam	-	70 - 260	-	0.36 - 0.6
Chenab	0.032 - 0.05	50 - 280	19 - 50	0.28 - 0.6
Sutlej	0.015 - 0.044	55 - 270	2 - 50	0.24 - 0.6
Kabul	-	100 - 260	-	0.4 - 0.6

Appendix for a more details on Seasonal Pumped Hydropower Storage plants.

To assess the potential of SPHS, the methodology integrates five essential components, which are: topography, river network and hydrology data, infrastructure cost estimation and project design optimization (Table 1). SPHS project suitability is highly sensitive to the topography, distance to a river and water availability, which together determine the theoretical potential. Whilst previous studies have used similarly high-resolution topography for reservoir estimation, the possibility of storing water and energy seasonally in dams or by pumping water to an upper reservoir has not been assessed for the Indus basin.

Data

The topographic data applied in this study is the digital elevation model called the Shuttle Radar Topography Mission (SRTM) [43], which has 3" resolution. The resolution is reduced to 15", assuming the center point, firstly, to reduce modelling time and secondly to combine with the river network data. The river network data applies the Strahler methodology and was taken from the Global-scale river network (GRIN) [44], which is derived from the SRTM data and has 15" resolution. To design and estimate the costs of the SPHS projects, we use detailed design methods [45] and cost-estimation [46] procedures which include the optimization of the tunnels' diameter and number of tunnels, that are explained in Table 1. For more details, please refer to Table B.6 and [28].

Global siting of hydropower and SPHS projects model

Details of the hydropower and SPHS Indus potential model framework are explained step-by-step in Figure 1, Table 1, Table B.6, Table B.7 and [28]. The model goes through each grid cell location delineated at a 15" resolution, implementing a detailed siting assessment that accounts for topography and hydrology in the calculation of project costs. The hydrological data were used to restrict the size of the storage reservoirs, according to water availability. This guarantees that there will be water available to fill up the storage reservoir without having a considerable impact on the overall river flow.

Table 3
Details of the cheapest hydropower projects presented in Table 2.

Details	Indus	Jhelam	Chenab	Kabul	Sutlej
Latitude (°)	35.0588	33.3699	33.1388	34.6379	31.6045
Longitude (°)	72.9532	73.5652	74.8181	69.7178	78.3272
Altitude where the dam is located (m)	696	414	500	2424	2127
Reservoir level variation (m)	100	75	75	50	125
Dam height (m)	200	150	150	100	250
Dam length (km)	0.52	1.8	0.45	1.35	1.04
Generation capacity (GW)	0.797	0.173	0.239	0.317	0.952
Storage volume (km^3)	1.951	3.462	3.549	0.131	1.125
Hydropower generation (TWh)	6.824	1.484	2.041	2.710	8.149
Energy storage without cascade (TWh)	0.718	0.955	0.979	0.024	0.5175
Energy storage with cascade (TWh)	2.715	3.064	3.590	0.493	4.040
Land requirement (km^2)	24.219	78.712	62.876	3.493	13.507
River discharge ($m^3 s^{-1}$)	588.2	170.5	234.6	467.2	561.9
Dam cost (billion USD)	0.522	0.553	0.300	0.175	0.722
Turbine cost (billion USD)	0.071	0.017	0.024	0.037	0.078
Miscellaneous costs (billion USD)	0.007	0.002	0.002	0.004	0.008
Electrotechnical cost (billion USD)	0.158	0.036	0.049	0.070	0.182
Land cost (billion USD)	0.011	0.035	0.028	0.002	0.006
Total construction costs (billion USD)	1.537	1.286	0.806	0.572	0.995
Water storage costs (USD m^{-3})	0.043	0.020	0.012	0.237	0.053
Energy storage costs without cascade (USD MWh^{-1})	116.4	73.1	44.7	1287.8	130.3
Energy storage costs with cascade (USD MWh^{-1})	30.752	22.799	12.199	63.151	8.532
Energy storage GW costs (USD MWh^{-1})	1.927	7.416	3.379	1.808	1.234
Hydropower generation cost (USD MWh^{-1})	12.236	31.093	21.456	47.480	15.325
Does the proposed dam exist?	No	No	Yes	Yes	No

The site selection model is divided into nine main stages (Figure 1 and Table B.7). For each land grid cell (point under analysis (PUA)), the model searches for rivers with sufficient discharge (higher than a yearly average of 100 $m^3 s^{-1}$) within 1 to 30 km of distance from a potential SPHS site, which consist of the tunnel length (Figure 1 (c)). If a large river is found, the model attempts to build dams of 50, 100, 150, 200 and 250 meters height, along 4 axes (N-S, W-E, NW-SE, NE-SW) and with a maximum length of 7.2 km in the PUA (Figure 1 (d)). If the topography allows the construction of such dams, it verifies whether the PUA is the lowest point of the dam (if it is not, the process stops with the intention of not repeating the same project) (Figure 1 (e)). Using the surrounding topography and observing limits to the maximum flooded area of the reservoir, the model identifies the side of the dam that results in a reservoir (Figure 1 (f)). Subsequently, the reservoir water level is varied to determine the flooded area vs. level and storage volume vs. level curves (Figure 1 (g)).

Developing hydropower projects takes substantially less time and the model is much simpler than finding SPHS projects. The main difference between both is that the hydropower model does not have to look for other rivers to extract water (Figure 1 (c)), instead it only develops projects on rivers with yearly average river flows higher than 100 $m^3 s^{-1}$. Additionally, the cost estimation does not include tunnel and excavation costs.

Project costs are subsequently estimated, divided between dam,

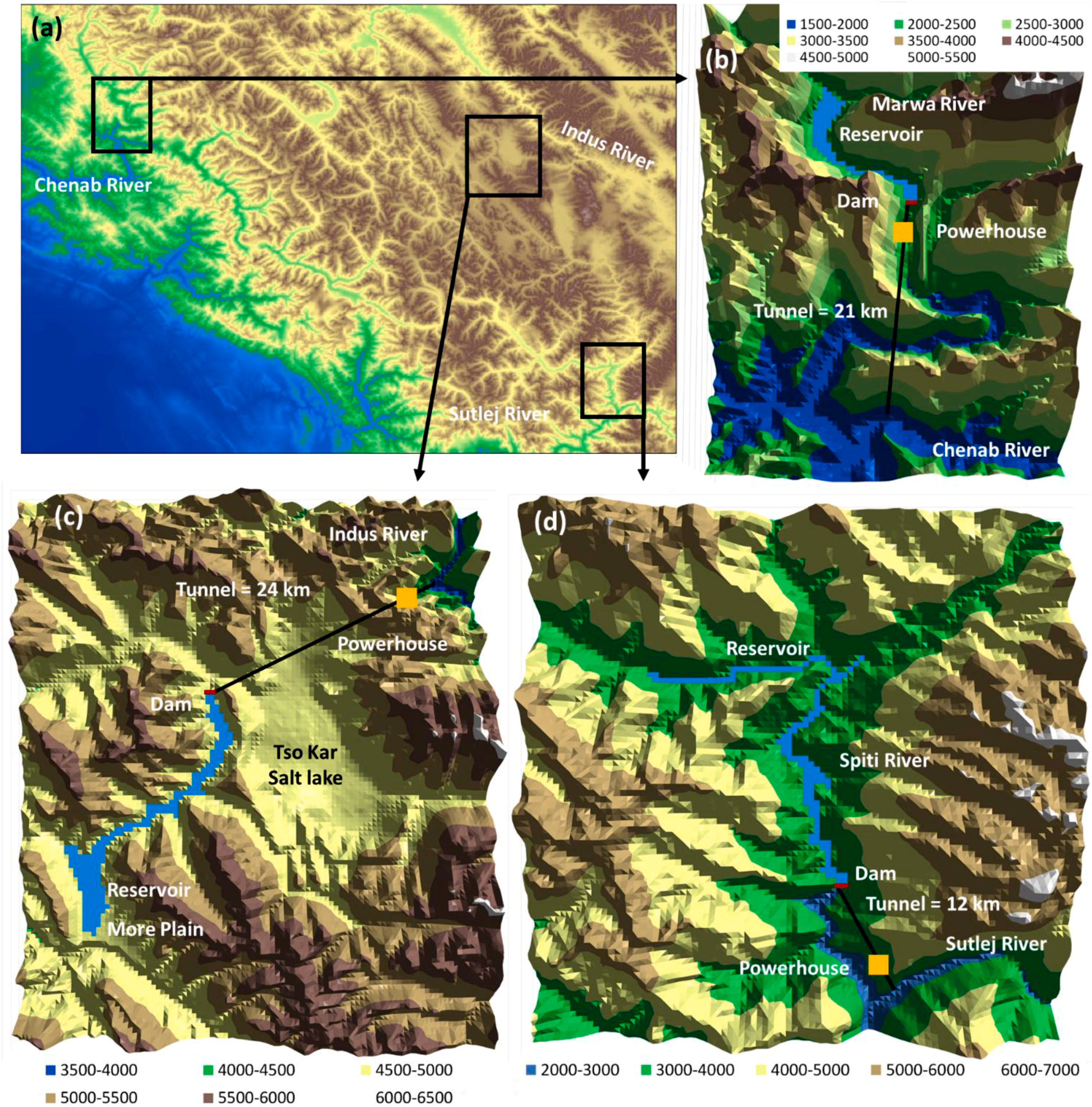

Figure 3. Description of the proposed SPHS plants. (a) Topography of the upper Indus basin, (b) Marwa, (c) More and (d) Spiti SPHS plants.

tunnel, powerhouse excavation, pump-turbine, electro-technical equipment and land costs [45,48]. In the analysis, the water storage capacity of the SPHS projects is limited according to the water availability of the main river. If the storage capacity is much higher than the amount of water available, the estimated cost of storage tends to infinity, as the reservoir will never fill up.

Cost estimation

The costs of water and energy storage service calculated in the Estimate Storage Cost stage vary according to the annual river flow, the seasonal and inter annual variation. These hydrological parameters have the main purpose to guarantee that there will be sufficient water in the river to be stored in the upper reservoir. The variation of the water and energy storage (with and without cascade) costs with the water available for storage is presented in equations (1), (2) and (3), respectively. The cost for additional short-term energy storage costs is presented in equation (2).

$$C_W = \frac{C_P}{W_S \frac{W_R}{W_S}} \begin{cases} \text{if } W_R < Q_A & \rightarrow W_S = W_R \\ \text{if } Q_A < W_R < 2Q_A & \rightarrow W_S = Q_A + 0.5W_R \\ \text{if } W_R > 2Q_A & \rightarrow W_S = 1.5Q_A \end{cases} \quad (1)$$

$$C_{Ewc} = \frac{C_P}{E_{Rwc} \frac{W_R}{W_S}} \begin{cases} \text{if } W_R < Q_A & \rightarrow W_S = W_R \\ \text{if } Q_A < W_R < 2Q_A & \rightarrow W_S = Q_A + 0.5W_R \\ \text{if } W_R > 2Q_A & \rightarrow W_S = 1.5Q_A \end{cases} \quad (2)$$

$$C_{Ewoc} = \frac{C_P}{E_{Rwoc} \frac{W_R}{W_S}} \begin{cases} \text{if } W_R < Q_A & \rightarrow W_S = W_R \\ \text{if } Q_A < W_R < 2Q_A & \rightarrow W_S = Q_A + 0.5W_R \\ \text{if } W_R > 2Q_A & \rightarrow W_S = 1.5Q_A \end{cases} \quad (3)$$

where, C_W is the cost of water storage in USD km^{-3}, C_P is the cost of the project (i.e. dam, tunnel, turbine, electrical equipment, excavation and land) in USD, Q_A is the yearly water available for storage in km^3, which is 50% of the annual river flow in the river section under analysis, W_S is the water storage capacity adjusted by the water availability in km^3,

Table 4
Details of selected SPHS projects presented in Figure 2.

Suggested name	More	Marwa	Spiti
River	Indus	Chenab	Sutlej
Latitude (°)	33.3735	33.5569	31.9061
Longitude (°)	77.9143	75.7854	78.5983
Altitude where the dam is located (m)	4635	2003	3002
Altitude of the river, lower reservoirs (m)	3875	1156	2608
Minimum generation head (m)	790	917	394
Reservoir level variation (m)	100	200	200
Dam height (m)	100	200	200
Dam length (km)	1.2	1.8	1.035
Generation capacity (GW)	1.0	1.0	1.0
Storage volume (km^3)	2.6	4.24	17.77
Energy storage without cascade (TWh)	5.42	10.57	21.53
Energy storage with cascade (TWh)	20.13	23.49	100.02
Yearly river flow (km^3)	5.24	5.48	6.58
Land requirement (km^2)	67.23	43.08	136.23
Tunnel length (km)	24	21	12
River discharge ($m^3 s^{-1}$)	33.24	34.77	39.91
Dam cost (billion USD)	0.36	0.77	0.66
Tunnel cost (billion USD)	0.45	0.43	0.35
Excavation costs (billion USD)	0.05	0.05	0.06
Pump turbine cost (billion USD)	0.08	0.08	0.08
Miscellaneous costs (billion USD)	0.01	0.01	0.01
Electrotechnical cost (billion USD)	0.17	0.17	0.17
Land cost (billion USD)	0.11	0.02	0.06
Total construction costs (billion USD)	2.26	3.07	2.78
Water storage costs (USD m^{-3})	0.14	0.20	0.02
Energy storage costs without cascade (USD MWh^{-1})	73.89	81.22	13.41
Energy storage costs with cascade (USD MWh^{-1})	16.27	36.53	2.89
Energy storage GW costs (USD MWh^{-1})	0.76	0.74	0.67
Tributary river flow ($m^3 s^{-1}$)	0.04	16.26	22.08
Hydropower generation (TWh $year^{-1}$)	0.01	5.28	3.20
Hydropower generation cost (USD MWh^{-1})	41726.32	130.24	90.86

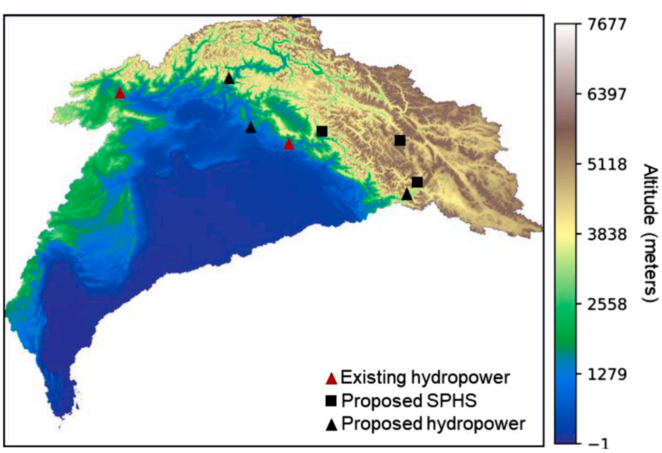

Figure 4. Location of projects described in Table 3 and Table 4.

C_{Ewoc} is the cost of long-term energy storage excluding the cascade in USD MWh^{-1}, W_R is the water storage capacity of the reservoir developed in the model in km^3, E_{Rwc} and E_{Rwoc} are the energy storage capacity of the reservoir developed in the model with and without cascade in MWh, respectively, C_{Ewc} is the cost of long-term energy storage including the cascade in USD MWh^{-1}.

$$C_{GW} = \frac{C_{PGW}}{G} \tag{2}$$

where, C_{GW} is the cost of additional generation capacity in billion USD GW^{-1}, C_{PGW} is the cost of additional generation capacity (i.e. tunnel, turbine, electrical equipment, excavation) in billion USD, G is the generation capacity in GW (fixed to be 1 GW for all SPHS plants proposed).

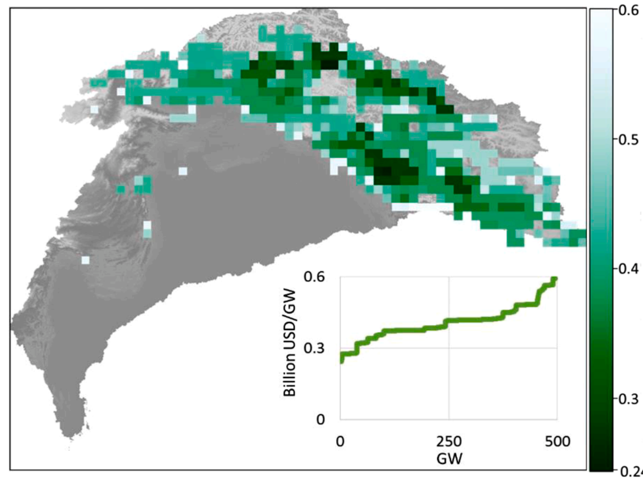

Figure 5. Short-term energy storage costs with SPHS plants.

Results

The results from the hydropower and SPHS plants siting computer model presented in this paper are divided in water storage, generation, long-term energy storage, and short-term energy storage cost. These outputs are presented in maps, capacity curves and a description of the costs.

The hydropower water storage cost varies from 0.001 to 0.05 USD m^{-3}, while SPHS varies from 0.015 to 0.05 USD m^{-3} (Figure 2 a, b). Worth noting that hydropower dams have a greater land requirement in comparison to SPHS. Analyzing the capacity curves in Figure 2b, the cost of water storage starts small with a small addition to the overall water storage potential. This is because of the possibility of the construction of effective, low altitude and short dams. After reaching the 300 km^3 capacity mark, there are several projects that store a lot of water with a higher cost, due to the requirement of larger and more expensive dams. Conventional hydropower generation cost varies from 12 to 50 USD MWh^{-1}, a low cost in comparison to SPHS (Figure 2 c, d) hydropower generation which varies from 50 to 300 USD MWh^{-1}. The wide range of cost variation for SPHS is a result of its highly sensitive to the topography, distance to a river, and water availability. The cost for hydropower suddenly increases after 20 GW installed capacity because the hydropower potential in the Indus and Sutlej rivers finishes and the cost of hydropower in the other rivers is higher. Hydropower long-term energy storage costs and SPHS (Figure 2 e, f) varies from 1 to 50 and 2 to 50 USD MWh^{-1}, respectively. Considering the high volume of sedimentation in the upper Indus Basin, SPHS plants have the advantage to provide additional energy and water storage for the basin with low sedimentation rates. Table 2 presents the cost range description of each main affluent of the Indus basin.

Table 3 details the cheapest hydropower projects presented in Table 2. It presents all the details of the dams that are estimated by the model described in Section 2. It turns out that the cheapest proposed projects for the Chenab and the Kabul reservoir were already built. This is convenient as it helps verifying the quality of the model results.

Figure 3.

Table 4 provides details of selected SPHS projects presented in Figure 4 and Figure 2. The project proposed for the Indus basin is located upstream of the Tso Kar salty lake. The upper reservoir would be filled with fresh water from the Indus river and from precipitation and ice melted from the mountains, that would end up in the Tso Kar lake. If there is an interest to maintain the Tso Kar salty lake with its current volume, some of the water from the upper reservoir would have to flow to the lake. The More, Chenab and Sutlej SPHS plants have large reservoirs and storage volumes, and their seasonal operation is combined with the existing hydropower generation in cascade to optimize the hydropower generation and water supply. Figure 4 presents the location of projects described in Table 3 and Table 4. The required transmission lines are presented in Table C8. The largest transmission line required would be 335 km for the More SPHS, which is not very large, however, the harsh weather and terrain increases installation costs.

The short-term energy storage cost with SPHS plants (Figure 5) presented a range of 0.24 to 0.6 billion USD GWh^{-1}. The cheapest alternatives for short-term energy storage can be seen in the middle of the Indus river and in the Beas river basin. Given the rapid reduction in battery prices, short-term energy storage solutions should be located close to the demand. Thus, the developments of daily and weekly PHS plants should be focused on the Beas river basin, which is close to Ludhiana and Chandigarh in India. Note that the potential for short-term energy storage is as high as 500 GW. This is because, in short-term energy storage, the water used for regeneration is re-used several times during the pumping and generation cycles.

Figure 6 (a) shows the costs of the different components of the proposed SPHS projects by the computer model. The costs of tunnel and electrotechnical components are significantly higher than the costs of the dam. This is because the model assumes that all projects have a 1 GW installed capacity, which is higher than the installed capacity required to store water seasonally in the upper reservoir. Thus, if the main objective of the SPHS is to store energy and water seasonally, it would be advisable to reduce the installed capacity of the plant to 500 or 250 MW depending on the site of the reservoir. Figure 6 (b) shows that the critical components of the hydropower project costs are the dam, electrotechnical equipment and turbine.

Discussion

Water demand and climate vulnerability

More importantly than energy generation, water is crucial for crop irrigation and food production in Pakistan. The main benefits of building storage reservoirs in the upper Indus basin is related to the regulation of the river flow, which prevent floods and stores water for the winter or years with lower than average rainfall. The main challenges in building hydropower and SPHS reservoirs is the increase in evaporation, which could lower the river flow downstream. Another challenge of regulating the river, is that water for irrigation is mostly required during the summer to produce mainly rice, maize, sorghum, millet, sugarcane and cotton [49]. Regulating the flow of the Indus river, without policies to adapt to new agriculture techniques could result in energy and water conflicts in the future.

Climate change is expected to increase average temperatures in the lower Indus basin, which increases the potential of the air that reaches the upper Indus basin to precipitate. This is expected to increase the frequency of flood events in the region [50] and increase the sedimentation rates of the rivers. SPHS plants can lower the impacts of climate change by providing seasonal storage services, while the conventional hydropower dams, would be partially empty to store river flow surges resulted from floods in the future.

High river sedimentation

Hydropower plants in the Indus basin have high rates of sedimentation in the region, which increases maintenance costs and shortens the lifetime of the reservoir, as they are usually filled with sediments within a few decades [4,9,10,51]. SPHS plants could have substantial benefits in the Indus basin because their reservoirs are limited to a small catchment area, and thus the sedimentation rates are substantially smaller and the reservoirs can last for hundreds of years.

SPHS plants in series

This section presents proposals for hydropower and SPHS arrangements that could be considered for the Indus basin based on the analysis carried out in the paper. The first proposal is the combination of two SPHS systems with one connection to the Indus River plant (Figure 7). The project consists of a 41 km tunnel for the Jalkol reservoir until the first powerhouse with a 1440 m generation head, and a 31 km tunnel for the Palas reservoir that connects to the Indus River with the second powerhouse, with a 920 m generation head. The high pumping/generation head denotes it can generate and store large amounts of energy with little water and land requirements. Comparing with the Kaprun site in Austria, the distance from the Leiter Glaisier to the Kaprun lower reservoir (Figure 7 (b)) is 35 km and the total generation head is around 1100 meters, which results in a tunnel efficiency index of 31.4 (1100 m generation head / 35 km tunnel). The proposed Jalkol reservoir has an index of 40.7 (2320 m generation head / 57 km tunnel) and the Palas

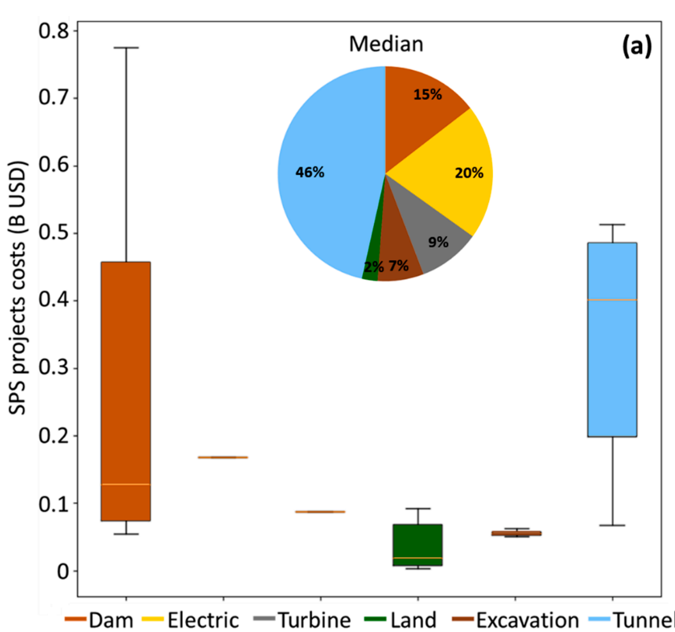

Figure 6. (a) Cost of SPHS projects with long-term energy storage, (b) cost of hydropower projects with generation. The range shows the values between 5% and 95% of the sample data, with the bars for between the first and third quartile. The line on each bar shows the median of each range.

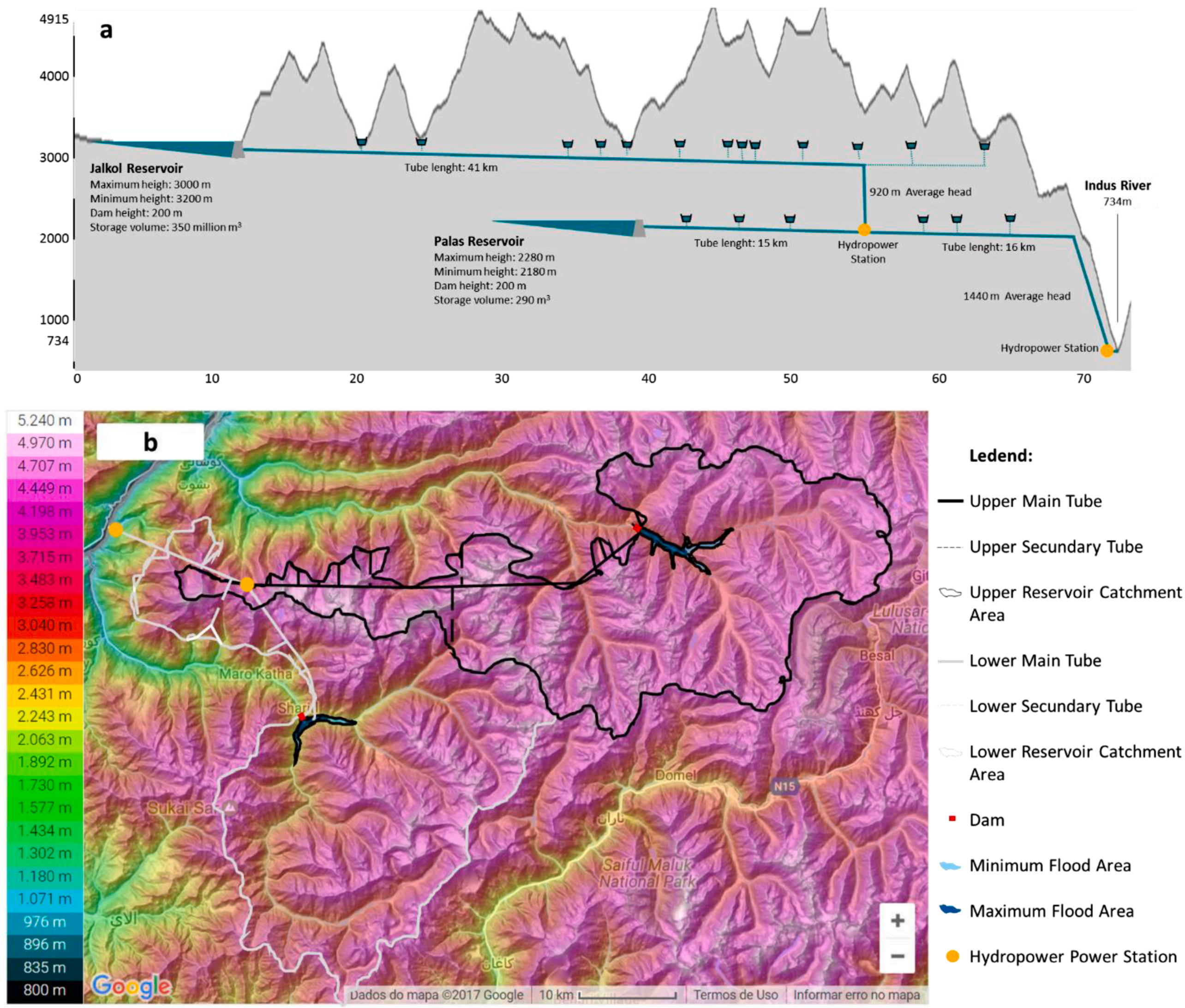

Figure 7. Proposal of a combination of two SPHS system with one connection to the Indus River.

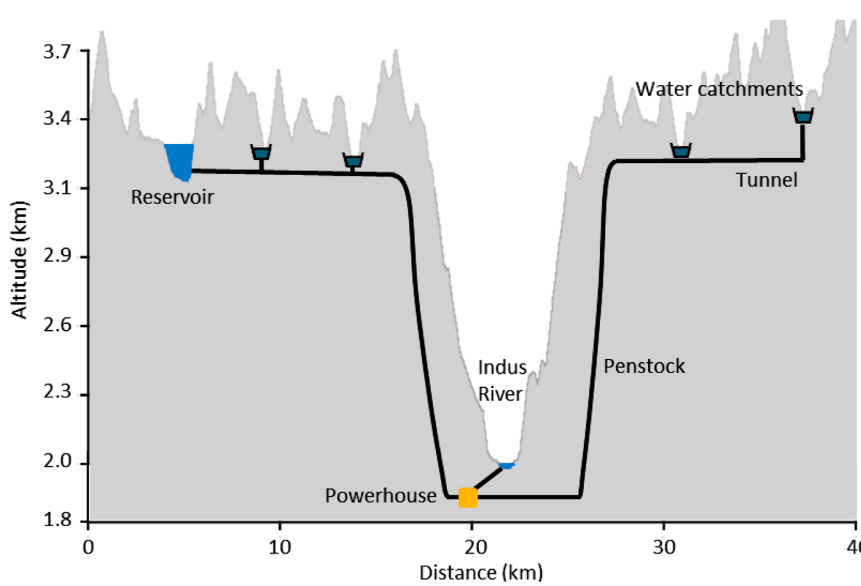

Figure 8. SPHS system with the powerhouse connected to reservoir and catchments on both sides of the river.

reservoir has an index of 46.5 (1440 m generation head / 31 km tunnel), which are both superior to the Kaprun project in Austria. Note, however, that pumped-storage plants have limitations in head of around 1,400 meters. Plants with higher heads are not commonly designed and produced, thus, are not currently available in the market due to the very high pressures involved.

SPHS plants in both sides of the river

Given the very steep terrain in the Upper Indus Basin, another arrangement of SPHS that could be implemented in the Indus Basin and provide a combination of hydropower and water storage is the possibility of developing two reservoirs, one on each side of the river, as shown in Figure 8. With the increase in capacity, the relative costs of the turbines, generator and excavation would be lower. Another possibility is to store water from one reservoir into the reservoir on the other side of the river if one of them is full. This would only be possible if the water level from the full reservoir is higher than the water level of the empty reservoir, so that the water could flow naturally under gravity from one reservoir to the other. The main benefit of catching water from both sides of the river is that it increases the water availability for the plant, which increases the power capacity of the turbine, generators, and substations, reducing overall costs. It also allows for the creation of only one large storage reservoir up the mountains to store water from both sides of the mountain. This reduces the need for building two reservoirs on each side.

Seawater closed loop SPHS plant

This paper only analyzed the potential for energy storage with open loop SPHS types. This type of plant is more convenient because it also stores water for the dams in cascade. However, due to the very large potential for efficient reservoir construction in the region, and the mountainous topography, closed loop SPHS plants can also be built. Given that the water in closed loop systems is reused innumerous times, the energy storage potential of the region is very large. An example of a closed loop SPHR project can be built between two existing lakes, as shown in Figure 9. It is estimated that this project can store 4.4 TWh of energy but could be increased to 10 TWh if additional water from the Indus Basis is added to the system. The main challenges of this project are the saltwater corrosion in the turbines, and the low temperatures that can freeze the water in the tunnel and damage the turbine. The advantage is that the energy storage process has no impact on the flow of the Indus river. Another interesting arrangement for the region that was not considered is to build pump-back PHS plants. These are conventional dams built in the main river with reversible pump turbines. This arrangement is interesting because, if the inflow of the dam is low, the pump/turbines can be used for energy storage instead of hydropower generation. This significantly increases the flexibility of the plant. Pump-back PHS require the lower reservoir to always reach the upper reservoir dam.

Future role of SPHS

Batteries and hydrogen are rapidly gaining the market for energy storage [53]. Pumped hydro storage will have to reinvent itself to remain competitive. Bloomberg predicts that the use of batteries for grid storage in 2030 will be 280 GW, which will surpass the global capacity of PHS plants [54]. With a battery cost expected to fall under 100 US $/kWh in 2024 and around 60 US$/kWh in 2030 [55], batteries will soon be cheaper than PHS plants with daily storage cycles. Regarding long-term energy storage (GWh), hydrogen will be an important competitor for PHS as the global network of production and distribution of hydrogen develops [56]. For instance, a full liquid hydrogen tanker with a volume of 267,000 m^3 (the size of a large LNG tanker) stores 415 GWh or 17 GWd of electricity, assuming that the efficiency to transform the hydrogen into electricity is 70%. This is equivalent to the energy stored on a monthly or seasonal PHS plant. This would significantly reduce the viability of seasonal PHS plants in countries that will rely on imported hydrogen in the future. Given that the overall efficiency for

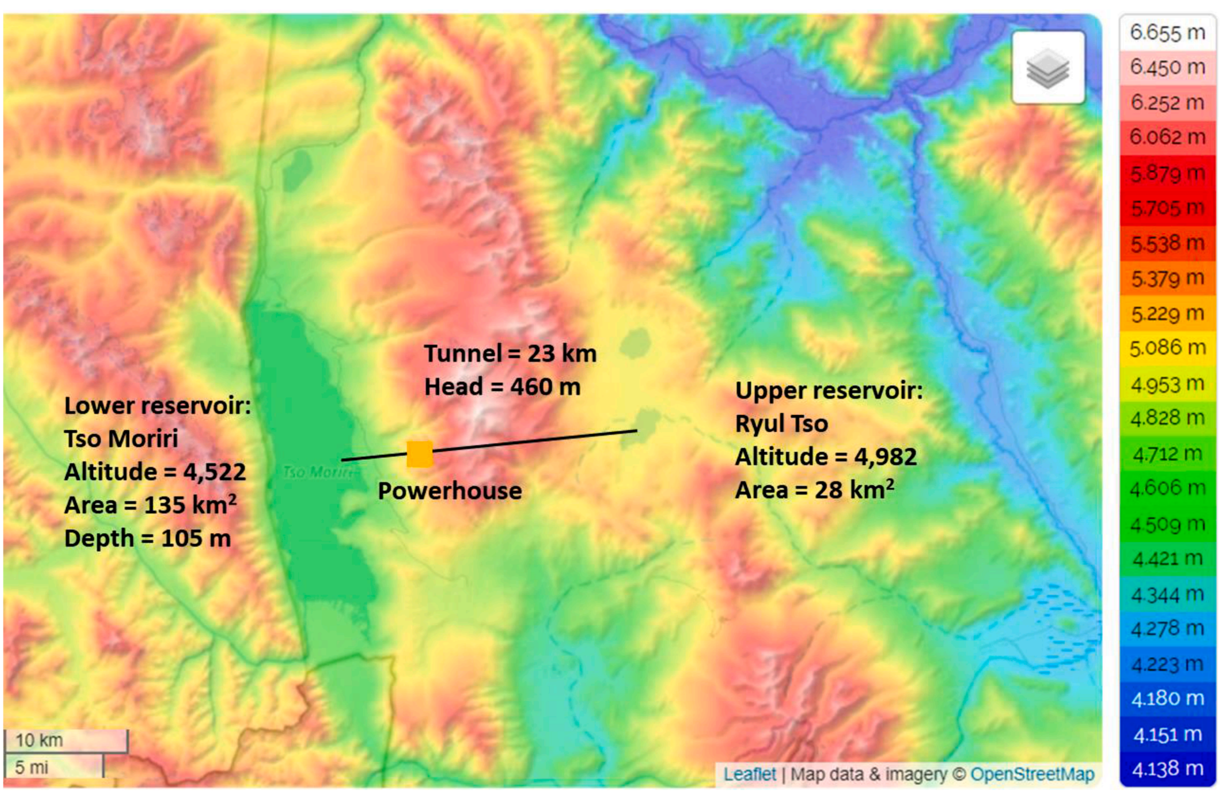

Figure 9. Possible closed loop project with existing salty lakes [52].

energy storage with batteries (90%) is higher than PHS plants (70-85%), and the efficiency of hydrogen (30-60%) is lower than PHS plants. It is likely that batteries will become more competitive than PHS for short-term energy storage to complement the generation from renewable energy sources, such as solar and wind power [57–60]. However, PHS will be more competitive than hydrogen for long-term energy storage. Thus, in the future, monthly and seasonal PHS plants will become more common than daily and weekly PHS plants. The Indus Basin having the lowest cost for long-term energy storage, has the potential to become the world's future long-term energy storage hub.

Conclusion

This article presented the results for the Global siting of hydropower and SPHS projects model in the Indus river basin. It is estimated a hydropower potential of 26 GW exists in the Indus basin, with an energy storage cost ranging between 12 and 50 USD MWh^{-1}, offering a vast and cheap energy storage potential, due to its appropriate topographical formation for the construction of effective storage reservoirs. It found that the levelized costs for hydropower generation in the basin with conventional dams are as low as 12 USD MWh^{-1}, the cost of energy storage is 1 USD MWh^{-1} and the cost of water storage is of 0.001 USD m^{-3}. In case of SPHS plants, the cost of energy storage is 2 USD MWh^{-1} and the cost of water storage is of 0.015 USD m^{-3}.

Given the large potential low cost for energy storage of the Indus basin, the region has the potential to become a major player in seasonal, and pluri-annual energy storage for Asia; a similar role as the Alps are used for energy storage in Europe. If an hydrogen economy is implemented worldwide, the Indus region could play an important role used as a cheap, stationary, long-term energy storage option for a globally integrated hydrogen economy.

Author Contributions

Conceptualization, J.H.; methodology, E.B.; formal analysis, G.F., L. V.; investigation, S.P.; data curation, A.V; writing—original draft preparation, J.H.; writing—review and editing, B.Z.; visualization, J.J.; project administration, P.S.; funding acquisition, A.N., Y.W., N.C.; resources, E.Q.; software, E.G.; validation, A.P.J.; formal analysis, P.B.; supervision, R.B.; All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A: Seasonal pumped hydropower storage (SPHS)

We investigate two alternatives to regulate the flow of the Indus River for hydropower generation: First, using conventional dams, which are built in the cross sections of the main river (Figure A.10 (a)). Second, SPHS plants, which are artificial reservoirs off the main river, with some or minor natural inflow (Figure A.10 (b) and (c)). Given that conventional hydropower dam is a widely developed technology, this section will focus on introducing the state-of-the-art of the SPHS concept.

Hydropower generation in high mountain locations using SPHS plants is not a new technology. Especially in mountainous regions of developed countries, SPHS's have been applied, for example, in Austria [62–65], Switzerland [66–69], Norway [70,71], Sweden [72,73] , Australia [74] and USA [73,75]. Basically, a SPHS consists of building a reservoir off to the major river at higher altitudes and a power/pumping station to generate hydropower or to fill up the reservoir. Famous examples of SPHS built in Austria, are the Kaprun and Malta hydropower systems [76,77]. These plants were built with the main objective of storing the melted water from glaciers on the top of the mountains and generating electricity. In addition, the use of dams to store water coming from the increase ice melting due to the future climatic scenario is a topic that is starting to be investigated from the scientific literature [78]. These pump-turbines reservoir are used to store energy when the price for electricity is low and generate electricity during high price periods [79]. Typically, the pump storage plants utilize the daily price spread (i.e., high prices during peak hours around noon and low prices during the night) to maximize revenues. More recently, the increased use of new renewable energy sources (i.e., wind and solar) in Europe requires energy balancing, which is partly provided by these storage systems. Furthermore, the pump turbines are also used to fill up the upper reservoir during the spring or summer, when there is not enough rain or snow to re-fill the upper reservoirs by natural inflows [80]. This practice is advantageous in countries where the costs of electricity during the summer is lower than in the winter, like in Europe. In summary, SPHS plants act as a combination of conventional hydropower plants and pumped storage plants [81].

Table A.5 presents the main characteristics of the pump storage and the aspects that could be relevant for the Indus Basin. SPHS could increase the energy security in Pakistan and could make a valuable contribution to the insertion of intermittent renewable energy sources in the country. Furthermore, the flexibility could provide the balancing energy that is needed. Water security can also be substantially improved with the implementation of SPHS.

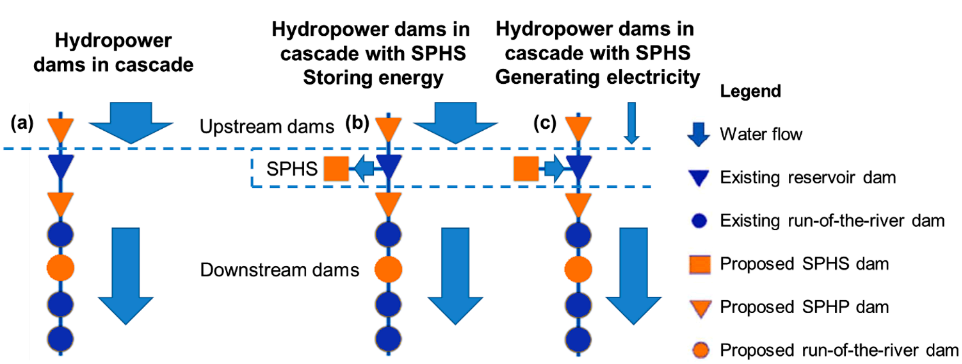

Figure A.10. Operation of (a) conventional hydroelectric plants (b) SPHS during periods of high-water availability (c) SPHS during periods of low water availability. Note that the same legend is used in other figures [61].

Table A.5
Characteristics of the seasonal pumped hydropower storage technology related to the needs of energy and water storage.

Challenges	Deploying seasonal pumped hydropower storage (SPHS)
Energy storage	
Highly seasonal hydropower generation [61,82,83]	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 [84–88]	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	Countries in high latitudes have a strong seasonal solar power generation profile. Seasonal storage allows energy to be stored in the summer and generate electricity 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. For example, they can consume more electricity in the summer for cooling or during the winter for heating purposes. Typically, the peak national grid demand can be two to three times as high as the minimum demand [89].
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 [90]	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 on stand-by for energy security reasons. The number of stand-by plants would reduce it seasonal pumped-storage is implemented.
Island electricity generation [91,92]	Costs of oil and diesel based electricity generation for island electricity generation might be higher than the combination of renewable sources and energy storage.
Water storage	
Inappropriate topography	SPHS 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	SPHS projects have much smaller sedimentation rates than conventional dams due to the smaller catchment area.
Lower environmental and social impacts [93]	Damming a major river for storage would result in higher environmental and social impact than damming a small tributary river. SPHS allows water storage without fragmenting the ecosystem of a main river, assuming that a cascade of hydropower plant is not installed in the river. The implicit comparison to conventional reservoir dams tends to minimize seasonal pumped-storage environmental impacts or disadvantages.
Better water quality control	Storing water in a SPHS reservoir 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. Usually, the water quality of a river deteriorates when the river flow is low and there is not enough water to dilute the pollutants in the water. In these low water availability periods, the SPHS plant will not pump water from the river. Water will be pumped into the river when the river flow rate is higher and the pollutants in the water are more dissolved. This will contribute to maintaining a better water quality in the reservoir. If the SPHS is still required to provide short term energy storage, another small reservoir can be built close to the river, however, water from the lower reservoirs would not be exchanged with the river water to maintain the water quality in the SPHS reservoir.
Flood control	SPHS plants can be used in combination with conventional flood control mechanisms to improve their efficacy. This combination consists of allowing the reservoirs on the main river to operate with low levels as the long-term storage is provided by the SPHS reservoir parallel to the river. So that when the flooding river flows reach the dam in the river, it will be nearly empty and can store large parts of the flood waters. This combination guarantees that the system will store water and energy seasonally and that the dam in the river will have available storage volume to contain the flood.
Transport with waterways	The improvement in water management resulting from a SPHS plant would reduce the chances that a waterway runs out of water [94].
Interbasin Transfer	SPHS projects can be combined with an interbasin transfer project to increase the water security of a region or provide balancing between watersheds.
Groundwater recharge	Pakistan has a vast network of channels. As the lower Indus basin is a sedimentary basin, the water percolates in the channels and enhances the recharging the groundwater of the basin. If the seasonal variation in the water flow in the lower Indus basin is reduced, the channels will have water for longer times and can increase groundwater recharge. This is convenient in Pakistan as it lacks infrastructure to distribute water resources.
Water security [95]	Increase the water storage capacity in regions where conventional storage reservoirs are not a viable alternative.
Potential issues resulted from SPHS plants	
Temperature change	SPHS reservoirs are usually several meters above the level of the river, which contributes to lowering the temperature of the water released by the plant. The operation of the SPHS plant contributes to reducing the temperature of the river flow. River temperature is an important driver for aquatic ecosystem health.
Earthquakes	Earthquakes are not unlikely in the region and pose a high risk due to the potential of dam failure. The magnitude of the earthquakes that may be induced by hydropower reservoirs can be estimated by equations in [96]. There is no study in the literature estimating the risk of SPHS reservoirs. Given that the reservoir of SPHS plants are placed on the top of a mountain or hinterlands, and not in a valley, they might be more susceptible to earthquakes.

Table B.6
Details of the data and methods applied in the model.

Data and methods description	Comments
Topographical data (SRTM)	Topographic data for latitudes between 60°N to 56°S.The reduction in resolution assumes the central point of 15 sec of the 3 sec data.
River Network, Strahler data (GRIN)	This data is derived from the same topographical data as above. This is used to give a better estimate of the tunnel length connecting the river and the reservoir.
Hydrological data (PCR-GLOBWB)	This data combines the estimated water availability and use over the period 1960–2010 and includes human activity. More details on the data can be seen in reference [47]. The annual discharge, seasonal and inter-annual variation are derived from this data. As the GRIN and PCR-GLOBWB data have different resolution, a methodology was created to increase the resolution of the PCR-GLOBWB data. This methodology consists of giving a single hydrological flow for each river Strahler stream order higher than 7 in each 5 degrees section. This is performed by finding the highest river Strahler stream order of each PCR-GLOBWB 6 min resolution, then taking an average of the hydrological flows for each river Strahler stream order number. A drawback of this methodology is that the river flow for each Strahler stream order in a 5-degree section will be constant. However, errors involving the topographic difference between the data are minimized. In order to improve the results using this methodology, it could have been applied to smaller sections of 1-degree or less. Assuming that there are uncertainties associated with the PCR-GLOBWB global hydrological model, the error of this methodology is small. Only rivers with a Strahler stream order above 7 were considered, as they have enough flow to justify the construction of a SPHS plant.
Pumped Storage Costs	This reference gives detailed data on pumped-storage costs, such as dam, tunnels, excavation, electrical equipment and turbine costs. The model assumes most cost estimates proposed by the reference [46]. It also assumes only one type of construction design for each of the components of the SPHS plant. This is because, it would be complex to create a model that compares different designs for each component to find the most optimum one. This gave a good preliminary estimate of the final costs. For the construction of the dam, the model assumes a rockfill dam with central moraine sealing, as described in Fig. B.1.1 [46]. For the construction of the tunnels it assumes drill and blast, as described in Fig. B.1.4 [46]. The penstock costs include the costs of digging the tunnel (Fig. B.9.2 [46]) and the cost of the embedded steel pipes (Fig. M.6.C [46]). The excavation varies with the generation head and the installed capacity, as described in Fig. B.10.1 [46]. The turbine assumed is Francis, as described in Fig. M.1.b [46] and Fig. M.4.A [46]. The selection of the turbine also depends on the generator, as described in Fig.E.8.2.a [46]. For the optimization of the turbine/generator system, the costs of different rotation speeds, as described in Fig. E.1.1a [46] and Fig. E.8.1.b [46], are compared to the average generation head and flowrates under analysis and the cheapest option is selected. Note that one turbine/generator system is proposed per tunnel.
Tunnelling Design	The methodology used to optimize the construction of the tunnels was taken from [45]. This methodology consists of comparing the capital costs of construction of the tunnels, such as the diameter and number of tunnels, and the costs of operating the plants. The cost of operating the plants depends considerably on the energy losses due to friction in the tunnels. The bigger the diameter and number of tunnels the more efficient is the plant.

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

Table B.7
Seasonal-pumped storage Indus basin 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 SPHS projects considering the limitations presented in this paper.	Fig. 1a
River Screening	This stage looks for a river with a reasonable amount of water to store. It makes sure that the SPHS upper reservoir is not in the same river as the lower reservoir, i.e. it is a parallel river. If finds rivers with Strahler stream order 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 stream order of 7 to 12 at less than 30 km from the upper reservoir the model will create a different SPHS project for each river.	Fig. 1c
Dam Screening	This stage creates five 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. 1d
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 SPHS project. This grid cell usually coincides with a tributary river.	Fig. 1e
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. 1f
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 water with the reservoir at a given level by the volume of water within the reservoir at its minimum level. In the model the minimum level of the reservoir is assumed to be zero.	-
Reservoir, Hydrology Comparison	The hydrology is included in the analysis to limit the water and energy storage capacity of the SPHS 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. In other words, this section does not remove the project that does not have enough water to fill up the reservoir. It calculates the cost of energy and water storage with a large reservoir, even if the water available in not enough to fill the reservoir. For example, if the reservoir is two times larger than the water available, then the cost of energy storage will be higher than if there was enough water to fill the reservoir. Thus, the reservoir becomes too expensive and is not selected. The same reservoir with a smaller dam is selected instead, as the cost of the dam and flooded area are smaller. In other words, the project is not cancelled it is just not selected.	-
Estimate Project Cost	This section calculates the project costs, which are divided in dam, tunnel, powerhouse excavation, pump-turbine, electro-technical equipment and land costs.	Table B.6
Estimate Storage Cost	The project costs are compared with the hydrology of the river to find the water and energy storage costs.	Eq. 1 Eq. 2

Table C.8
Required transmission lines from proposed SPHS plants.

Plant	Demand location	Distance (km)
Marwa	Islamabad, Pakistan	250
More	Ludiana, India	335
Spiti	Chandigar, India	220

Appendix B: Global siting of hydropower and SPHS projects model

The shortcoming and the way forward for the improving the model are the inclusion of transmission costs, the costs the land and for relocating people from where the reservoirs would be built. Due to the large computation time, the topographic resolution used was 15'', which limits the minimum size of the dams to around 450 meters. Using available resolution of 3'' the dam cost would improve [97]. It would also be interesting to estimate the maximum altitude for SPHS to avoid water freezing in the tunnels, and the reservoir sedimentation rate and add to the model. Several other limitations that applied to this model are described in [28].

Appendix C: Additional results

The location of hydropower plants analyzed with the computed model in Indus and Jhelam river basins are represented with white dots shown in Figure C.11, hydropower plants in Chenab and Satluj river basins are presented in Figure C.12, and the hydropower plants analyzed in Kabul and Kunar river basins are presented in Figure C.13.

Figure C.14a presents the tunnels for the proposed SPHS plants by the computer module in white, connecting the river (lower reservoir) and the SPHS reservoir (upper reservoir). Similarly, Figure C.14b presents the SPHS proposed plants, not in white, but with an increase in topography of 500 meters for each SPHS tunnel. This is with the intention to show the locations with the highest concentration on proposed SPHS projects.

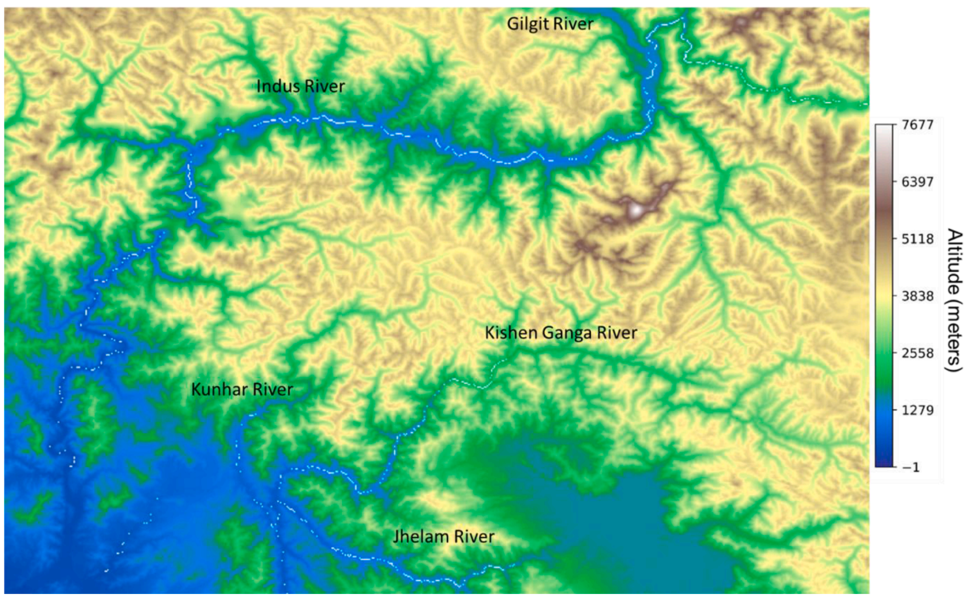

Figure C.11. Hydropower projects investigated on the Indus and Jhelam river basins. The white dots are the locations where the dams were proposed.

Figure C.12. Hydropower projects investigated on the Chenab and Satluj river basins. The white dots are the locations where the dams were proposed.

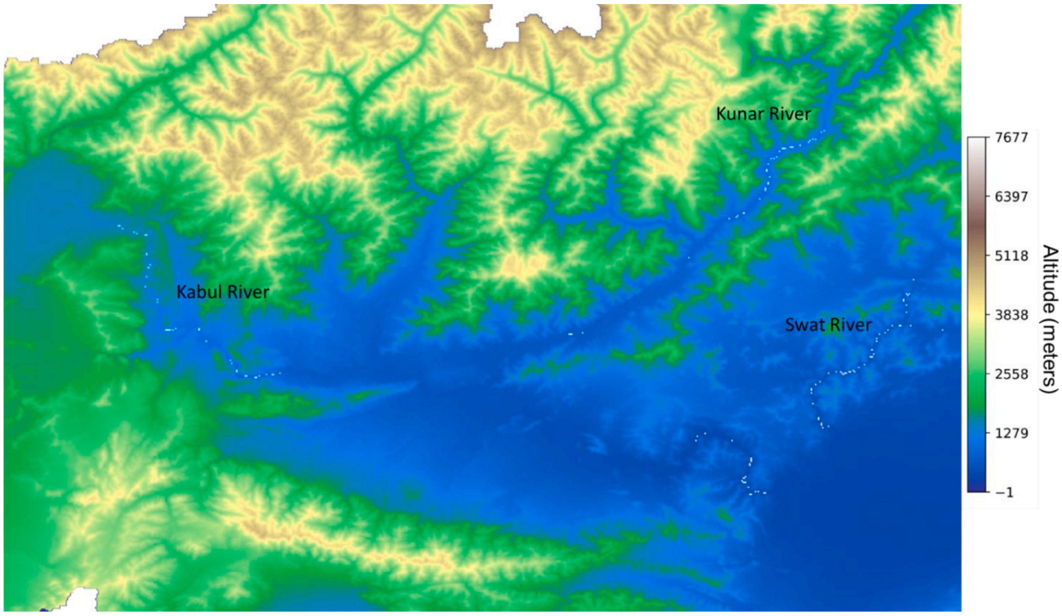

Figure C.13. Hydropower projects investigated on the Kabul and Kunar river basins. The white dots are the locations where the dams were proposed.

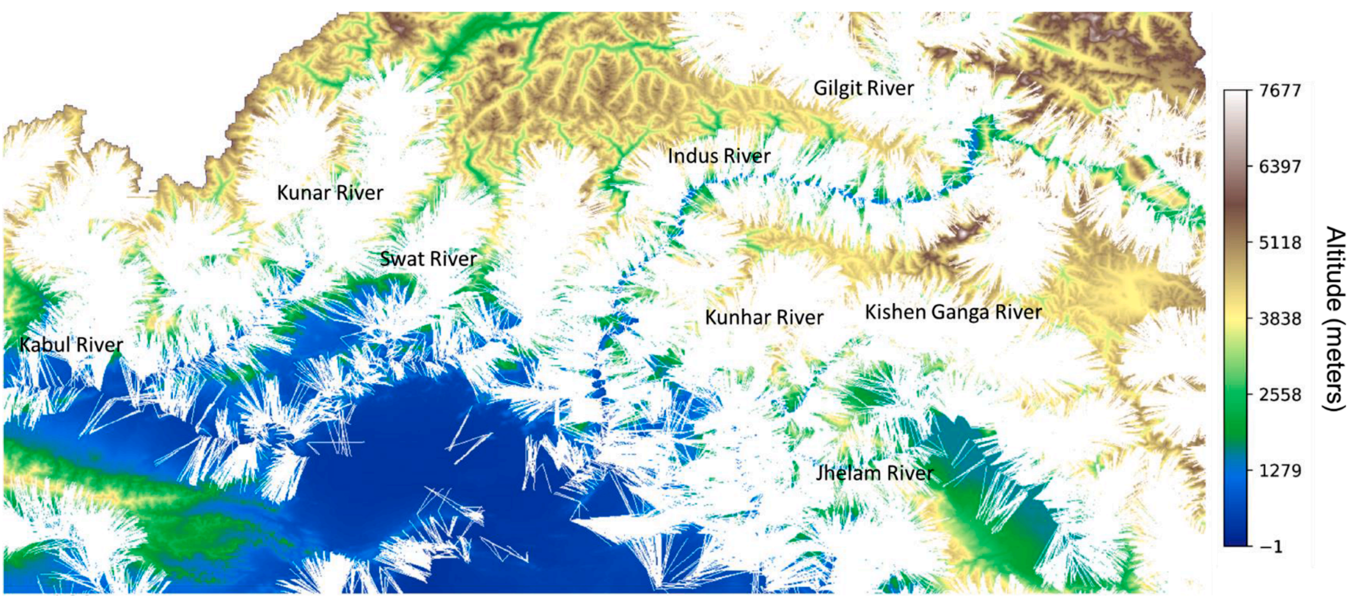

Figure C.14. Seasonal pumped hydropower storage plants developed by the model in the Indus basin, where the tunnels are represented in white.

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