Balancing smart irrigation & hydropower investments for sustainable water conservation in the Indus basin

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Abstract

Indus River Basin (IRB) region of South Asia is severely water-stressed with irrigation receiving 90-95% of total surface water allocations and depletion of fossil groundwater reserves of more than 30 km^3/year. Simultaneously, many supply-driven hydropower reservoirs, are planned in the basin. The reservoirs constructed upstream inflict severe environmental damages and reduce water availability for irrigation downstream. Policymakers promote smart technologies as a demand-based solution to reduce water consumption in irrigation. However, the effects of such technologies are not yet well understood, and unintended consequences (such as irrigation efficiency paradox and other nexus externalities) have recently begun to appear. Therefore, we use an integrated assessment model to analyze the proliferation of smart technologies in the IRB. The analysis suggests that if the Indus countries adopt a demand-based approach and irrigate their land completely using smart technologies, surface and groundwater withdrawals are indeed reduced. However, this reduction comes with a 33% increase in total expenditures, an increase in consumption across water and energy sectors, and higher withdrawals from fossil groundwater reserves. On the other hand, we find that if the countries were to balance their investments between smart and hydropower technologies it would not only reduce the increment in expenditure to 28%, but would also conserve irrigation water while avoiding the increased multi-sectoral consumption and environmental degradation. Thus, balancing investments between smart irrigation and hydropower

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projects can significantly reduce the economic and environmental (including conservation of water resources, meeting environmental flow targets, among others) costs of multi-sector water conservation in the IRB.
Keywords: River basin management; transformation pathways; systems integration; irrigation efficiency; water-energy-land nexus; integrated assessment modeling; smart irrigation and hydropower

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1. Introduction

The Indus River Basin (IRB) is a transboundary region in South Asia (Figure 1a). Published estimates of the basin area span a huge range (164,867 - 266,000 km^2) that includes interbasin transfers and complex geomorphology [1]. Approximately 300-million people reside in the IRB from four riparian countries; Pakistan (61 %), India (35 %), Afghanistan (4 %), and China (less than 1 %) [2]. Snow and glaciers in the Himalayan and Hindu Kush mountains are the primary sources of freshwater, contributing an estimated 1.51 times to total discharge naturally generated in the downstream areas [3]. Surface water flows through several important and well-known tributaries, including the Upper Indus, Ravi, Beas, Sutlej, Chenab, Jhelum, and Kabul rivers (among others), that merge in Southern Pakistan to create the lower Indus River and the Indus delta and ultimately drain into the Arabian Sea.

The Indus Water Treaty, a water-sharing agreement negotiated in the 1960s, partitions surface water resources along the shared border between India and Pakistan such that flows in the Eastern Rivers (Ravi, Beas, and Sutlej) are allocated for India's use, while flows in the Western Rivers (Upper Indus, Chenab, and Jhelum), are allocated for Pakistan's use. Some additional considerations for other water uses are allowed for in the Treaty, and these conditions continue to be a source of dispute between countries [4]. Surface water diversions (canals) are used extensively to move water between the impacted river systems and to support irrigated agriculture and electricity generation. For example, almost 90 % of Pakistan's food is grown with Indus water [5], and the Punjab province of India, with only 1.5 % of the national area, utilizing Indus water to support the production of about 20 % of the nation's wheat and 11 % of the rice production [6]. There is also more than 30 GW of installed hydropower capacity in the IRB and an estimated 50 GW of untapped potential in

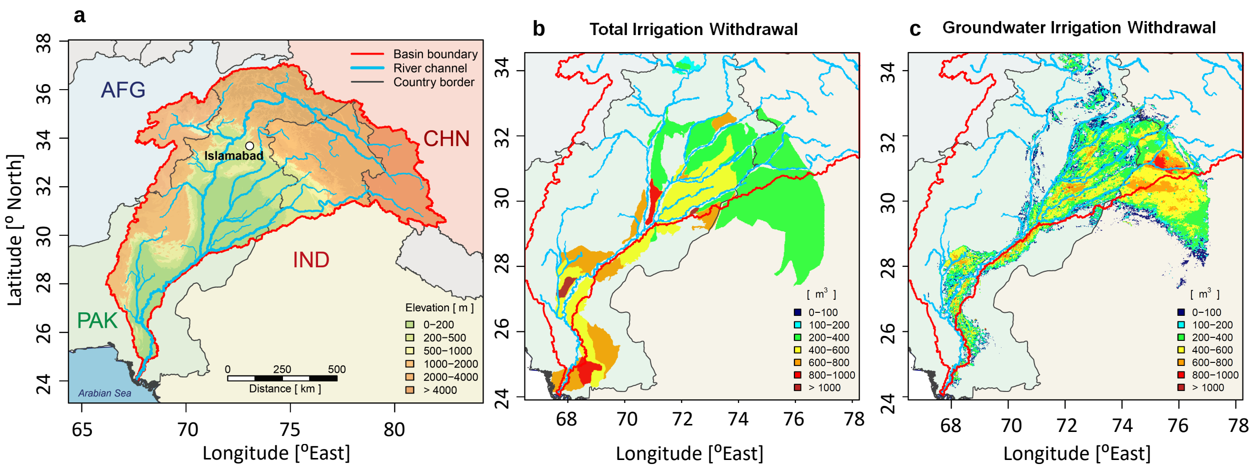

Figure 1: The Indus River Basin (IRB) region of South Asia. a) Hydrological basin delineation according to the hydroBASINS dataset and country boundaries according to the GADM dataset (note that some borders are disputed); b) Total annual irrigation withdrawals in 2008 within the irrigated part of the IRB (including canal transfers) [8]; and c) Annual groundwater withdrawals for the irrigated IRB in 2008 [8].

Pakistan's part of the basin [7].

At the same time in the IRB, surface water extractions reached capacity in the 1980s, limiting expansion to new users unless consumption was reduced upstream [9]. This state of affairs continues to the present day. The excessive surface water use means very little or no flow reaches the Indus delta during some parts of the year, causing severe impacts on water quality and the delta geomorphology [10, 11]. Being the lowest riparian in the IRB, Pakistan faces severe environmental damages due to the steady drying up of the Indus delta [12]. Some experts are of the opinion that a minimum flow of 12.23 Mm^3/day in Rabi season (Rabi is the cropping season from October-March) and 46.21 Mm^3/day in Kharif season (Kharif is the cropping season from July-October) should be maintained [12, 13] to avoid this environmental degradation. Yet, due to the extensive use of surface water in upstream regions, these environmental flows have not been maintained [14]. Irrigation is a significant concern, as it is estimated to divert up to 95 % of total available surface water [2, 9]. The irrigation and canal system has a long history and constitutes the largest contiguous irrigation network in the world [15, 16]. Farmers in the region use diverted river water to flood their fields, with less than 40 % of this water contributing to crop requirements [16] with the rest of the water going to return flows and evaporation from wet soil or transpired by weed [17].

The increased water demands have been met in the recent past by relying on distributed tube-wells that extract water from underground aquifers to supplement or fully replace canal-based surface water supplies [18]. In 2007, groundwater withdrawals for irrigation reached approximately 68 km^3 or 45 % of total irrigation water use, of which almost half (31 km^3) came from non-renewable groundwater resources [8]. Other research estimates that groundwater in certain regions of the IRB is being pumped at a rate that is 18 times (1800 %) greater than the average renewable recharge rate [19]. Electricity for irrigation is subsidized both in India and Pakistan, leading to inefficient groundwater use [20] (Supplementary Figure S6). At the same time, groundwater irrigation coupled with outdated agricultural practices causes degradation in soil quality. This degradation is further pronounced by seasonal variations in the water table [21].

Many multipurpose reservoirs, perceived as a supply-based solution to address the growing demand of agriculture for irrigation water [22] have been constructed in the IRB. Moreover, a large number of reservoirs are either in the construction phase or are being planned for construction in the near future. These reservoirs support both the energy generation from hydropower and water withdrawals for irrigation (in addition to many other uses, for example, urban demand, industry, and the environment, to name a few). The hydropower reservoirs also act as buffers for the irrigation system against variation in precipitation and snowmelt by ensuring continuous supply through stored water [23]. Releases from the reservoirs in the IRB are at their maximum in the summer season due to simultaneous peaks in energy and crop water demand. Despite the non-consumptive nature of hydropower and its ability to service both energy and irrigation sectors, water management in the IRB is becoming increasingly complex. This can be attributed in large part to the varying regulatory needs across different water uses, flood risk mitigation, salinity control [14] and rapidly growing pressure on the basin water resources [23, 24]. Not only this, but hydropower projects also inflict severe environmental damages in the downstream areas by interrupting essential water flows to the river delta. Furthermore, the absence of suitable infrastructure and installed technologies to estimate crop water demand implies that the reservoirs are operated in a supply-based mode. This, coupled with rigid irrigation schedules imposed at the watercourse level through obsolete colonial-era mechanisms, leads to large wastage of valuable surface water resources. Studies indicate that the potential of reducing these wastages through management of operations in supply-based systems is limited, and further improvements may only be achieved through the introduction of modern or 'smart' irrigation technologies [25].

In order to combat the aforementioned problems associated with hydropower technologies, many policymakers promote demand-based solutions to reduce the water consumed in irrigation. This reduction is brought about by increasing water use efficiency through modern technologies without compromising crop production. Irrigation modernization through the introduction of new technologies and management strategies has the potential to avoid long-term risks from water scarcity [26]. Smart technologies utilize feedback and demand-driven algorithms to optimize asset management and are increasingly being promoted by water system operators and basin planners to manage complex water networks and devise water allocation schemes [27]. Smart irrigation technologies help farmers monitor weather and soil conditions and enable the use of different forecasts and algorithms for optimizing irrigation scheduling [28, 29, 30, 31]. Smart technologies enable real-time tracking and control of irrigation systems based on a combination of energy use and water availability indicators [32, 33]. Real-time tracking of canal flows can isolate potential maintenance issues while also ensuring allocation schemes are maintained [34, 15]. It is important to note that robust tracking of ground and surface water flows, accompanied by regional cooperation on data sharing, is critical for avoiding the recently emerging pitfalls of irrigation efficiency (IE) policies [35].

An important pitfall associated with smart technologies intended to increase irrigation efficiency is a phenomenon commonly known as the 'Irrigation Efficiency Paradox (IEP)' [35, 25, 36, 37]. Increasing irrigation efficiency (IE) by adopting more water-efficient technologies is typically perceived as a water-conserving practice in the agriculture sector [25, 38]. The common understanding behind this perception is that increased on-farm IE leads to less water consumption at the farm, thus resulting in more water becoming available for use in other parts of the basin. However, field measurements and research evidence show that increasing on-farm IE does not always result in increased water availability at the basin scale. This is due in large part to the adjustment of agricultural practices by the farmers in a way that increases crop water demand (for instance, by increasing irrigated areas or planting more water-intensive crops). Thus, special care must be taken while advocating demand-driven IE technologies for conserving water in the irrigation sector. IE programs must be accompanied by appropriate water accounting and demand control frameworks in order to realize the full water-saving potential of smart irrigation technologies (the interested reader is referred to [35, 25] for further details).

Despite significant research into the on-farm benefits of smart irrigation and the regional benefits of constructing dams for irrigation and electricity production, there is a lack of multi-sectoral analysis linking regional cooperation strategies and technology diffusion pathways to policy objectives outside the water sector. Many co-benefits regarding sustainability objectives can be obtained by the rollout of smart technologies if they are proliferated appropriately. Potential benefits include reduced energy demands in the irrigation sector, lower air emissions, reduced land use, and better utilization of existing (and future) infrastructural capacity to meet development targets. Similarly, hydropower technologies offer many multi-sectoral benefits for water resource planning due to the nexus relationships connecting energy production to water availability up and downstream from irrigation systems [39].

In the IRB, the potential of the supply-side solution is almost exhausted, especially in the Indian region. In contrast, the potential of demand-side solutions is largely untapped all over the basin [2]. Recent studies suggest that water conservation at the regional level requires both supply and demand-based solutions [40]. An integrated or nexus approach that considers long-term transformation across multiple sectors and administrative basin areas is needed to unravel how supply and demand-side cooperation influences the water scarcity problem. Here we consider the proliferation of smart irrigation technologies (Figure 2) in a spatially and temporally resolved engineering-economic modeling framework of the IRB to track on-farm water saving and its effect on the other connected sectors.

This work contributes a new analysis of diffusion pathways for smart irrigation (demand-based) and hydropower (supply-based) solutions in the IRB using a nexus approach to map synergies and trade-offs for the water, energy, and land sectors along with achieving the minimum environmental flow standards. We incorporate smart irrigation and hydropower interventions into a spatially and temporally resolved engineering-economic model of the region to quantify the impact of smart irrigation and construction of reservoirs for dams on water saving costs, energy- and land use. The results demonstrate how policies targeting uptake of smart irrigation technologies can be co-designed to maximize benefits for water users across the IRB. Most importantly, we show that smart technologies combined with hydropower can reduce the long-term operational cost of water and electricity supply in all countries. Thus simultaneous adoption of supply and demand-driven technologies should be considered as a critical mechanism for achieving sustainable water conservation in the IRB.

2. Modeling the future scenarios in the integrated assessment model

The NExus Solutions Tool (NEST) is utilized in this work to analyze the multi-sector impact of smart irrigation diffusion in the IRB. NEST is an open access modeling platform that links a spatially and temporally resolved infrastructure optimization model covering water, energy, and land-use decision making to a high-resolution gridded hydrological model projecting water resource availability, hydropower potential, and irrigation water requirements under climate change [39]. NEST co-optimizes water, energy, and land-use decision-making using a reference system scheme that explicitly features the interactions and adaptation interventions across sectors (see [39] for reference water, energy, and land systems). The reference system scheme is a concept from the energy systems optimization literature and refers to the input-output supply-chain representation that defines how technologies, resources, and demands are connected in the model. Nexus interactions featured in NEST implementation for the Indus include water for energy and land activities and the energy needed to run processes in the water and agriculture sector (see Appendix). For example, NEST optimizes water allocation across urban, rural, industrial, and agricultural sectors while simultaneously expanding the power and water supply system to meet future demand requirements. Importantly, NEST incorporates capacity expansion as an endogenous adaptation intervention, enabling the model to transform the integrated system design in response to policy targets or resource constraints. NEST optimizes the system by minimizing total system costs. Outputs from NEST include the investment and operational costs for the technologies in each model region from 2016 to 2050.

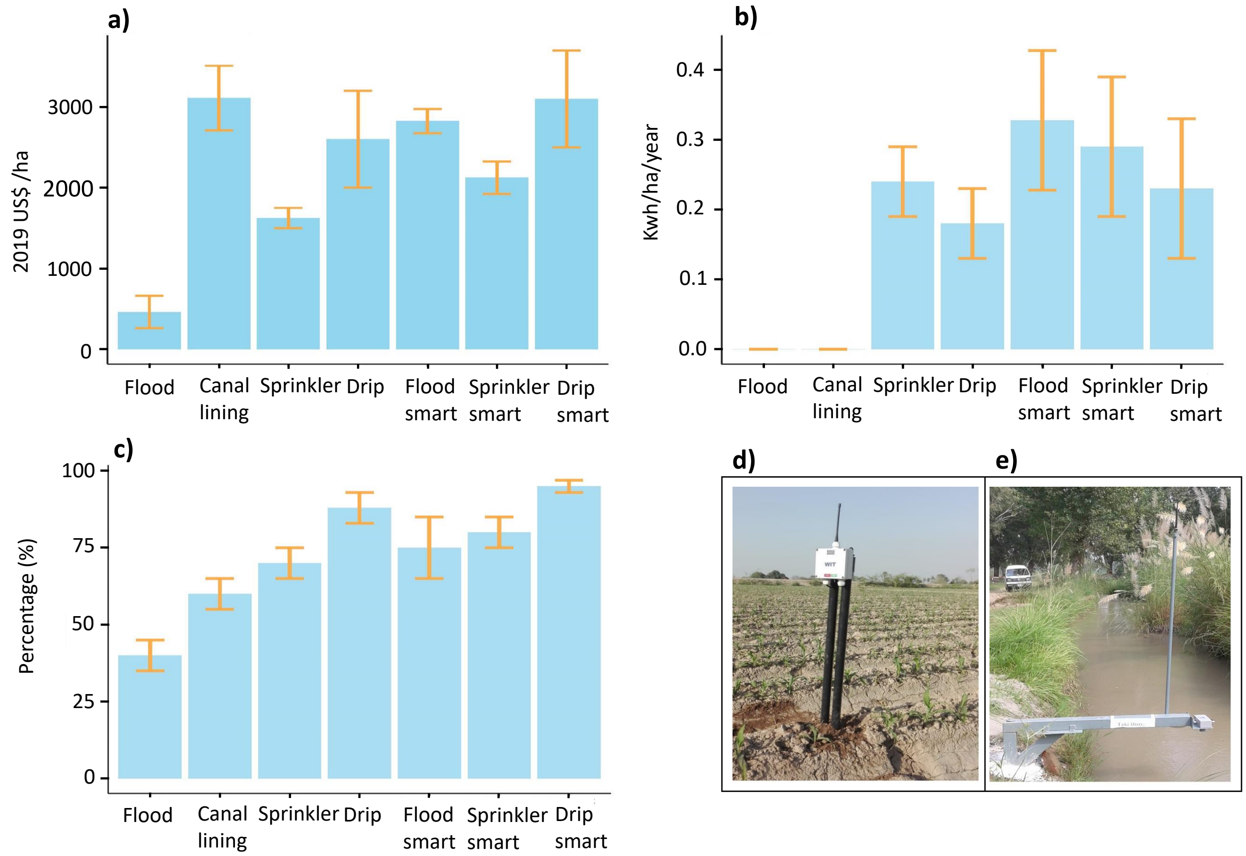

Figure 2: The conventional and modern (so-called smart) irrigation technologies and corresponding performance parameters that are required for implementation in NEST. a) The investment cost requires irrigating the land with given technologies options [41, 42, 43] (investment, fixed, and variable cost are listed in Supplementary Table S3). b) The energy use of each technology during irrigation [44] c) Water use efficiency measured as a ratio of water diverted from the freshwater resource into the farm field to that contributing to crop growth [17, 45, 41, 46, 47, 48]. The uncertainty bars show the possible variation in the values. The smart sensors pictured here were developed by the Center for Water Informatics & Technology (WIT) and have been installed at multiple locations in the Punjab province in Pakistan. d) The soil moisture sensor. e) The water accounting flow sensor [34].

2.1. Conventional and smart irrigation technologies

The model incorporates a stylized representation of multiple irrigation technology options, with the optimization routine in NEST selecting the location, size, and operational schedule over the future time horizon. The selected technologies are based on existing trends and discussions with project implementers from the irrigation planning districts in the IRB. The technologies and corresponding performance parameterization is summarized in Figure 2. Flood irrigation is the current practice in nearly all locations, and measures such as canal lining, sprinkler, and drip irrigation are considered in the model as conventional options to improve irrigation water efficiency. The smart irrigation technologies are parameterized to incorporate additional performance boosts from processes such as laser field leveling, soil moisture sensors (Figure 2d), and real-time control of water and energy use via metering infrastructure (Figure 2e). The parameterization of costs and performance are based on average data obtained from the literature and the extensive local experience of this study's co-authors in the design and implementation of smart technologies in the IRB [34].

Precision irrigation advisory service (PIAS) [49] maintain records and process the data taken from the smart technologies; some of them are presented in Figure 3. The real-time data is transmitted from farmer to canal aggregator and then to basin aggregator or policymaker who established PIAS. After extracting the valuable information from processed data, PIAS advises the farmers when, where, and what to irrigate not only to increase crop yield but also to conserve water and energy. In precision irrigation, water can be used more efficiently and effectively, and avoid under-irrigation (water stress) and over-irrigation (farmers spray more water than needed) [49, 50]. PIAS utilized smart technologies such as flow sensor, real-time feedback, irrigation automation, soil moisture sensor, power management, automated gate control, coordinate management with upstream and downstream, satellite and drone monitoring, and balancing electricity supply and demand. From these technologies, smart water meter (flow sensor) (Figure 2e) and soil moisture sensor (Figure 2d) are included in the modelling framework for this study. All other technologies presented in Figure 3 only elaborate the meaning of smart agriculture water management.

2.2. Scenario analysis

The analysis explores the scenarios outlined in Table 1. A baseline scenario explores a continuation of current trends and does not include the use of smart irrigation. The baseline scenario is used for comparison, but it is important to emphasize the profound environmental damages anticipated to occur under such scenarios. For example, currently, about 55% of electricity in IRB is produced from fossil fuels, the share of energy generation from renewable is less than 5% of total production (see [39, 52, 53] for further details related to baseline scenario and existing policies). Hydropower is under-exploited (Figure A1) [39]. In the baseline scenario, from Figure 4b, we estimate more than a fourfold increase in electricity demand in

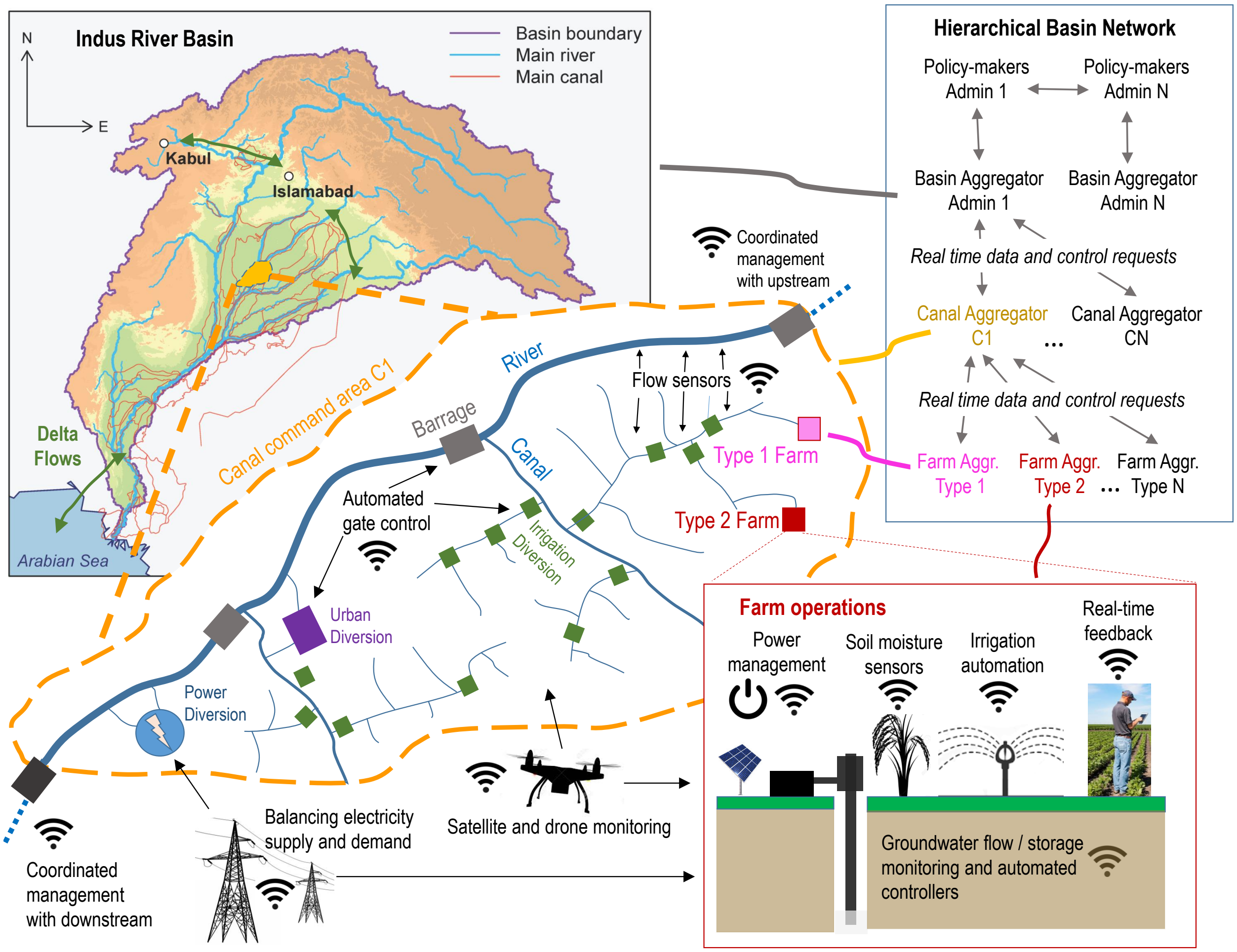

Figure 3: A presumed representation of an agricultural canal command area in the Indus basin equipped with smart irrigation technologies [51] for precision irrigation advisory service.

the IRB by 2050, as compared to 2020. Furthermore, we estimate a greater than fourfold increase in GHG emission (Figure 4d) related to oil, gas, and coal consumption, adding the IRB contribution to climate change. At the same time, according to the FAO projections, agriculture products demand will increase by 45% between 2020 and 2050 (Figure 4a) [52]. In the absence of more efficient irrigation technologies (see Figure 2c for water use efficiency), water withdrawals will increase by around 25% (currently 180 km^3, Figure 4c), water price, water stress, and average food production cost will increase by more than double (Figure 4d). The increase in water withdrawals and water stress pose challenges not only to the farmers (irrigation sector) but also to the other sectors, for example, the urban area, which will suffer from reduced water access. The improvement in irrigation efficiency after the adoption of

Policy mechanism	Scenario: Baseline	Hydro	Balance-0	*Smart-50*	*Balance-50*	Balance-NE
Water conservation	No conservation targets for irrigation.	Minimum flow in Indus delta area of **46Mm^3/d** (July-October) and **12Mm^3/d** (October-March).	Minimum flow in Indus delta area of **46Mm^3/d** (July-October) and **12Mm^3/d** (October-March).	Minimum flow in Indus delta area of **46Mm^3/d** (July-October) and **12Mm^3/d** (October-March).	Minimum flow in Indus delta area of **46Mm^3/d** (July-October) and **12Mm^3/d** (October-March).	Minimum flow in Indus delta area of **46Mm^3/d** (July-October) and **12Mm^3/d** (October-March).
Smart irrigation	No smart irrigation technology is available	No smart irrigation technology is available	Smart irrigation is deployed if **cost optimal**.	By 2030, **50% of irrigated area** in each model region is utilizing smart technology.	By 2030, **50% of irrigated area** in each model region is utilizing smart technology.	By 2030, **50% of irrigated area** in each model region is utilizing smart technology.
Hydropower penetration	In future, Install **all planned** hydropower projects in the Basin.	In future, Install **all planned** hydropower projects in the Basin.	In future, Install **all planned** hydropower projects in the Basin.	In the future **no new** hydropower installed in the system.	In future, Install **all planned** hydropower projects in the Basin.	In future, Install **all planned** hydropower projects in the Basin.
Cropping pattern	Crop activities can utilize all available cropping areas and match with historical location.	Crop activities can utilize all available cropping areas and can be **shifted within countries**.	Crop activities can utilize all available cropping areas and can be **shifted within countries**.	Crop activities can utilize all available cropping areas and can be **shifted within countries**.	Crop activities can utilize all available cropping areas and can be **shifted within countries**.	Crop activities can utilize all available cropping areas and can be **shifted within countries**.
Air emissions	No emission target implemented	No emission target implemented	No emission target implemented	No emission target implemented	No emission target implemented	No new coal or oil-fired power generation beyond that planned.

Table 1: Settings for policy mechanisms represented in each scenario included in the model analysis. Existing policies, including the Indus Water Treaty, are included in each scenario. The other necessary common assumptions are list in Supplementary Table S2. The choice of 50% is arbitrary, however, varying this does not qualitatively change the conclusions (see supplementary material). GHG represents greenhouse gas.

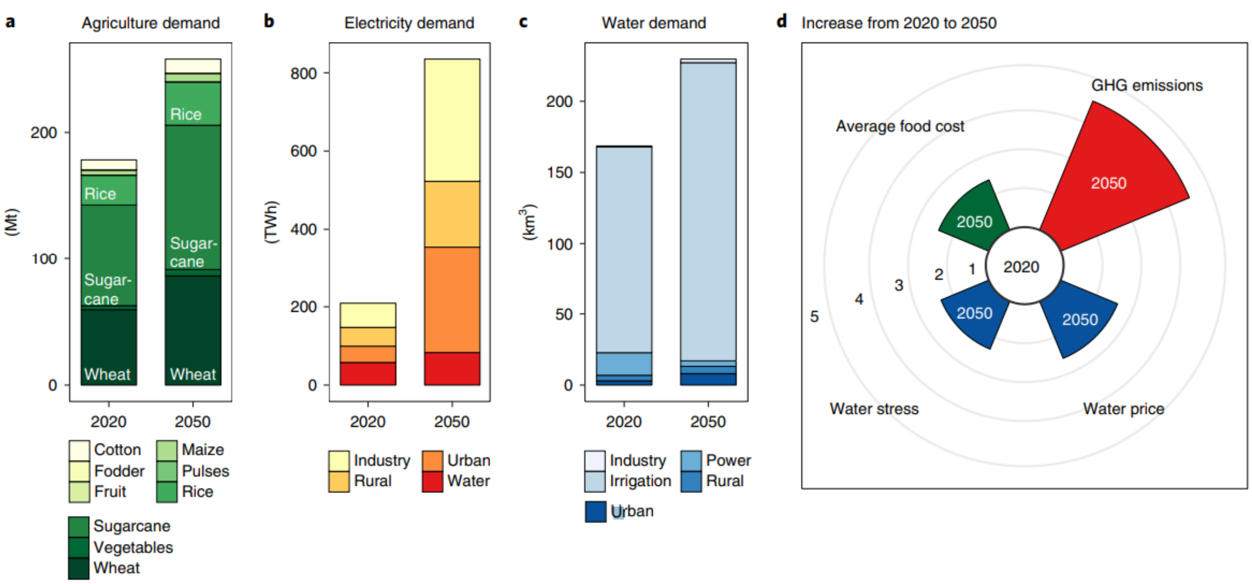

Figure 4: Expected demand growth in IRB from 2020 to 2050. **a**, Demand growth in agriculture products, **b** electricity, **c** and water. **d** Fold increase in average food and water price, water stress, and GHG emissions. Figure from [52].

modern irrigation technologies outlined in Figure 2 can significantly reduce non-recovered water losses and reduce water consumption if efficient irrigation technologies are used in combination with IE policies [54, 35, 17].

In order to ensure a fair comparison, we have formulated a Hydro scenario, which represents an alternative future in which each country proceeds with regional targets (for example, increase environmental flow [55], reduce water stress [26], etc.) with only planned hydropower projects without the availability of smart irrigation technologies. We also allow the model to optimize the cropping pattern and shift the cropping activities within the country, which involves crop reallocation to achieve maximum yield while minimizing water consumption. Additionally, we have formulated other scenarios to highlight the benefits of the penetration of a more demand-based approach (smart irrigation technologies) with or without a supply-based approach (hydropower).

Moving forward, to explore the costs and benefits of adopting the irrigation efficiency programs, we formulate a complete demand-based scenario. Therefore, a *Smart-50* scenario explores an alternative future in which each country proceeds with regional targets by increasing the penetration of smart technology. Each model region is constrained to ensure at least 50% of the irrigated area features smart technologies. The scenario mimics a future where countries take a demand-side approach to irrigation efficiency by focusing on technology-based targets to find the best ways to conserve water resources.

Finally, a *Balance-50* scenario (50 is the same as in Smart-50) combines the policies of both supply (hydropower) and demand (smart technologies) simultaneously. This scenario takes the latter one step further by incorporating all policy targets to identify the cumulative effect of smart irrigation technologies and the installation of new hydropower on water, energy, and land management. A *Balance-0* scenario explores an alternative future in which the smart irrigation technologies are available, but model free to utilize them for irrigation if it is cost-optimal (0 represents that there is no constraint on smart irrigation is implemented). In this scenario, all other assumptions are the same as taken in the Hydro scenario. Additionally, we simulate other scenarios by varying the smart irrigation penetration level (25-100%) to understand the relationship between costs and benefits of investing in such technologies. The outcomes are shown in Supplementary Table S1, Figures S1, S2, and S3.

Additionally, a Balance-NE is simulated for clean energy and low emissions targets that highlight the role of renewable in the future evolution of the water-energy-land systems. In this scenario, all policies remain the same as in the Balance-50 scenario, except the implementation of additional low emission targets. This scenario forced the model to maintain the GHG emissions level in future at the level of 2020, and no new coal or oil-fired power will be generated beyond that planned.

3. Synergies and trade-offs among smart irrigation and hydropower penetrations

This section presents the output of the modeled scenarios. First, we present the obtained expenditure portfolio. Afterwards, the water and energy sectoral changes induced by modeled scenarios and the trade-offs between smart irrigation and hydropower penetration is presented. Finally, this section quantifies nexus interaction, namely, energy consumed for water technologies, water consumed in energy production technologies, and water for irrigation in the IRB for all modeled years (2020 to 2050) under all tested scenarios.

3.1. Expenditure portfolio for modeled scenarios

This section presents a comparison of the expenditure portfolio between the baseline and the alternative future scenarios; Hydro, Balance-0, Smart-50, Balance-50, and Balance-NE. Figure 5 shows the yearly average attached investment and operating costs for each country and the entire basin for the baseline and the different alternative future scenarios. The difference in the expenditure of Smart-50 and Balance-50 compared to the Balance-0 scenario and the difference in expenditure between Balance-50 and Smart-50 are also presented in Figure 6. On the other hand, the difference in expenditure between other tested scenarios are presented in Supplementary Figures S8.

In *Hydro* scenario, each country meets the policy targets by reducing the investment attached to the land use by optimizing the cropping patterns. On the other hand, the operational cost remains the same as in the baseline. This scenario highlights the importance of crop shifting; for example, it is more cost-optimal for the entire Indus to change the historical cropping patterns while maintaining the environmental flow standards with planned hydropower.

In *Balance-0* scenario, each country achieves the ambitious targets outlined in Table 1 by optimizing smart irrigation technologies in the IRB. All Indus countries follow a similar expenditure trend as in the Hydro scenario. Intuitively, NEST optimizes the total system

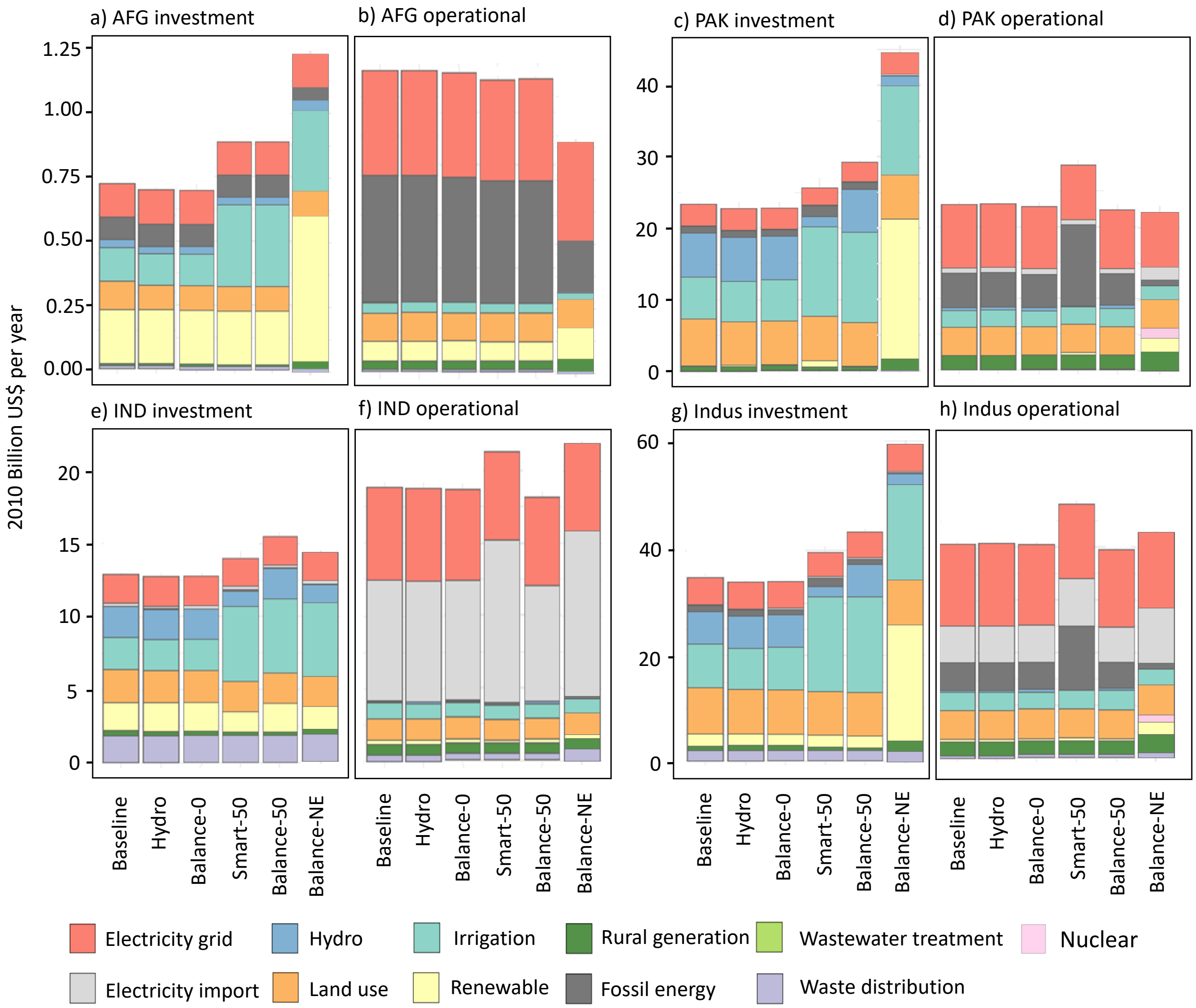

Figure 5: Total average yearly costs for the scenarios outlined in Table 1 for Afghanistan (AFG), Pakistan (PAK), India (IND), and all over the Indus. The investment and operational (this includes fixed and variable costs of operations and costs of electricity import see [39] for more details) costs are calculated in 2010 US$. The irrigation technologies costs are calculated in 2019 US$. This figure illustrates that (apart from other) for overall Indus, annual investment and operational costs for the Smart-50 scenario are almost US$15B/y more than Hydro scenario. On the other hand, this cost would shrink to US$8B/y for the Balance-50 scenario.

cost, and the smart irrigation technologies have higher investment cost (Figure 2a) compared to flood irrigation, therefore, it is cost-optimal for Indus countries to continue flood irrigation, but it is not a water conservation approach (see next section). Consequently, the model implements the constraint to uptake smart irrigation technologies for irrigation (Smart-50 and Balance-50 scenarios).

Moving forward, in Smart-50 scenario, each country requires more investment compared

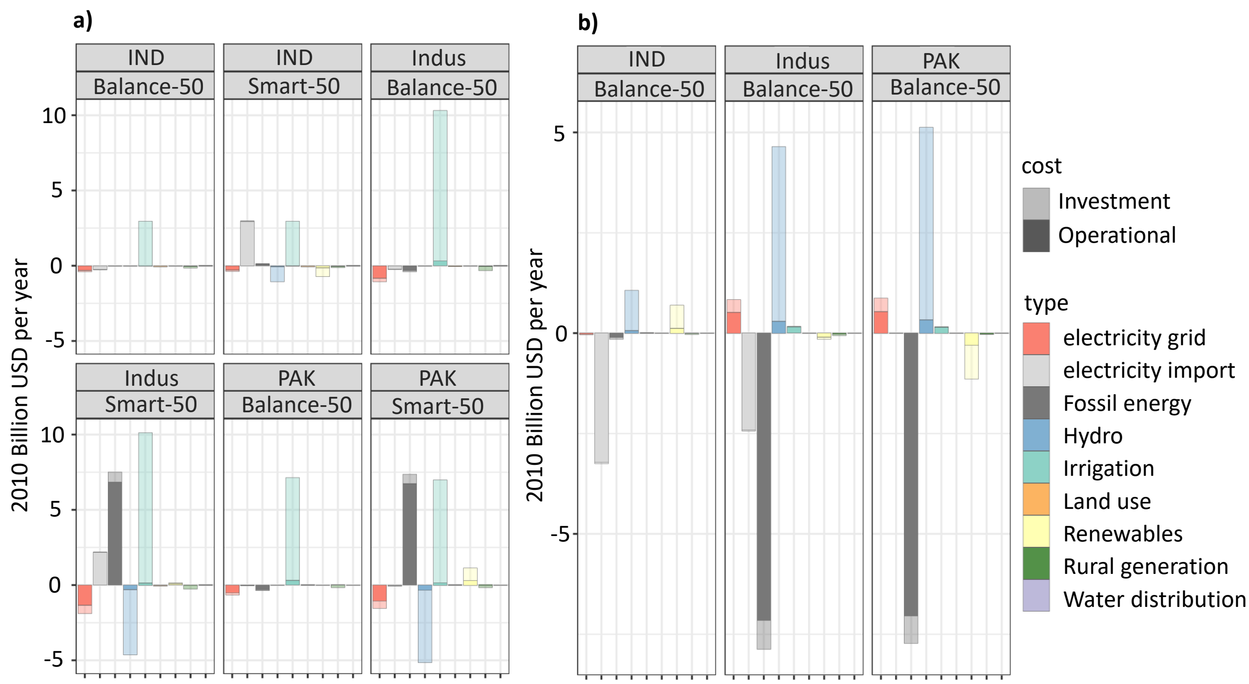

Figure 6: a) Difference in expenditure of Smart-50 and Balance-50 scenarios compare to the Balance-0. b) Difference in expenditure between Balance-50 and Smart-50 scenarios.

to the Balance-0 scenario. This is to address the most urgent problem of controlling the water withdrawals in the irrigation sector and protecting the Indus delta's rich ecosystem by meeting the minimum environmental flow (see Table 1). Compared to the Balance-0 scenario, Pakistan needs to invest around US$2.5 billion/year (Figure 5c and 6a) to support the irrigation efficiency program using smart irrigation technologies. In these investments, the significant portion is only attached to the irrigation sector; for example, the irrigation sector utilizes an additional US$7 billion/year (Figure 5c and 6a) to cover the cost attached to the efficient irrigation technologies (Figure 2a). To meet the energy demand related to irrigation, Pakistan also needs to invest additionally around US$0.5 billion/year (Figure 6a) in the production of fossil-fuel-based electricity, and it could save around US$5 billion/year (Figure 6a) by not installing the planned hydropower in the future. Since the planned hydropower projects are not implemented in this scenario, a large portion of the operational cost will be dedicated from renewable energy sources to fossil-fuel-based electricity generation. Specifically, the increase in operating costs represents the low variable cost in running the dams compared to fossil energy production. India would need to invest an additional US$1 billion/year (Figure 5e) compared to the Balance-0 to support the IE program. India's annual operational cost also increases by US$2 billion/year by importing the electricity from the country's regions outside the Indus basin (see [52] for the trade of electricity). Afghanistan requires a similar trend in investments cost, although proportionally smaller; US$0.2 billion/year (Figure 5a), but operational cost remain the same as in Balance-0 scenario (could save up to US$0.01 billion/year by reducing the energy generation by fossil fuel).

In Balance-50 scenario, Pakistan would require additional investment US$3 billion/year (Figure 5c and 6b) compared to a Smart-50 scenario to support the smart irrigation program while simultaneously constructing the planned reservoirs for the combined purpose; production of energy, to release the water for irrigation and satisfy minimum river flow requirements. At the same time, Pakistan will save around US$8.5 billion/year (Figure 5c and 6b) in terms of operational cost by reducing fossil-fuel-based electricity generation. Thus Pakistan would save around US$3.5 billion/year (investment + operational) in a Balance-50 scenario. Similarly, India would invest around US$1 billion/year (Figure 5e), in which a significant portion will go to the irrigation sector and hydropower generation. India would save around US$2.5 billion/year (Figure 5f) in terms of operational cost by reducing the electricity import from the other parts of the country that are not included in the IRB. Thus India would save around US$1.5 billion/year (investment + operational) in this scenario. Due to the low hydropower potential in Afghanistan [56], it would invest as a similar trend as it invests in the *Smart-50* scenario. Thus, the entire Indus, compared to the Smart-50 scenario, would need to invest US$4 billion/year (Figure 5g) to implement both supply and demand-based approaches simultaneously, but it could save around US$10 billion/year (Figure 5h) in terms of operational cost.

In the Balance-NE scenario, due to implementing the emission constraints, Afghanistan and Pakistan increased their investment compared to Balance-50 for shifting the energy sector from fossil-fuel-based electricity generation to renewable. On the other hand, Afghanistan significantly decreased operational costs attached to fossil energy generation. Overall, Pakistan's operational cost remains almost the same but with a change in the distribution between sectors. For example, the cost-saving of fossil-fuel-based electricity can be spent on electricity import and generation from nuclear. India decreased their investment by not

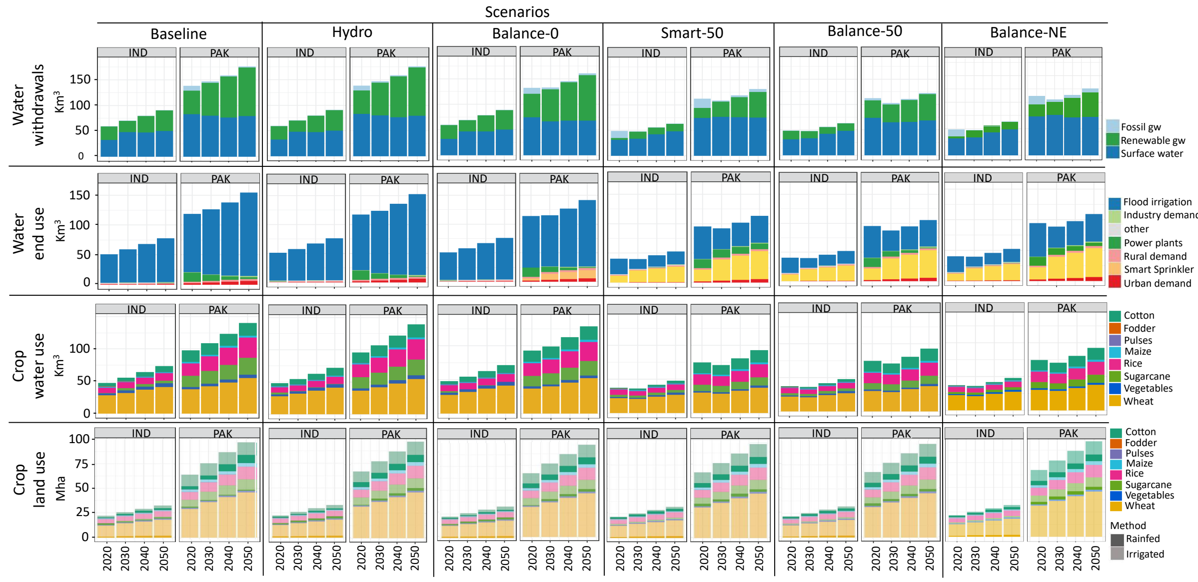

Figure 7: Comparison between different scenarios of yearly values for Pakistan (PAK) and part of India (IND) in the IRB. The fossil and renewable groundwater is distinguished using the groundwater recharge scenario from the the Community Water Model (CWatM, see Appendix) and the irrigation efficiency losses. The rows of this figure represent the change in sectoral consumption: row 1, the water withdrawals from different sources [km^3], row 2, the water used by different technologies [km^3], row 3, the water used by crops only [km^3], row 4, total land used for farming different crops [Mha]. We differentiate between irrigated (semi-transparent) and rainfed areas (dark color). And the columns of this figure represent scenarios. Smart-50 scenario reduces the water withdrawals but increases the share of fossil groundwater. On the other hand, the Balance-50 scenario reduces water withdrawal more than the Smart-50 scenario and also reduces the fossil groundwater share.

installing the new hydropower projects and increased the operational cost by investing in the import of electricity.

3.2. Sectoral changes induced by modeled scenarios

The *Hydro*, *Balance-0*, *Smart-50*, *Balance-50*, and *Balance-NE* scenarios include multiple policy objectives (see Table 1) across different sectors, which are considered simultaneously by NEST. Therefore, the specific policy objectives can be analyzed separately or in combination. The implication of multiple sectors is not necessarily the same when assessing multiple policies simultaneously or individually. However, to understand the implication of each scenario's policy on water, energy, and land systems, this section explored each policy independently, as represented in Table 1.

3.2.1. Water sector changes

Figure 7 depicts the water withdrawals by different sources, water end-use by different technologies, water and land use for agriculture (crops) in Pakistan and India from 2020 to 2050 for all the tested scenarios. The results for Afghanistan have not been shown here because only 4% of the Indus area lies in Afghanistan, which has comparatively low hydropower and irrigation potential. [56]. In the baseline scenario (first column of Figure 7), we assume that enough water is present in the basin to meet increasing water, food, and energy demand while fulfilling the Indus Water Treaty (see Introduction), but neglecting the environmental flow requirements, water efficiency guidelines, and hydropower constraints presented in the other scenarios.

The second column of Figure 7 represents water sector changes under the Hydro scenario. In this scenario, a negligible reduction in water withdrawals is observed in India and Pakistan because no smart irrigation technology is available. Furthermore, the third column of the Figure 7 depicts the sectoral changes induced by the Balance-0 scenario. NEST considered it optimal for some parts of Pakistan to uptake sprinkler irrigation along with flood irrigation to conserve water resources. Intuitively, constraining the use of surface water for environmental purposes (see Table 1) has the most impact on Pakistan's water use activities because it is the most downstream country [12]. Therefore, Pakistan faces the most significant challenge in meeting increasing water demand while simultaneously allocating the standard flow to ecosystems when already water is scarce. Consequently, a minor reduction of surface water withdrawals is observed (compared to the Hydro scenario), and the remaining renewable groundwater is the primary water source. Moreover, this has an enormous impact on the agriculture sector, where Pakistan and India address water scarcity by decreasing the water use in agriculture or adopting rain-fed crops (see supplementary Figure S7 for land used by the rainfed crop under different scenarios).

In Smart-50 scenario, an uptake in more smart irrigation technologies is observed (Intuitively, we constrain the model to irrigate 50% of irrigation area with smart technologies). Consequently, in India and Pakistan, most of the existing flood irrigation is substituted by the smart sprinkler (Figure 2) technology in line with other modern technologies, which reduces water consumption in irrigation. Specifically, it is essential to note that the total agriculture-able land is already utilized in most modeled regions in India. Furthermore, the Indus Water Treaty obligations do not allow India to use the western river water for irrigation (see Section 1). Therefore, to fulfill water conservation targets by meeting increasing food demand, India reduces the water consumption per hectare in the *Smart-50* scenario. Importantly, as already discussed, the smart irrigation technological framework provides the basin-wide water accounting facility and enables the water efficiency policies to account for complex interactions among water losses during irrigation and groundwater availability to ensure a combination of non-renewable groundwater and surface water sources are conserved.

Moving forward, the fifth column of Figure 7 represent the sectoral changes under the combination of both policies (the hydropower and smart irrigation) simultaneously operating in the model; the *Balance-50* scenario. In this scenario, Pakistan and India significantly reduce the water withdrawals in all modeled years compared to the Balance-0 and Smart-50 scenarios individually. Specifically, both countries swap the share of fossil groundwater with renewable groundwater to ensure sustainable water conservation. The reduction in fossil groundwater is due to the development of reservoirs in the upstream area, which increases the recoverable return flows that decrease by adopting the irrigation efficiency program. Furthermore, compared to the Smart-50 scenario, Pakistan reduces the water use in power plants from the year 2030 to 2050 because the significant electricity is now produced by hydropower, which has non-consumptive water use. However, land use in agriculture follows a similar trend to the Smart-50 scenario.

Moreover, in the Balance-NE scenario, due to the reliance on renewable and not installation large hydropower dams, the water withdrawals, water end-use, crop water use, and crop land use follow a similar trend as in the Smart-50 scenario.

Finally, in summary from Figure 7, the overview of the individual policy objective shows that constraint on environmental flow in the Balance-0 scenario will reduce water use in power plants and continue flood irrigation as the primary irrigation method in the basin. In fact, after the surface water, renewable groundwater is the primary source of water in the region because reservoirs increase the recoverable return flows, especially in Pakistan. However, in the Smart-50 scenario, the results show that it is optimal for all the IRB countries to uptake the smart sprinkler irrigation technology along with the other technologies. This

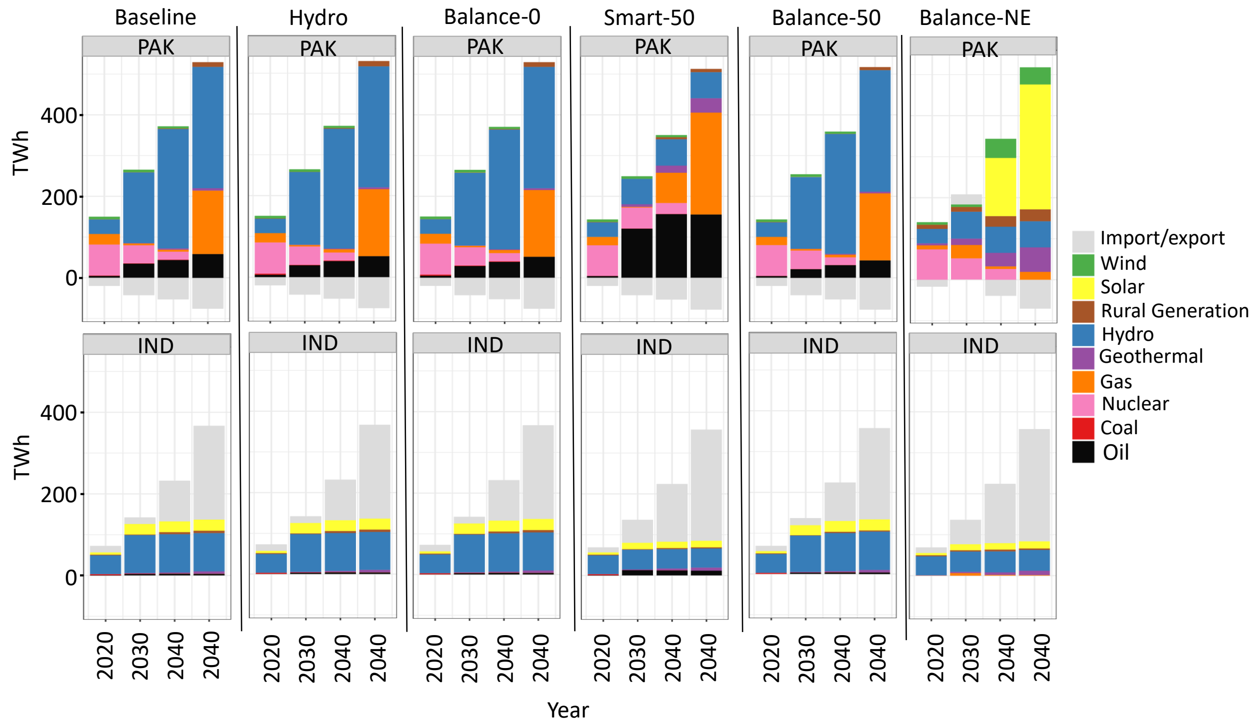

Figure 8: Model-estimated projection of yearly total (2020-2050) electricity generation under each scenario represented in Table 1 for Pakistan (PAK) and India (IND). Import/export represents the amount of electricity imported or exported to the countries' regions located outside the basin. For example, the Indian Punjab imports electricity from states not part of the basin.

reduces the water withdrawals more than the Balance-0 scenario but increases the share of fossil groundwater because the increase in irrigation efficiency through smart irrigation technologies reduces the groundwater recharge [35, 17]. In the entire Indus, with an additional US$13 billion/year (US$5B/yr investment and US$8B/yr operational) of investment and operational cost (Figure 5g, h), the smart irrigation technologies could save around 20km^3 of water per year (see Figure 7, combine saving of Pakistan and India compare to Balance-0 scenario). In contrast, hydropower and smart irrigation technologies combined penetration may be considered a win-win strategy, being both cost-effective (US$5B/yr cheaper than Smart-50 scenario), reducing water withdrawals more than individual implementation.

3.2.2. Energy production portfolio

Figure 8 shows the model's output related to the yearly total electricity generation in Pakistan and India from 2020 to 2050 under all the scenarios permutations tested. The model produces electricity to meet the demand in the baseline scenario without considering each sector's ambitious targets (summarized in Table 1). Under the baseline scenario, Pakistan used oil, nuclear, and gas to produce most of the electricity along with the hydropower generation. Pakistan's part of the basin also exports electricity to regions outside the basin boundaries. India primarily relies on hydropower, uses solar energy, and imports electricity from the regions in the country located outside the basin. The trend of electricity production under the Hydro and Balance-0 scenarios is similar to the baseline.

In the Smart-50 scenario, the energy production is not bounded by hydropower, and no emission constraints are implemented. Therefore, the energy sector in Pakistan increases the share of oil and nuclear (among others), and India increases the electricity import along with the share of oil. In the Balance-50 scenario, the energy production trend follows both policies, i.e., smart and hydropower. Under this policy, due to less water consumption in the irrigation sector, Pakistan could produce hydro-based electricity all year round. As a consequence of the planned hydropower policy, compared to the Smart-50 scenario, Pakistan mostly phases out the oil, reduce the share of gas used in electricity production and transforms the electricity sector by adopting hydropower. India also increases its share of hydropower but still relies mainly on the import of electricity.

The energy production portfolio presented here shows comparatively less integration of renewable energy sources such as solar and wind in the coming decades. Although hydropower dams are also considered the renewable energy source [57] nonetheless, it has a high socio-environmental impact on local communities. Therefore, dams are considered to be less acceptable renewable energy source [58, 59]. On the other hand, out to 2050, apart from hydro, our results represent that the energy sector also depends on fossil fuel-based electricity generation, which is unlikely to be considered sustainable given the very concern about climate change. Recent studies [60] show that integration of renewables can not only abate fossil dependency but also can allow avoiding massive hydropower deployment in the tropical basins. Therefore, we simulated an additional scenario for clean energy and low emission targets; the Balance-NE scenario. This scenario illustrates that from 2020 to 2050 model almost completely phase out fossil fuel-based electricity generation. Consequently, the electricity sector will mainly rely on renewable sources such as solar, wind, geothermal, and others.

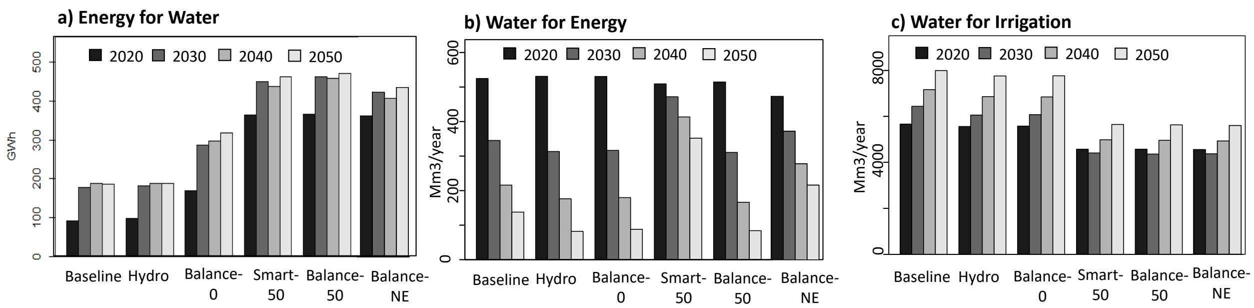

Figure 9: Quantification of nexus interaction, namely energy (electricity) consumed for water technologies, water consumed in energy production technologies, and water for irrigation in the IRB for all modeled years (2020 to 2050) under all tested scenarios. a) Energy used in the water sector, including urban, rural, and agriculture. b) Water withdrawals and consumption intensities for all energy technologies incorporated in NEST [39], for example, water required for cooling thermal power plants. c) Water withdrawals and consumption in irrigation. We observe that smart irrigation requires almost double energy in water technologies compare to the baseline, but it reduces a substantial amount of water consumption in irrigation. On the other hand, hydropower and smart irrigation combined could simultaneously minimize water consumption in energy and irrigation.

3.2.3. Nexus interactions

Figure 9 shows the nexus interaction between energy and water under baseline and different future projections for the Indus basin. Figure 9a shows the energy used to allocate water across sectors including urban, rural, and agriculture, for example, the energy requires for distributing, pumping, and treating water. From this panel of the figure, separately looking at a single scenario assists in following what policy drives change energy use for allocating water in different sectors. Furthermore, in the Balance-0 scenario, the energy use is slightly higher than the Hydro because the model chooses smart sprinkler technology (see the third column of Figure 7) for irrigation along with flood irrigation. The pressurized system involved in sprinkler irrigation requires a significant amount of energy (Figure 2b). Whereas, the energy use for water in the Smart-50 scenario is almost 50% higher than Balance-0 scenario because the irrigation sector utilizes the smart irrigation technologies (Figure 7b), which require a significant amount of energy (Figure 2b). Moreover, in the Balance-50 scenario, the energy use is slightly higher than the Smart-50 scenario due to both policy actions: hydropower and smart irrigation. The surface water diversion for constructing new dams would not require a large amount of energy, and this represents that the higher amount of energy is only dedicated to smart technologies. In the Balance-NE scenario, the energy used in the water sector is slightly less than the Balance-50 scenario due to the less reliance on hydropower and, therefore, less energy required for water diversion and distribution.

Figure 9b depicts the water withdrawals and consumption intensities for energy production technologies. In the Balance-0 scenario, most of the energy production in the entire basin is dominated by the hydropower plants (Figure 8b) because reservoir releases are non-consumptive (see Section 4). Thus the water used for energy production would still be accessible for other purposes. Furthermore, in the Smart-50 scenario, the water consumption in energy production is higher than Balance-0 scenario because the major share of the energy production is fulfilled using the oil and gas power plants (Figure 8c), which require a significant amount of water in all phases, for example, fossil-fuel extraction, processing, and transport, power production, etc., [61]. Moreover, in the Balance-50 scenario, the energy production is dominated by the hydropower power plant, similar to the Hydro and Balance-0 scenario. Therefore, water consumption is following a similar trend as follows in the Balance-0 scenario. In the Balance-NE scenario, water for energy production slightly increases than the Balance-50 scenario due to high reliance on renewable, which also requires water for washing, cooling, and other processes.

Figure 9c depicts the water consumption in irrigation. In the Balance-0 scenario, the irrigation sector uptakes smart sprinkler technologies along with flood irrigation (Figure 7) which is the main irrigation technology. Therefore, the water for irrigation is slightly lower than the Hydro. On the other hand, in the Smart-50 scenario, the irrigation sector utilizes a smart sprinkler, which has a higher irrigation efficiency (Figure 2c). Consequently, the Smart-50 scenario requires less volume of water to meet the agriculture-related water demand (Figure 4a). Furthermore, in the Balance-50 scenario, the water for irrigation follows the trend almost similar to smart irrigation because the balanced polices uptake both the smart irrigation technologies and planned hydropower plants. In the Balance-NE scenario, due to the same smart irrigation penetration level, the water withdrawals and consumption in irrigation remains the same as in the Balance-50 and Smart-50 scenarios.

Finally, from Figures 7, 8, and 9, the results show that balancing hydropower (supply-based) and smart technologies (demand-based) could simultaneously transform the water, energy, and land sectors. The water supply-side works by reducing the surface, renewable, and non-renewable groundwater withdrawals (last column of Figure 7). Whereas the demand-side works by reducing the water consumption in agriculture (third panel in the fourth column of Figure 7) and in energy sectors (Figure 9b).

4. Discussion and Conclusions

This study utilizes the integrated assessment modeling framework to identify the sectoral changes under planned hydropower and penetration of smart irrigation technologies while achieving the Indus River Basin's water conservation and environmental flow standards. The long-term water, energy, and land systems pathways are developed to understand the hydropower and smart irrigation policy implications in agriculture water management.

A significant reduction in surface and renewable groundwater is observed by adopting a purely demand-based approach and increasing fossil groundwater withdrawals. Some researchers have shown that the increase in irrigation efficiency using smart irrigation technologies declines the groundwater recharge [54]. Hence, while using smart irrigation technologies may be assessed as a gain from one perspective (reduce surface and groundwater withdrawals), it may appear a loss from another perspective (increase the fossil groundwater withdrawals and decline the groundwater recharge). Thus, an alternative future is simulated where the Indus simultaneously adopts the combined planned hydropower and smart irrigation penetration policies (Balance-50 scenario), which collectively reduces surface, renewable, and fossil groundwater withdrawals. However, this requires an average yearly investment of approximately US$4 billion/year. At the same time, the Indus countries can collectively save US$8 billion/year in terms of operational costs, compared to the exclusive adoption of smart irrigation technologies beyond 2020.

The transformation of the energy production sector under each alternative future (Figure 8) has also been presented. The results illustrate that the demand-based approach phases out hydropower generation by increasing the share of oil and gas in the energy sector. In contrast, the balanced policy actions ensure renewable energy generation all year round. The quantification of the nexus interaction between water and energy is also presented, which indicates that even though the demand-based approach reduces water consumption in irrigation, it increases the energy consumption in water technologies (Figure 9). The results demonstrate that hydropower development in parallel with the adoption of smart irrigation reduces the water consumption in the energy and irrigation sectors but increases the energy consumption in the water sector compared to the baseline. Therefore, it depends on the judgment of the policymaker to address the water scarcity problem by adopting the supply-side, demand-side, or a combination of both solutions.

Additionally, the scenarios by varying smart irrigation technology penetration levels have also been simulated (Supplementary Tables S1, Figures S1, S2, and S3). We find that the combination of hydropower and smart irrigation technologies still performs better in terms of cost and water conservation even if the irrigation technologies are deployed at the maximum level (Balance-100). Furthermore, an additional scenario for clean energy and low emission targets has also been simulated (Balance-NE; all policies are the same as in Balance-50 except additional low emission targets are implemented). This scenario illustrates that from 2020 to 2050, with additional investment cost compared to Balance-50, the model almost completely phase out fossil-fuel-based electricity generation.

The results presented here depend on climate parameters, such as glacier melt and precipitation patterns, which have high uncertainties. For the coming decades, these uncertainties will also affect the prediction of water trends [62, 3]. Indus basin climate change uncertainty is a complex matter requiring a broader range of sensitivity cases. The future work is directed toward addressing these uncertainties based on the knowledge of discharge portion originated from glacier and mountain snow. Moreover, this study considered hydropower as non-consumptive water use. Generally, evaporated water from dams is regarded as consumptive water use [63], which is not considered here. Furthermore, several policies implementation requires additional assessment and planning; for example, a large-scale crop shifting has implications on land-use change, food market, wages, employment, and education (among others). These socio-cultural aspects, such as employment, wages, and education, are not fully incorporated in the presented modeling framework. Moreover, this study illustrates that the balancing investments between smart irrigation and hydropower projects can significantly reduce economic and environmental (including conservation of water resources, meeting environmental flow targets, among others) costs. There is a high risk of misinterpreting the environmental cost represented here—the reason is that the environmental cost of dams includes the socio-environmental aspect of dam reservoirs [58]. However, the

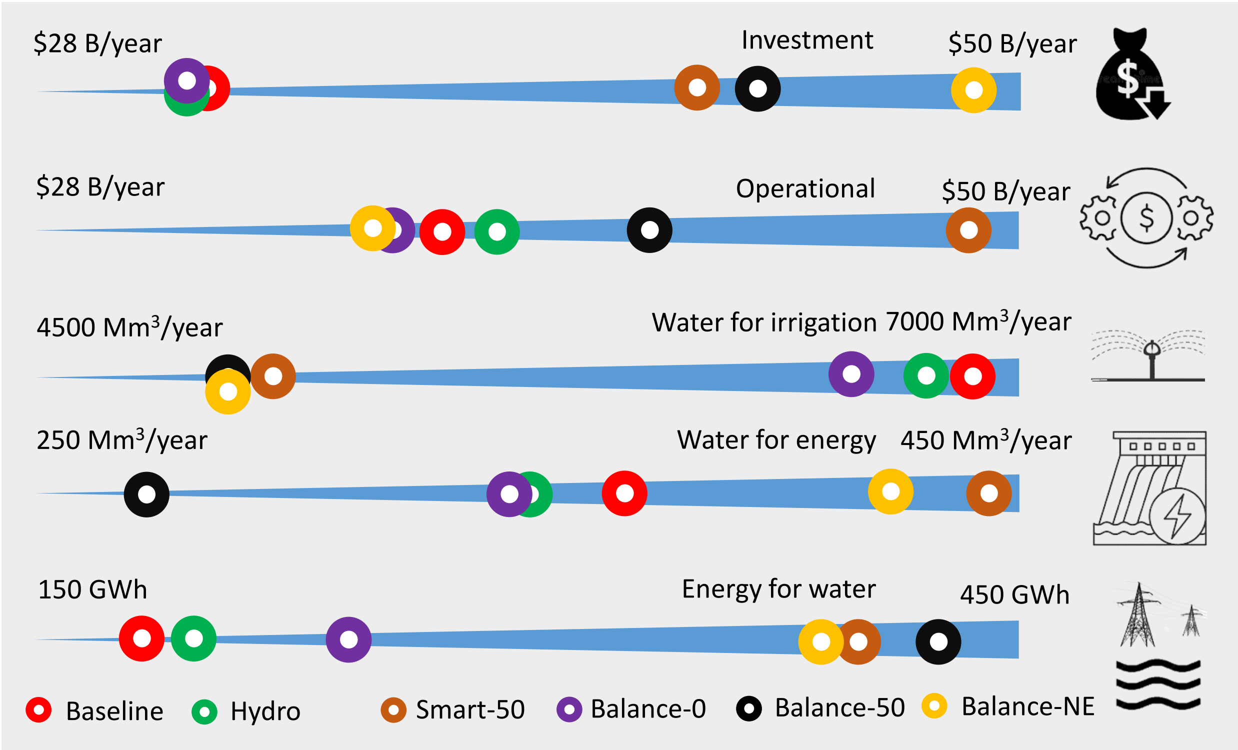

Figure 10: Average yearly values of leading indicators of all tested scenarios for the entire Indus basin. Investment and operational costs are taken from Figure 5. Nexus interactions; water for irrigation, water for energy, and energy for water are the same as defined in Figure 9. We observed that, although the investment cost is high in the Balance-50 scenario, the operational cost is cheaper more than the margin of increased investment compared to the Smart-50 scenario. Therefore, cumulatively Balance-50 is cheaper. At the same time, the water for irrigation and water for energy is minimum in Balance-50, which shows that the balancing is a more water-conserving approach. Energy for water is high in the Balance-50 scenario because hydropower and smart irrigation technologies are both in place simultaneously, and therefore, first, the energy generation is renewable-based; second, energy is utilized in smart technologies. On the other hand, Smart-50 depends on fossil-fuel-based energy generation (Figure 8), which is not environmentally sustainable. Finally, Balance-50 performs better in terms of cost, water conservation, and environment-friendly energy production. Thus simultaneous adoption of the supply and demand-side technologies should be considered as a viable policy for sustainability.

socio-environmental cost of dam reservoirs is not completely incorporated in the modelling framework; therefore, the representation of environmental cost in this study is restricted to the economic benefits only. Furthermore, the socio-environmental cost associated with large installed and planned hydropower projects is a truly complex calculation and touches on a highly controversial subject such as displacement and resettlement of local communities [58, 59]. We acknowledge this limitation and hope to address it in future. Therefore, the afore-mentioned limitation requires due consideration before the results presented herein are used for devising policy.

In conclusion, we show how the Indus countries could reduce their cost of conserving water resources by implementing the supply and demand-based approaches individually or simultaneously. Figure 10 shows the leading indicators of all tested scenarios for the entire Indus basin. This represents that the implementation of collective policy action (supply and demand-based) appears to be a win-win strategy, as it delivers the necessary environmental benefits at a lower cost than either of the individual strategies. More water-efficient irrigation technologies can conserve water resources and guide important changes in the agriculture and energy sectors. For example, our results show how smart irrigation and hydropower projects provide higher river flow to downstream regions that suffer from water scarcity. Polices supporting such balanced strategies should be implemented even if with restricted crop shifting, which is both socially and politically challenging to implement.

Appendix

This study utilizes the NExus Solutions Tool (NEST) to develop long-term basin-wide pathways for water, energy, and land systems under the smart technology diffusion and planned hydropower policies for agricultural water management in the IRB. The framework links a gridded hydrological model to an infrastructure capacity planning model. The model implementation is detailed in Vinca et al. (2020) [39]. The NEST framework integrates engineering-economic and distributed hydrological modeling, with the data sources summarized in [39]. The distributed hydrological model employed in NEST is the Community Water Model (CWatM). CWatM calculates evapotranspiration, surface water, and groundwater flows on a $0.1^\circ \times 0.1^\circ$ gridded representation of the basin area. CWatM was previously calibrated to the IRB and applied across an ensemble of climate futures [39]. The information from CWatM is converted into resource potentials (surface water, groundwater, and hydropower) and irrigation water requirements (evapotranspiration) for constraining water use in the engineering-economic modeling.

The engineering-economic model is an optimization framework implemented in MESSAGEix and solving the following system of equations using the CPLEX barrier method:

$$\min f(\mathbf{x}) = \sum_{r \in R} \sum_{t \in N} \mathbf{c}_t^{\mathrm{T}} \, \mathbf{x}_{r,t} \, \delta_t \; ; \; \mathbf{A} \, \mathbf{x} \, \geq \, \mathbf{b} \tag{1}$$

The optimization decision variables ($\mathbf{x}$) are the capacity and operation of technologies and processes from time $t \in T = \{2015, 2020, 2030, 2040, 2050\}$ and sub-regions $r \in R$, where R is representing a set of polygons that are the intersection between sub-basin and country boundaries. The objective function f is the total discounted cost across all regions and time steps, considering time-varying costs $\mathbf{c}$ for investment, fixed, and variable components for each technology. The discount factor δ is calculated using a discount rate of 4% annually. The model co-optimizes water, energy and land-use choices using a linear system scheme (i.e., $\mathbf{A}$ and $\mathbf{b}$) in each sub-basin region that explicitly features the interactions and adaptation interventions across sectors. The spatial resolution of the model is determined by the intersection of sub-basin catchment units and country boundary polygons to form what is referred to as Basin Country Units (BCUs). The BCUs enable the explicit tracking of flows across countries' boundaries while maintaining a hydrologically consistent reduced form river network that supports long-term river management. Likewise, a reduced-form and expandable electricity transmission network computes optimal electricity transfers and inter-basin electricity trading. Crop yields are aggregated nationally to meet projections of future production quotas. The framework considers the allocation of water and electricity across urban, rural, manufacturing, energy, and agricultural sectors, where future demands are generated based on econometric models fit to historical data (see [39]). Multi-sector sustainability policies can be implemented in the framework by incorporating constraints on future land, water, and energy indicators.

Water from different resources (surface, aquifer, and saline) is accounted for and allocated across sectors (urban, rural, energy, and agriculture). Internal runoff in each BCU, regulation of reservoirs, and water flowing from adjacent nodes through rivers or canals all contribute to available surface water. Renewable and non-renewable groundwater use is distinguished using groundwater recharge scenarios from CWatM and the efficiency losses from irrigation (Figure 2c). Simultaneously, return-flow volumes are managed, including opportunities to recycle wastewater streams within and between sectors. River flow and conveyance technologies move water between nodes. Sectoral water withdrawals and return flow occurring outside the energy and land systems (i.e., municipal and manufacturing sectors) are exogenous and, together with endogenous water requirements for power plants and crops, drive the investments in water distribution and wastewater treatment infrastructure. Nexus interactions across sectors are accounted for explicitly, including the energy required for pumping and treating water and the water needed for crops and electricity generation (Figure 9). The integrated water system representation is depicted in our previous work [39].

Monthly irrigation intensities are estimated for each crop and BCU in NEST using the modeled evapotranspiration from the hydrological model and crop-specific coefficients reflecting variable growing seasons and irrigation application rates. The amount of water needed for each crop is calculated using the CROPWAT approach [64]:

$$w_{n,x,y,m} = \max \left\{ \left(k_{n,x,y,m} \cdot e_{n,x,y,m} - p^*_{n,x,y,m} \right), 0 \right\} \tag{2}$$

In the above equation, n is the node where the crop is located, x is the crop-type, y is the investment period (annual), m is the operational period (sub-annual), w is the irrigation intensity per unit area $[m^3/ha]$, k is the crop coefficient, e is the reference evapotranspiration $[m^3/ha]$ and p^* is the effective precipitation $[m^3/ha]$. The reference evapotranspiration is calculated with CWatM using the Penman-Monteith method. The effective precipitation is estimated following the CROPWAT approach: [64]:

$$p^* = \begin{cases} p \cdot (4.17 - 0.2 \cdot p) & p < 8.3\text{mm/day} \\ 4.17 + 0.1 \cdot p & \text{otherwise} \end{cases} \tag{3}$$

For non-paddy crops, p is the 10-day moving average daily precipitation in mm/day, and for paddy crops, it is the 3-day moving average to account for saturated soils [65]. Irrigation intensities can optionally be calibrated such that, when aggregated across a given BCU, reproduce annual historical withdrawals when multiplied by the historical cropping area. Regionally specific crop coefficients are assembled for each country in the basin [39].

The irrigation intensities are calibrated such that when multiplied by the historical cropping pattern, reproduce annual irrigation deliveries are reported across the IRB. We apply the dataset described in Cheema et al. (2014) [8] to parameterize historical irrigation withdrawals at 1-km spatial resolution covering the irrigated IRB. The dataset utilizes a combination of reported data from the provincial irrigation planning authorities and satellite-derived hydrological indicators. Notably, the irrigation canal system extends outside the geophysical basin boundary. To account for the irrigated grid-cell areas located outside the basin boundary, we included the local climate conditions at these locations in the averaging to the BCU-level by associating each irrigated grid-cell external to hydrologically-defined basin boundary with its nearest BCU.

For electricity systems, an asset-level power plant database is developed by merging different global and local datasets describing individual projects. In an initial step, power plants within the basin are identified using the 2017 version of the World Electric Power Plants database (WEPP). The WEPP database includes the location information for some plants. For others, the information is missing; in our analysis, missing locations in the WEPP database are geocoded using an automated process that cross-references the plant name and location with data queried using google maps. Additionally, we incorporated a global hydropower database that includes small-scale systems missed in the WEPP database [66]. Finally, we reviewed national planning and recent news articles to identify and geocode planned hydropower and large-scale dam projects in the IRB. We focused the search on large projects currently under construction or in the later planning stages of development (see Supplementary Figure S4).

Figure A1 depicts the mapped hydropower generation capacity and its classification by riparian country. Overall, we identify more than 30 gigawatts of installed power generation capacity within the hydrologically defined basin boundary that is mainly situated in Pakistan and, to a lesser extent, in India (Supplementary Table S4). Importantly, there are more than 40 gigawatts of planned capacity, specifically hydropower generation systems, in the Pakistan and Indian portions of the basin. The plants are classified by age (vintage) and aggregated to the BCU-level. In BCU, the model generates exogenous demand profiles, such as electricity, according to coupled climate-human development narratives from the Shared Socioeconomic Pathways (SSPs) (the common scenario assumptions represented in Supplementary Table

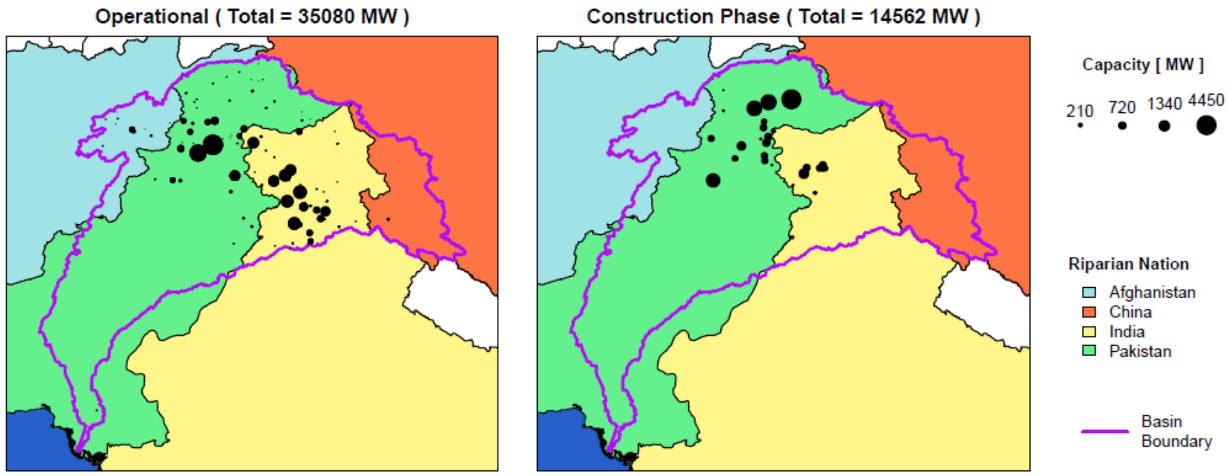

Figure A1: Hydropower generation capacity and its classification by riparian country, including the disputed territories (see [67] for the official map of Pakistan).

S2). In this study, the SSP2 (middle-of-the-road) scenario is explored in the analysis. The existing and planned capacity of power generation in the IRB is represented in Supplementary Figure S5. Hydropower is the primary source of generation capacity in the IRB. Therefore, a number of large-scale hydropower projects are also planned in the basin which are listed in Supplementary Table S2. In this table, the author estimate the electricity generation capacities based on the technically reported data [39]. For the planned power plants, the model is forced to invest in and build the planned capacity in the stipulated investment year. For hydropower systems, the existing capacity is assumed to respond linearly to network flows upstream from the BCU, and normalized such that the design capacity is output under a design flow rate taken to be the 70th percentile of the naturalized flow in the same network.

Wind and solar power potential are assessed using gridded power production time series generated with the Renewables.ninja application programming interface. The wind and solar time-series span 30 years of hourly estimates at 3 arc minutes. The sites within each BCU are categorized into three different quality classes using the estimated capacity factors. It is important to emphasize that climate impacts are unaccounted for in the wind and solar potentials.

A set of exclusion criteria limit the locations (grid-cells) where additional hydro, wind, and solar installations can be accommodated. The exclusion zones are defined similarly to previous work [39, 52, 44] and include the following: 1) lakes; 2) protected habitat areas and national parks, 3) forests, 4) where the shortest distance to a population center with more than 100 residents is more than 250 km away, and 5) urban areas. Additionally, for hydropower systems, we assume that new projects can not be built within 10 km of existing projects. Finally, all necessary details are presented in previous literature [39, 52, 68].

Common scenarios assumptions

The common assumptions for the future scenarios presented in this paper are listed in Supplementary Table S2 and also presented in our previous literature [39, 52].

Data and code access

The input data and the model code is available online at https://github.com/iiasa/NEST. The new version of NEST 1.1 includes all the advancements from the previously published version [39, 52] and is in line up with the results presented in this paper. The documentation and code for CWatM also can be found at: http://cwatm.iiasa.ac.at/, and similarly, documentation and code for energy-economic model MESSAGEix can be found at: https://messageix.iiasa.ac.at/

Declaration of Competing Interest

There are no conflicts of interest reported by any of the authors.

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