

# Integrated Climate-Land-Energy-Water Solutions: Modelling and Assessment of Sustainability Policy Options

by

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B.Sc., Politecnico di Milano, 2014

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We acknowledge with respect the Lekwungen peoples on whose traditional territory the  
university stands and the Songhees, Esquimalt and WSÁNEĆ peoples whose historical  
relationships with the land continue to this day.

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## Abstract

This dissertation reviews the progress in climate, land, energy and water (CLEW) multi-scale models and proposes a framework for quantitative assessment of multi-sector long-term policies. The so-called CLEW nexus approaches have shown their usefulness in assessing strategies to achieve the Sustainable Development Goals in the contexts of increasing demands, resource scarcity, and climate change. This thesis contributes to existing research by (1) focusing on the palette of feasible long-term sustainable solutions at different scales to face current and future sustainable development challenges; (2) improving understanding of how CLEW models can best advise on sustainable development research and highlighting the strengths and limitations of existing configurations; (3) inquiring what is needed for new tools to be accessible, transferable and successful in informing the final user. This dissertation first reviews a set of models that can meet the needs of decision makers discussing research gaps and critical needs and opportunities for further model development from a scientific viewpoint. Particular attention is given to model accessibility, usability, and community support. The review explores at different scales where and why some nexus interactions are most relevant, finding, for example, that both very small scale and global models tend to neglect some CLEW interactions. This dissertation also presents the Nexus Solutions Tool (NEST): a new open modeling platform that integrates multi-scale energy-water-land resource optimization with distributed hydrological modeling. The new approach provides insights into the vulnerability of water, energy and land resources to future socioeconomic and climatic change and how multi-sectoral policies, technological solutions and investments can improve the resilience and sustainability of transformation pathways while avoiding counterproductive interactions among sectors. Finally, a case study analysis of the Indus River Basin in South Asia demonstrates the capability of the NEST framework to capture important interlinkages across system transformation pathways towards the United Nations' Sustainable Development Goals. The results show how the Indus countries could lower costs for development and reduce soil pollution and water stress, by cooperating on water resources, electricity and food production.

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# Contents

Supervisory Committee . . . . .	ii
Abstract . . . . .	iii
Acknowledgements . . . . .	iv
<b>Contents</b>	<b>v</b>
<b>List of Tables</b>	<b>vi</b>
<b>List of Figures</b>	<b>vii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation, Research Questions and Objectives . . . . .	2
1.2 Structure . . . . .	4
Introduction Bibliography . . . . .	5
<b>2 Climate-Land-Energy-Water nexus models across scales: progress, gaps and best accessibility practices</b>	<b>7</b>
2.1 Introduction . . . . .	8
2.2 Climate, land (and food), energy and water nexus modelling background . .	9
2.3 Methods, review approach . . . . .	10
2.4 CLEW nexus models . . . . .	12
2.4.1 Modelling scale and resolution . . . . .	12
2.4.2 Sectoral coverage: state of the art and compromises . . . . .	14
2.4.3 Cross-sector interlinkages . . . . .	19
2.4.4 Geophysical bias . . . . .	20
2.4.5 Model structure and nexus integration . . . . .	22
2.4.6 Availability, accessibility and usability . . . . .	23
2.5 Discussion: emerging gaps and way forward . . . . .	24
2.5.1 Methodological limitations . . . . .	24
2.5.2 Sectoral representation and nexus interlinkages . . . . .	26
2.5.3 CLEW linkage to Sustainable Development Goals (SDG) and challenges . . . . .	26
2.5.4 The lack of common assumptions . . . . .	27
2.5.5 Way forward for scientists and modellers . . . . .	28
2.5.6 The right model for the right user . . . . .	28

Chapter 2 Bibliography . . . . .	28
<b>3 The Nexus Solutions Tool (NEST) v1.0: An open platform for optimizing multi-scale energy-water-land system transformations</b>	<b>37</b>
3.1 Introduction . . . . .	38
3.2 Modeling framework . . . . .	39
3.2.1 Community Water Model (CWatM) . . . . .	40
3.2.2 MESSAGEix . . . . .	40
3.2.3 Reference system . . . . .	42
3.2.4 Enhancements to the MESSAGEix model . . . . .	52
3.3 Modeling SDG implementation in the Indus River Basin . . . . .	53
3.3.1 Model setup . . . . .	54
3.3.2 Scenario analysis . . . . .	60
3.4 Results and discussion . . . . .	61
3.4.1 Role of water storage and seasonal effects . . . . .	61
3.4.2 Quantifying investments to achieve the SDGs . . . . .	63
3.4.3 Synergies and trade-off among SDG targets . . . . .	64
3.4.4 Uncertainty and sensitivity . . . . .	67
3.4.5 Structural limitations and further developments . . . . .	69
3.5 Conclusions . . . . .	71
3.6 Code availability . . . . .	72
Chapter 3 Bibliography . . . . .	72
<b>4 NEST case study: Transboundary cooperation a potential route to sustainable development in the Indus Basin</b>	<b>80</b>
4.1 Introduction . . . . .	81
4.2 Towards Sustainable Development Goals (SDGs) . . . . .	83
4.3 Role of cooperation . . . . .	87
4.4 Discussion . . . . .	88
4.5 Methods . . . . .	91
4.5.1 Cost calculations and assumptions . . . . .	93
4.5.2 Water-energy-land indicators . . . . .	94
4.5.3 Modelling scenarios assumptions . . . . .	95
4.5.4 Full results consultation and visualization . . . . .	95
4.6 Data availability . . . . .	96
4.7 Code availability . . . . .	96
Chapter 4 Bibliography . . . . .	96
<b>5 Conclusions</b>	<b>102</b>
5.1 Key insights and contributions . . . . .	102
5.2 Future directions . . . . .	104

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<b>A Appendix A</b>	<b>107</b>
A.1 Model references . . . . .	107
A.2 Additional tables . . . . .	111
Appendix A Bibliography . . . . .	114
<b>B Appendix B</b>	<b>117</b>
B.1 Exogenous demands . . . . .	117
B.2 Canals, hydroelectric projects and power plants data . . . . .	119
B.3 Costs and Capacity Factor assumptions . . . . .	122
Appendix B Bibliography . . . . .	125
<b>C Appendix C</b>	<b>127</b>
C.1 Supplementary Figures . . . . .	127
C.2 Supplementary Tables . . . . .	131
C.3 Supplementary Discussion . . . . .	135
C.4 Supplementary Methods . . . . .	136
Appendix C Bibliography . . . . .	139

# List of Tables

2.1	Comparison of CLEW models . . . . .	13
2.2	Comparison of CLEW models sectoral implementation . . . . .	17
3.1	Data sources leveraged to parameterize the NEST implementation of the IRB. . . . .	55
3.2	Calibration parameters values for convergence of CWatM. . . . .	56
3.3	Policy scenarios embedding specific SDG targets, [74] . . . . .	61
4.1	Scenario assumptions for <i>BAU SDG</i> , and <i>SDG-coop</i> , in addition to common assumptions for all scenarios, Supplementary Table C.1. . . . .	87
A.1	Criteria and sectoral coverage to assess sectoral gap in Figure 2.2a . . . . .	111
A.2	Criteria and thematic inclusion to assess thematic gap in Figure 2.2b . . . . .	112
A.3	Discrete assessment of Interlinkages visualized in Figure 2.3 . . . . .	113
B.1	Major conveyance canals in the NEST implementation of the IRB . . . . .	119
B.2	Additional planned hydropower projects included in the NEST implementation of the IRB. Locations, capacities and dates are approximate and estimated by the authors based on reported technical data. . . . .	120
B.3	Investment, fixed and variable costs and capacity factor values for model technologies. Sources: [1, 3, 4] and local data . . . . .	123
B.4	Investment, fixed and variable costs and capacity factor values for model technologies. Sources: [1, 3, 4] and local data. . . . .	124
C.1	Supplementary Table 1 . . . . .	131
C.2	Supplementary Table 2 . . . . .	131
C.3	Supplementary Table 3 . . . . .	132
C.4	Supplementary Table 4 . . . . .	133
C.5	Supplementary Table 7 . . . . .	134

# List of Figures

1.1	Schematic of the main interconnections between climate land energy and water systems. Designed adapting resources from Nucleartist Freepik.com. . . . .	3
2.1	Increasing scale of the CLEW model considered and structure and nexus integration . . . . .	15
2.2	Sector and thematic gap, summary of simplifications of water, energy and land systems compared to advanced sectoral models . . . . .	19
2.3	Number of models including interlinkages across sectors with level of detail based on Table SI A.3 . . . . .	20
2.4	Summary of accessibility aspects. . . . .	25
3.1	The NEST modeling scheme . . . . .	41
3.2	Delineation of spatial units in NEST. . . . .	44
3.3	The water sector representation in each BCU . . . . .	46
3.4	The energy sector representation in each BCU . . . . .	48
3.5	The agriculture sector representation in each BCU . . . . .	50
3.6	Comparison between the simulated streamflow by the calibrated model and the observation . . . . .	57
3.7	Ensemble mean monthly runoff in each country and the IRB as a whole . . . . .	58
3.8	Urban and rural population (a),(b) and per capita income (c), (d) for SSP1, 2 and 5 in 2050 and 2010 for each riparian country's part of the IRB. . . . .	59
3.9	Surface water balance for a specific BCU (PAK.8) in 2050 . . . . .	62
3.10	Monthly electricity generation under the <i>multiple SDG</i> scenario . . . . .	63
3.11	Basin investment and operational cost and nexus flows . . . . .	65
3.12	Comparison electricity generation, water requirements and land use among different scenarios . . . . .	68
3.13	Total monthly runoff availability in 2020 under different RCP and climate models (a). Total costs under different climate model, RCP and SSP assumptions (b) . . . . .	69
3.14	Changes in model outputs in response to a variation (-25%,+25%) of input parameters . . . . .	70
4.1	Expected Indus basin demands growth from 2020 to 2050 in, agriculture products (a); electricity (b) and water (c) . . . . .	83

4.2	Maps of annual Water Stress indicator (WSI) in the Indus basin . . . . .	84
4.3	Total basin average yearly costs, break down into country, and socio-environmental benefits . . . . .	86
4.4	The implications of cross-boundary cooperation . . . . .	89
B.1	Exogenous agriculture products (a), electricity (b) and water (c) demands. For each country and the whole Indus basin, from 2010 to 2060. . . . .	118
B.2	Existing (a), (b) and planned (c), (d) power plant capacity in the NEST implementation of the IRB. Sources: World Electric Power Plant (WEPP) Database, [5, 6] . . . . .	121
B.3	Average highest irrigated and non-irrigated yield for each crop-country pairing in the NEST implementation of the IRB as well as the corresponding rates of residue generation. Sources: [2] . . . . .	125
C.1	Supplementary Figure 1 . . . . .	128
C.2	Supplementary Figure 2 . . . . .	129
C.3	Supplementary Figure 3 . . . . .	130

# Chapter 1

## Introduction

The relationships between climate, land (and food), energy and water sectors (CLEW) have been extensively studied and assessed [1, 17]. Water is key for agriculture, for generating electricity, supporting human life and maintaining natural ecosystems. Energy is required to supply clean water and to power irrigation and farming technologies. These interlinkages entail trade-offs: for instance, land can be managed with various degrees of water intensity and used to either produce biofuels, food, or for installing solar fields that produce electricity. Water storage plays a fundamental role in generating carbon-free electricity, but can also be used to regulate flows for irrigation and reduce flood risks (Figure 1 illustrates some of the major interactions, without precluding many other possibilities).

The above mentioned interactions are also dependent on climate, which affects for instance the water cycle (i.e. precipitation, evaporation and snow and glacier melt), crop evapotranspiration and yield, as well as power plant efficiency and cooling requirements [6]. Likewise, human activity affects climate, mostly via anthropogenic greenhouse gas (GHG) emissions.

Projections for climate change in the coming decades increase the uncertainty around resource availability and system resilience. Temperature increase as well as the associated glacier melting are the most prominent and discussed phenomena of climate change, but changes in seasonal variability of local climate and extreme events might also seriously challenge the society we live in [19, 20]. In addition, with continuous population and economic growth, it becomes urgent to find ways to develop in a sustainable way. This involves guaranteeing education, equity, human rights towards increased well-being, while protecting the planet for future generations. The United Nations' Sustainable Development Goals (SDGs) provide 17 broad targets and diverse indicators for guiding policy makers towards prosperity for humanity and the environment. Many of the SDG indicators are interdependent and relevant to the CLEW nexus. Thus implementation strategies should be based on a broader systems perspective [12, 14, 16].

The omission of the nexus interactions has already lead to several wrong policy choices.

One famous example occurred in the early 2000's, when a significant portion of US corn started to be used for ethanol production. This led to immediate consequences for Mexico, which relied on US corn export. The country suffered from a sudden increase in corn prices that afflicted the poor and led to hunger in the country [21]. Liu et al. also mention the case of the Aral Sea, where water flowing into the sea was diverted to create irrigated desert croplands resulting in a substantial loss in biodiversity and fishery as the lake shrank [7, 13]. Numerous cases are also related to water bodies, such as lakes or rivers shared among countries, which are often the cause of disputes and, in some cases, of international conflicts on resource management (e.g. between Tajikistan and Uzbekistan or Pakistan and India in the Indus basin [10, 15, 18]).

While it is important to acknowledge and study the interactions between CLEW sectors, it is crucial to develop tools that rely on real data and system approaches to provide solutions to existing questions [5]. Qualitative methods can help increase awareness on the nexus issues and to solve conflicts [3, 4]. Quantitative methods, ranging from simple calculators to complex simulation or optimization models (e.g. hydrological models, Integrated Assessment Models (IAMs)), can be used to guide policies and infrastructure development and to quantify risks and uncertainties [2, 4, 8, 9, 11].

As thoroughly explained in Chapter 2, the study of CLEW nexus strategies supporting policies for sustainable development has rapidly grown in the last ten years, resulting in numerous qualitative and quantitative approaches. This dissertation focuses on models that integrate multiple sectors at different scales and that are suitable for quantitative assessments.

## 1.1 Motivation, Research Questions and Objectives

The main aim of this thesis is to contribute to the state of the art of CLEW analysis that can inform policy makers and the scientific community around sustainability issues that require multi-sectoral integrated assessment.

The research is motivated by a number of the aforementioned issues summarized as:

- critical challenges are expected for the coming decades across WEL sectors: such as population and demand growth, resource scarcity and climate change;
- climate, land, energy and water systems are highly interconnected, both with simple and complex relations, therefore tools need to capture this complexity;
- Although existing CLEW models continue to rapidly advance providing increasing complexity versatility, important limitations and research gaps remain. There is a need for more analyses, together with transparency that help the diffusion of new advanced tools.

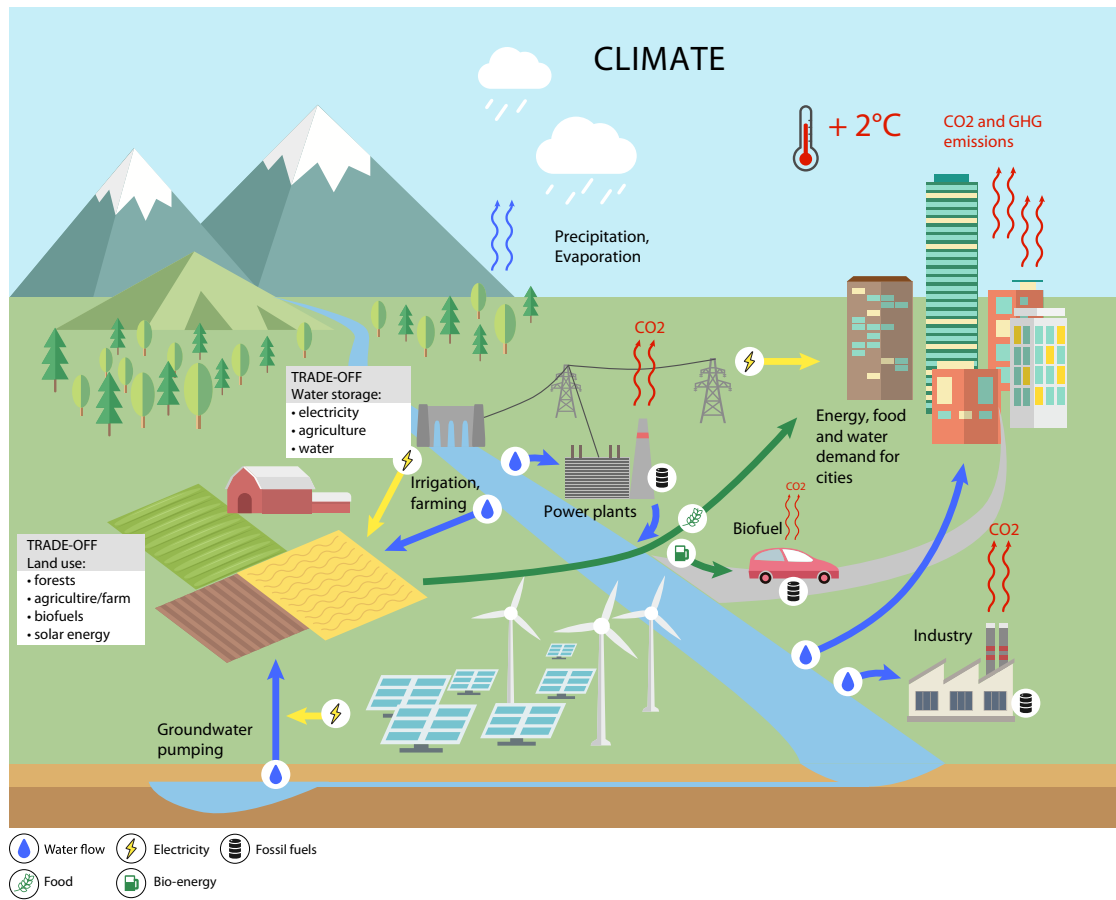


Figure 1.1: Schematic of the main interconnections between climate land energy and water systems. Designed adapting resources from Nuclartist Freepik.com.

The main research objectives of this dissertation are i) to investigate both the usefulness of new tools in innovative research and the more practical aspects of tool accessibility and effectiveness in communicating result successfully; ii) to advance modelling capabilities by contributing a new and versatile framework that links dynamically distributed hydrological and infrastructure optimization through geospatial analytics and scenario generation algorithms; and iii) to apply and illustrate the usefulness of the new approach in exploring innovative solutions in a case study. Specific research questions are:

1. What is the palette of feasible long-term sustainable solutions to face growing energy-water and land demands, resource constraints and climate change?
2. How can existing and future CLEW models best advise on sustainable development research? What are the strengths and limitations of existing configurations?
3. What is needed for such tools to be accessible, transferable and successful in informing the final user?

Question 1 is the ultimate question WEL models are designed for. Clearly, it can only be addressed after structuring an entire framework for the analysis and the answer will vary for each case study and will depend on a large number of variables.

## 1.2 Structure

To address these questions, this dissertation starts with a review and comparison of existing tools that represent CLEW nexus linkages, identifying the most innovative aspects and limitations (Chapter 2).

A major contribution of this thesis is the development of a new framework that interconnects and expands existing models into an integrated CLEW model, the NExus Solution Tool (NEST). This development, primarily undertaken at the International Institute of Applied System Analysis (IIASA), is presented in Chapter 3.

This is followed by the application of the NEST model to study cross-sectoral sustainable development goals in the Indus basin, and explore the role of transboundary cooperation in that context (Chapter 4). This work which involved the participation of stakeholders from different countries in the basin into the model and scenario development provides an innovative perspective for the region.

In conclusion, Chapter 5 summarizes the main insights and findings of this dissertation.

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## Chapter 2

# Climate-Land-Energy-Water nexus models across scales: progress, gaps and best accessibility practices<sup>1</sup>

### Preamble

Approaches that integrate feedback between climate, land, energy and water (CLEW) have progressed significantly in scope and complexity. The so-called nexus approaches have shown their usefulness in assessing strategies to achieve the Sustainable Development Goals in the contexts of increasing demands, resource scarcity, and climate change. However, most nexus analyses omit some important inter-linkages that could actually be addressed. The omissions often stem from technical and practical considerations, but also from limited dissemination of new open-source frameworks incorporating recent advances. This chapter reviews and presents a set of models that can meet the needs of decision makers for analysis tools capable of addressing a broad range of nexus questions. Particular attention is given to model accessibility, usability and community support. The other objective of this review is to discuss research gaps, and critical needs and opportunities for further model development from a scientific viewpoint. A major focus is given to explore at different scales where and why some nexus interactions are most relevant. Results show that both very small scale and global models tend to neglect some CLEW interactions, but for different reasons. The former rarely include climate impacts, which are often marginal at the local level, while the latter mostly lack some aspects because of the complexity of large full CLEW systems at the global level.

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<sup>1</sup>The body of this chapter has been submitted for publication to the journal *Frontiers in Environmental Science*

## 2.1 Introduction

Interconnections between hydrology and water systems, natural and human land use, energy resources and climate have attracted increasing attention in the last decade. The so called Climate-Land-Energy-Water (CLEW) nexus perspective aims at understanding complex issues that are intrinsically interconnected in our world and addressing the sustainable development objectives (see Figure 1 for a simplified diagram)[65, 89, 102].

Advances in analytical modelling and computational capacity have allowed the development of increasingly comprehensive tools for quantitative analysis to better inform policy makers on the benefits and trade-offs between sectors [2]. A large number of models focusing on bilateral linkages (e.g. water-energy, water-land) have been developed and widely reviewed [2, 25, 55]. Recent reviews highlight the issue of having tools that embrace the Water-Energy-Food Nexus complexity and at the same time are useful for stakeholders [18, 52]. For instance, Dai et al., 2018 state that: "none can or do provide a singular framework for performing a "nexus study" " [18]. However, as of today some models have been successfully used in nexus studies where also climate is considered an important system as much as energy, water and land. The most recent studies incorporating all CLEW sectors have shown that restricted bilateral perspectives (and models) omit important feedback and should therefore be updated with comprehensive methodologies [35, 99].

Some of the outcomes of this paper have been to some extent touched by previous reviews, such as the limitations of model-linking and spatial resolution [50, 55]. This are expanded with reflections on community effort oriented at defining new CLEW standards or integrating with other models to better include socioeconomic aspects. Moreover, the above-mentioned reviews cover mostly global models (also included in this manuscript), and no consideration on different scales, as a determining factor in the development approach [50, 55]. In some cases, mostly at small spatial and temporal scales, neglecting some interactions does not particularly affect the outcomes. However, at the country, basin, or even larger scales, and when considering long-term perspectives, responses between CLEW sectors are always present and should therefore be considered. The major barrier to using models that include all CLEW linkages are the complexity of methodology, and the difficulty of gathering data and expertise from different sectors, which limits numbers of groups that have the resources to build and maintain broad cross-sector capacity, both at the academic and institutional level [52, 81]. This review identifies research gaps and provides a perspective on some of the required developments for full CLEW models from a scientific point of view.

Ramos et al., 2020 review stands out by presenting models that actually focus on equal importance to all the CLEW interactions across scales[81]. The paper however only focuses on the models within the CLEWs framework [44], excluding a notable number of available models that provide a comprehensive coverage of the CLEW nexus, both as upgrades of

pre-existing models and as totally new developments. This article reviews these models with the primary aim of guiding decision makers in selecting the analysis tool best suited to their needs. In addition to previous reviews, particular attention is given to factors that reinforce models' longevity and usefulness, such as community support, accessibility and availability.

The paper starts with an overview of the CLEW nexus and the evolution of modelling streams. This is followed by a detailed comparison of a selection of models; an assessment of pros and cons; and a discussion of research gaps. This review concludes with a summary of recommendations for prospective users and modellers.

## **2.2 Climate, land (and food), energy and water nexus modelling background**

It has been recognized for some time that unraveling the synergies and trade-offs between climate, land (or food), energy and water is of fundamental importance to understanding the complexity of our planet, and to formulating effective policies for sustainable development [25, 65]. The United Nations' Sustainable Development Goals (SDGs), are intrinsically linked to CLEW sectors and involve numerous interdependencies [28, 64, 70, 73]. The concept of CLEW nexus modelling has been incorporated into the analysis frameworks conceptualized at the International Atomic Energy Agency (IAEA), the Food and Agriculture Organization (FAO) and the Royal Institute of Technology in Stockholm (KTH) [44, 89]. The generic modules in the CLEW framework have been linked in various combinations and applied to several case studies for integrated assessment of the SDGs. Ramos et al., 2020 presents the history of the CLEWs framework and a detailed review of various models and application to 2019 [81]. Concurrently, more research efforts have been directed at water-energy, energy-land or water-land bilateral interactions, and increasingly to linkages among water, energy and land (WEL) resources [2, 55, 66]. The major focus has remained on balancing WEL interactions across multiple sectors and a better understanding of the synergies and trade-offs in future scenarios. However, the climate dimension has not been considered at the same level of detail as the sectoral representations [7, 9, 65].

Another stream of CLEW nexus analyses is represented by the development of globally integrated assessment models (IAMs). These models have also been used in the last decade to inform the Intergovernmental Panel for Climate Change (IPCC) on the correlations between human energy use and production with climate, and their scope has been expanded in recent years to also incorporate a representation of land and water systems [6, 11, 15, 75, 98]. Decarbonization analyses have shown that nexus modelling is needed at multiple scales to better assess the interaction with policies impacting different sectors and administrative levels [41, 87, 91]. Spatial and temporal scales are therefore important factors

that affect not only the structure of nexus models and the representations of energy, water and food supply but also the couplings and feedbacks between sectors [10, 53, 58].

A number of studies have demonstrated that system integration can identify strategies that avoid or minimize trade-offs and achieve synergies [13, 23, 45, 54, 60, 69, 74, 78, 86]. Most of these studies have focused on, or considered interactions between, two or three of the CLEW systems, for instance, quantifying the economic benefits brought by joint water-energy system planning [8, 24, 44, 56, 62, 76, 96, 101, 106]. Other examples of focused nexus interactions are studies analyzing impacts of energy decisions on land use, including bioenergy supply-chain interactions [1, 21, 71].

More recent studies, using models that attempt to integrate all salient CLEW nexus interactions, have shown that virtually all interaction matters, and are often related to the representation scales. Recent multi-scale studies with country or basin scale resolution show the importance of considering simultaneous CLEW interactions for instance in water reservoir management for power generation and storage for agriculture [77, 92, 99]. Conversely, global estimations of future water requirements for cooling power plants and those on virtual water related to future food trade both lack the other side of the medal and would benefit from a full CLEW system representation that takes into account all synergies to provide better assessments [19, 34, 75].

The Integrated Multisector Multiscale Modeling project (IM3) is a great example of coupling open-source models to cover nexus interlinkages and study for instance the relation of changes in the water cycle for thermal power plants [105]. Some models operate at the urban scale and show that for specific questions, such as heatwave exposure in an urban environment, some components of the CLEW nexus are not that relevant [95]. However, when considering only water-energy nexus when studying climate-change impacts at the national level, neglecting future changes in water requirements from other sectors might compromise the reliability of the results [100].

There is clearly a need to develop more competencies and technical solutions to build and run models that better represent the complexity of the natural and socioeconomic system we live in. This manuscript reviews some of the models with this potential and attempts to unveil the underlying complexity to different users.

## 2.3 Methods, review approach

The models compared in this review have been selected by using some systematic research approach complemented with manual selection to narrow on the main focus (full CLEW nexus models), direct interaction with the researchers and developers of the selected models. A first systemic review on the SCOPUS database using the CLEW keywords, together with 'Nexus modelling', 'Integrated analysis', and 'Nexus scale' resulted in a substantial

list of models. This list has been drastically cut to only include models with the representation of all the climate, land, energy and water sectors. Next, during the information validation phase, all main authors and developers of the selected models were engaged to validate the information presented in this manuscript. During this phase, it was also asked to the developers suggestion to expand the list with other novel CLEW models that we had not yet identified. This further expanded the final list with additional models and subsequent contact with their authors/developers.

During the validation phase the following questions were asked:

1. Would you agree on the following classification concerning your model? [Table extract] If no, how would you change it?
2. Could you please suggest the most recent references for: (a) Documentation, online data/code repository; (b) Published application studies
3. Which of the following Nexus linkages are included in the model?
  - (a) Water to Energy: water for power plant cooling; water for hydropower, storage
  - (b) Water to Land: agriculture water use evapotranspiration
  - (c) Water to climate: any
  - (d) Energy to water: energy (or just electricity use) for water distribution, pumping, desalination
  - (e) Energy to Land: energy (or just electricity use) use in land preparation or food chain production
  - (f) Energy to climate: GHG emissions
  - (g) Land to water: irrigation, canal, water reservoirs
  - (h) Land to Energy: biomass production from crop or crop residues
  - (i) Land to climate: de- and afforestation impact on GHG
  - (j) Climate impacts on Water: change in ET rates and evaporation, precipitations, changes in demand
  - (k) Climate impacts on energy: power plant cooling requirement, energy demand change, energy efficiency
  - (l) Climate impacts on Land: crop yields
4. Could you name any other recently-developed model, not from you or your team, that you think has the most relevance to the above-mentioned models?

Other models, listed below, were mentioned by developers or initially considered by the author and in the end not included in the review for one of the above-mentioned reasons. This however does not make the models or framework less worth being referred to, examined or used.

- IM3 framework more references in SI
- ELENA [4]
- PRIMA [59]
- AWASH [84]
- TIMES-MARKAL [67]

## 2.4 CLEW nexus models

This Section provides a high-level description and assessment of the models currently available and maintained (to 2020). In particular, we examine the scales (spatial and temporal) at which various sectors are represented and resolved; the level of detail/complexity with which CLEW sectors are represented; the cross-sector linkages and geophysical biases; the scope of model uses and levels of integration; and we finally provide an evaluation of models accessibility and usability.

### 2.4.1 Modelling scale and resolution

The scale of a model defines the spatial or geographical delineation of the real system that the model represents. Examples of different scales are a province/state or a country, a national or transboundary hydrological basin or agro-ecological zone, or simply a physical area defined in hectares or in terms of the elements that characterize it. Similarly, temporal scales range from seconds to years or decades. The scales determine the spatial or temporal scope within the modelling work. Up to a certain extent, temporal and spatial scales are often correlated [63]. For instance, it is unlikely for a model representing CLEW dynamics in an urban district to have a ten-year time scale because the uncertainties related to boundary conditions (what happen at the interface of the modelled system with the outside) and future projections would become extremely high. On the other hand, global models are hardly ever resolved at an hourly scale, since mapping hourly dynamics for the entire world would be computationally prohibitive and require too much data. However, both global and district scale models can have a yearly time-step.

Scale and resolution are sometimes confused or used interchangeably, especially regarding the temporal dimension, where the two often converge into the same concept. In this paper we use the term *scale* to refer to the overall delineation of the system, and with the term *resolution* we refer to the smallest spatial or temporal unit of the model at which inputs are defined and outputs and model variables determined/updated.

Complex models such as CLEW models include different sub-models or sectors which are often best studied at different resolutions, while still representing the same scale. For

Table 2.1: Comparison of CLEW models

Model	Structure <sup>b</sup>	Nexus integration	Scales	Uncertainties/ Nexus limitations	Questions best answer <sup>c</sup>
IMAGE	Simulation model	Integrated	Global, 26 regions and gridded land and water use 30x30 seconds, 5y time-steps up to 2100	Soft-link between model components (economy, agriculture and energy). Not all policy can be assessed, like R&D cannot	Impacts of human development (energy, food and water consumption) on global environmental change.
REMIND-MAGPIE <sup>a</sup>	Optimization general-equilibrium	Iterative soft-link of integrated models	REMIND: Global, 12 regions, 10y time-steps up to 2100; MAGPIE 0.5°x0.5°grid	No responses of energy choices on water. Soft-linking between model components.	Energy technology and land use in climate mitigation policies.
MESSAGE-GLOBIOM	Optimization, partial-equilibrium	Integrated	Global. 11 regions; time horizon up to 2100, 5 and 10 time steps	Only biomass-land use and water for cooling nexus	Global energy mitigation strategies, policy costs and impacts on land sector
GCAM	Market clearance simulation model	Integrated	Global. 32 regions, time horizon up to 2100, 5 year time steps	Up-scaling and downscaling water and land variables	Energy and food tradeoff in crops and water management. Water scarcity issues. SDG assessment. Link to global climate
COFFEE	Optimization	Integrated	Global, 18 regions; time horizon up to 2100, 5y time-steps	Water-land and crop representation link	Global mitigation strategies, policy costs and impacts on land sector
CLEWs framework [81]	generic framework formulation	Soft-link	Different scales: urban, national, regional and global	Depends on specific case: soft-linking, boundary conditions	Explores questions at different geographical scales framed with stakeholders.
WEAP-nexus [72] <sup>a</sup>	Nexus function	Integrated	River basin. Up to 2100, 10 year time steps, monthly time sub-steps.	Boundary conditions No energy-land nexus	Detailed spatial assessment of tradeoffs in water use, locally embeds climate impacts
ECHO [53]	Hydro-economic optimization model	Integrated	Continental scale with basin catchments; long-term horizon, monthly dimension.	Simplified energy supply sector	Water resource assessment considering other sectors' transformation
Nexus Tool 2.0 <sup>a</sup>	Simulation model	Integrated	Country or basin, static simulation given set demands and fixed technology capacity	No optimization, no intertemporal dynamics. No validation of input (like hydrological model) tested for simulation	Cross sectoral impacts and sensitivity of interactions, risk assessment of nation/basin resources
BLUES	Optimization model	Integrated	Country, 6 sub-regions. Long-term time horizon	Hydrological linkage under development	Brazilian mitigation strategies, energy-land-emissions and economic impacts
NEST [99]	Optimization model	Soft-link of integrated models	River basin, time horizon up to 2100, 10y time-steps and months	Uncertainty at boundary conditions for cross country basins	Basin nexus tradeoffs, policy cross-sectoral impacts and cost
WHAT-IF [77]	Optimization model	Integrated	River basin; medium-long-term time horizon, 10t time-steps and months	Uncertainty at boundary conditions for cross country basins, representation of groundwater	Tradeoffs in water management for agriculture and energy production
NexSym	Simulation model	Integrated	Local scale, town level. 1 year time-step for 50 years horizon	Uncertainty at boundary conditions	Techno-ecologic questions for local CLEW systems

<sup>a</sup> Information could not be validated with the authors

<sup>b</sup> 'Structure': Market clearance simulation models add a market balance equation for various commodities within the simulation model; general-equilibrium models include a macro representation of the whole economy, partial-equilibrium models mostly represent one or few economic sectors; Nexus functions assess one indicator on impacts from other sectors

<sup>c</sup> What the contacted developers indicated as the main model purposes, not excluding additional other applications.

instance, hydrological models and agricultural and land use models often require a very fine spatial resolution, defined with grid maps (e.g. portion of Decimal Degrees (DD)) predicated either by the gradients of underlying physical processes (e.g. heat transfer) or of the represented physical environment (e.g. soil humidity). Energy system models often have a simplified resolution consisting of a few discrete points for a country. The discrepancy in resolution is one of the major challenges when working with interconnected sectors in a single modelling framework, or with linked models.

This is most commonly addressed using concepts from global climate models: via up-scaling (aggregating) or downscaling some of the information [17, 57, 63]. Other strategies identify spatial and temporal definitions that intersect existing ones (in ECHO, GCAM and other models, river basins are crossed by political border maps and agro-ecological zones). It should be noted that trade-offs on resolution are also adopted in single-discipline models; for example renewable energy modelling the representation of intermittent energy production, which presents features ranging from seconds to seasonal [12], is often simplified IAMs and linked to energy system model with multi-year temporal resolution [49].

Local and regional models, which are generally more oriented to implementation analyses, present a higher level of detail (or resolution) than others, but include less interconnection across sectors. This is noticeable in Figure 2.1, where all the local scale models and some country models include weak interlinkages to the climate sector. On the other hand, global models, which grant a higher level of aggregation and coarse representations, include all the CLEW sectors, but with limited interconnections compared to national models. This is due to the large amount of data that would need to cover all interlinkages and still poses computational challenges. The models with the highest number of interlinkages are those at the country or river basin scale.

An important limitation at small scales and fine resolutions is to collect data across multiple sectors with the same level of detail [26]. Local data collection is particularly critical in areas that lack official surveys or research from governments or institutions. Local data scarcity is often overcome with assumption through extrapolation or downscaling of data at a larger scale or coarse resolution [17, 57, 63]. Another limitation for small-scale models is the assumptions needed to represent any possible interaction with outside the model scope [68]. Boundary conditions are critical also at larger scales, such as basin and national and it is particularly relevant when import and export of resources are involved. To overcome it, price curves of external resources are often used, which require additional information on the boundaries [77, 99].

#### **2.4.2 Sectoral coverage: state of the art and compromises**

Models are used to represent in a simplified way real systems and interactions. The level of detail of this representation usually depends on the research scope and questions, and

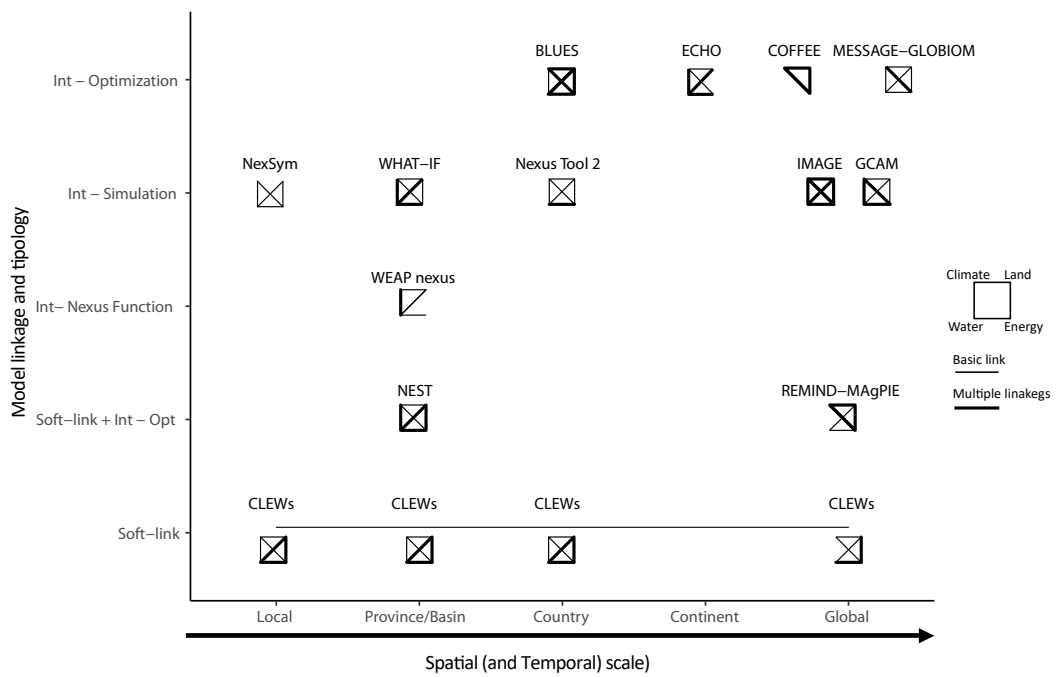


Figure 2.1: Increasing scale of the CLEW model considered and structure and nexus integration. Methods distinguish between soft-linked and integrated modules and simulation and optimization models. The squared symbols represent the interlinkages between climate, land, energy and water sectors, as displayed on the right panel (more detail in Supplementary Table A.3).

this is particularly evident for newly developed CLEW nexus models. It is however not the case of the global models showed in this review, as most of them originated from energy-climate IAMs. Some of these models show a large disparity between the detail of land and water sectors, compared to the energy sector. Some models have invested or are currently investing important resources to fill this gap, for instance integrating linkages to land use and agriculture models (MESSAGE-GLOBIOM, REMIND-MAGPIE), or hydrological models (IMAGE, GCAM). Almost every model, including newly developed models, show some bias on detail in sectoral representation, often because of the main research questions and expertise. Consequently, most models include state-of-the-art features of the CLEW system, but applying simplifications to deal with nexus interactions. Below are reported the status of state-of-the-art modelling and cases of simplification. Table 2.2 includes a brief description of sectoral representation.

Table 2.2: Comparison of CLEW models sectoral implementation

Model	Water	Energy	Land
IMAGE	Hydrological model fully included (LPJm), also linked version of PCR-GLOBWB (nutrients)	Energy supply from primary to final energy; some efficiency and demand instruments; GHG emissions	Food demand, spatial land allocation, crops, irrigation efficiencies, livestock
REMIND-MAgPIE *	Water availability for agriculture, no other human and energy use. Post-process calculation of cooling water	Energy supply from primary to final energy; some efficiency and demand instruments; GHG emissions	Food demand, spatial land allocation, crops, irrigation efficiencies, livestock, forest
MESSAGE-GLOBIOM	Water demands, cooling technologies, water distribution and treatment	Energy supply from primary to final energy; some efficiency and demand instruments; GHG emissions	Land use, biomass availability
GCAM	Hydrological model linking to water demands from all sectors and supply, groundwater	Energy supply from primary to final energy; some efficiency and demand instruments; GHG emissions	supply, demand, and land use for food, fiber, forestry, and bioenergy products, land cover for natural ecosystem types.
COFFEE	None	Energy supply from primary to final energy; some efficiency and demand instruments; GHG emissions	Crop production, land use change with forestry
CLEWs framework	Hydrological model linking to water demands from all sectors and supply, groundwater	Energy supply from primary to final energy; some efficiency and demand instruments; GHG emissions	Crop production, land use change
WEAP-nexus *	Hydrology, water supply and demand technologies, groundwater	Hydropower, water distribution/pumping	Crop water requirement
ECHO	Hydrology at basin level, river routing, water supply technologies, groundwater	Hydropower, thermal plants, cooling options. electricity demands	Crop products demand, irrigation with different technologies
Nexus Tool 2.0 *	Water sources and supply technologies	Energy sources and supply techs, energy demand	Crop products demand, irrigation types, water and energy requirements
BLUES	Hydrological model linked, water for energy and crops, groundwater	Primary to final energy; Localized renewables and hydropower; CO2 emissions	Crop production, land use change with forestry, biomass for energy
NEST	Hydrological model linked, water for energy and crops, groundwater	Secondary to final energy and biomass, Localized renewables and hydropower; CO2 emissions	Crop production and demand, irrigation technologies, biomass, residues, pollution
WHAT-IF	Hydrology timeseries as exogenous input, reservoir, groundwater, wetlands	Electric energy production, trade and markets, capacity expansion model, CO2 emissions	Agriculture production, yield water response function, crop markets and trade
NexSym	Aquifer, irrigation, cooling power plant, wastewater treatment plant	Residential electricity and heat consumption and production	Vegetation ecosystem, wheat crop, irrigation and fertilization

\* Information could not be validated with the authors

## Energy.

Depending on the scale of analysis, energy system models include detail on primary energy, such as fossil fuel supply, a number of energy supply and processing technologies, and representation of demand, often driven by individual choices [5, 36]. Focus on specific generation technologies has lead, for instance, to incorporate spatial data of solar and wind renewable energy, hydropower and seasonal pump storage into models [32, 47, 79, 99]. Most models at local or national scale deal with the problem of dispatchable electricity by linking with unit commitment models, which explore the feasibility of projected energy system in meeting realistic hourly electricity demand variations [103]. When considering the global scale, with a division of the globe in macro-regions and yearly or multi-year time steps, the validation of the electricity system is often simplified, using curves that dispatchability to solar and wind installed capacity [49].

Other important sectors are usually included with more or less detail in energy-oriented IAMs, but then simplified or neglected in most of the CLEWs models. For example, transports, industry, and the residential sectors offer less connection to the land sector

and get often reduced into energy and water demands [40].

### **Water.**

A large portion of the models includes hydrological assessment, with the possibility to evaluate the impacts of human withdrawals and climatic changes on the water cycle, water demands and resources. Highly complex physical dynamics, such as soil water transfer, evaporation and evapotranspiration (ET) are often included with nonlinear systems of equations [14, 88]. The major aspects often neglected or simplified, which also represent growing research areas, are related to groundwater, alternative water sources (wastewater, desalination) and water quality [33, 51, 94]. In this context, water models are used to understand the impact of human demands on water resources and quality, as well as possible climate change impacts on human requirements. Interactions with other models, linking for instance hydropower and water for power plant cooling and crop growth models, allow making such assessments more reliable and robust. Some common simplifications of hydrology in CLEW models are aggregated annual water availability and constraints on demand to reflect, for instance, environmental limitations.

### **Land.**

Land use, vegetation, modelling of crops and forest growth, are intrinsically connected to water. Therefore, some models embed hydrology with nutrients models and plant life-cycle representation [88]. Other frameworks include forestry modelling or link to food and wood industry, relating to socioeconomic factors [22, 39]. Such models can inform on how policies targeting hunger and sustainable food production could be pursued, and what are climate change implications on crop yields, or possible advancement that could help guarantee a balance between human needs and the ecosystem. In CLEW models, these dynamics are sometimes reduced to simple energy and water requirements per crop or food type. Or, in particular in global models that have an important energy component, the main focus has been so far on biomass availability at given energy prices.

### **Climate.**

Climate is a complex system and Atmosphere-Ocean General Circulation Models (AOGCM) still present a high level of uncertainty. Most of the CLEW models include climate dynamics in a simplified way, by linking to reduced-complexity models within the Coupled Model Intercomparison Project (CMIP6) [27, 29]. Models such as MAGICC, Hector and FaIR mimic climate response to input emissions of greenhouse gases to estimate radiative forcing, global mean atmospheric GHG concentrations and global mean temperature [27,

38]. These models are sometimes used iteratively with CLEW integrated assessment models, or just used as exogenous pathways of GHG concentration and global temperature. A set of Representative Concentration Pathways (RCP) describes some possible climate scenarios that can be closely related to the future level of anthropocentric emissions, but also to implications on the water system, such as changes in precipitations, runoff and evapotranspiration for plants [97]. All these aspects are more or less included in the CLEW models that link land use and vegetation modules to other sectors.

Figure 2.2 (and Table SI A.1) show the balance between the level of detail for each sector in the considered models and offer a view on where there is potential for further development. It appears evident that most of the models adopt consistent simplification or lack of detail particularly in the water sector, followed by land. Smaller-scale models also reduce the scope in the energy sector. On the other hand, no models are lacking water and energy advanced features simultaneously, indicating that most models have a strong water or energy basis.

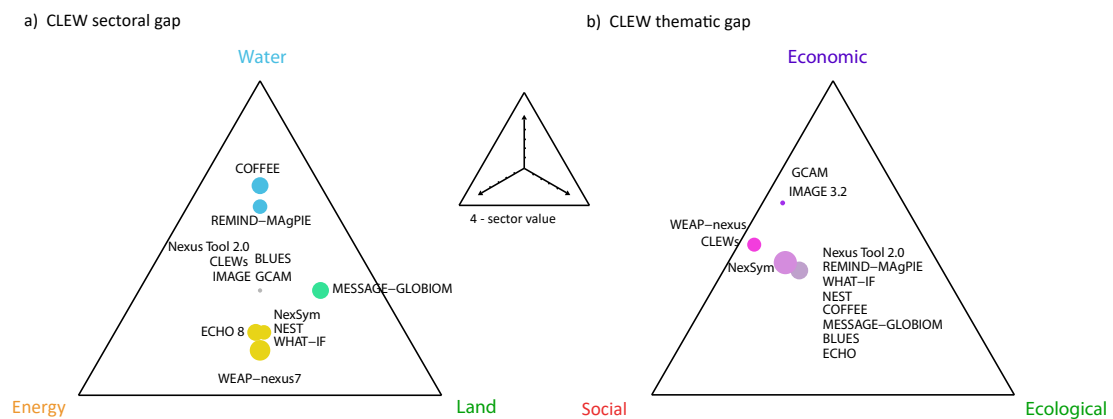


Figure 2.2: Sector gap, summary of simplifications of water, energy and land systems compared to advanced sectoral models (a). Thematic gap, simplifications or omission of possible social, economic and ecological aspects (b). Size depending on the total gap considering CLEW sectors (The explanatory diagram in the center refers to *sector value* in Tables SI A.1 and A.2)

### 2.4.3 Cross-sector interlinkages

As extensively mentioned above and in other literature, the innovation in CLEW models stands in the cross-sector interactions that have often been neglected in the past but are intrinsic in our system. It was also mentioned that there is a correlation between scales and interlinkages. While small-scale models tend to focus on specific nexus interactions that are present in the analyzed system (often neglecting climate aspects), national and basin models are those that integrate most interlinkages. Because of a relatively detailed

resolution in hydrology and crop modelling, interlinkages of country and basin models are also quite detailed (Figure 2.1 and SI table used to make the figures). Global models need to deal with a much larger scope and adding a high number of interconnection might increase significantly the complexity. In addition, soft-linked models require approximation of flows, costs, or commodity levels that are exchanged between modules. While integrated models have often reduced representation thereby making it difficult to endogenize nexus interactions.

Accounting for energy used in pumping and water distribution technologies, water for energy purposes (hydropower or cooling) and water for agriculture are the most represented nexus linkages (Figure 2.3). This is followed by biomass for energy production and accounting for GHG emissions from the energy sector. Also climate impacts, especially on the water cycle, are well embedded in many models. A slightly less explored aspects are the energy impacts in agriculture and land use, aside from biomass competition for food crops, and their consequences on the climate.

What is ignored by all the models is any possible influence of changes in water management, such as creation of new storage reservoirs, river diversion, or increased irrigation on local and global climate.

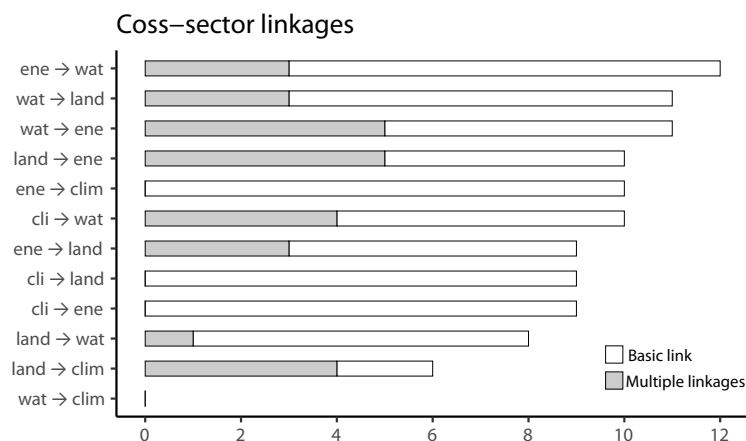


Figure 2.3: Number of models including interlinkages across sectors with level of detail based on Table SI A.3

#### 2.4.4 Geophysical bias

In conclusion to the previous paragraphs, it appears evident that the spatial and temporal scope, the resolution and the detail of sectoral representation, and the cross-sector interlinkages are all closely related to the scale of models. This influences the research questions that can be properly answered. Most of the models considered have strong geophysical representations, which means natural systems such as water bodies and vegetation are represented with high detail. Also human interactions with such systems are clearly well

represented in all of the CLEW sectors as a force driving change.

Ecosystem services, biodiversity loss are often included in nexus analysis, but only in a limited number of cases, and lacking detail, for instance of species loss and aquatic ecosystem [42, 46, 90]

Comprehensively, CLEW models are well suited for dealing with environmental questions, the relation between our society and the Earth system, primary markets (e.g. electricity, heat, food), and, to some extent, ecosystem challenges. This is confirmed by looking at Table 2.1 where modellers were asked to state what is the best use for their models (*"Question best answer"* column) and all referred to the relationship between human development and the geophysical system. Liu et al., 2018 also point out that the CLEW approach is centered on natural systems and it is harder to relate with other social and economic aspects of our society, such as education, equality or institutions [65].

Nevertheless, several studies have focused on inequality implications such as hunger, energy access and water access, also under the perspective of climate change [16, 31, 85]. But IAM still struggle to fully represent inequality aspects, and this challenge increases when multiple sectors are under scope [82]. Similarly, other social aspects, that often dominate the daily political discussion, and therefore are strong drivers of policy and change, are also poorly embedded in CLEW models. Aspects such as public acceptance or environmental policies and investments, or climate-induced migration are widely explored in the literature, also with quantitative methods, but indirectly considered in most CLEW studies [20, 93]. The major input for social aspects in CLEW models comes from stakeholders that are often engaged to shape appropriate scenarios.

Economic aspects, such as decisions or behavior of individuals and companies, governments and finance, are not at all represented in the models here considered. In particular, while assessing a large range of environmental and development policies, CLEW models do not focus on how such policies could be financed. This is an enormous implementation barrier that is explored in the literature, contemplating microfinancing, and financing for international agreements. For example, the IAM community often represents climate mitigation policies as perfectly implemented through global carbon prices, which in reality is far from being achievable. Li et al., 2017 developed an Agent Based Model (ABM) that mimics the interactions between governments, individuals and companies with regards to water, energy and food consumption[61]. Hyun et al., 2019 developed the ABM–RiverWare that connects a hydrological model to an ABM to study the change of farmers' water withdrawals under different climate-change related risk and socioeconomic scenarios [48, 104].

Figure 2.2 b shows this asymmetry in terms of inclusion of societal and economic problems. Most of the models here considered link to macro-economic indicators of country or global GDP under the scenario framework of the Shared Socioeconomic Pathways [83] to assess

investments, cost of resources or commodities (i.e. water, equivalent carbon). Clearly, additional approaches, such as linking with ABM could complement the CLEW analysis, improving feasibility, acceptability and implementation aspects of policy results.

### 2.4.5 Model structure and nexus integration

The models considered in this article present mostly two types of solution methods, simulation and optimization. Simulation models are used to predict possible effects and implications across different variables and sectors, based on input assumptions that could simulate policies. For instance, given exogenous input demands, costs and share of technology use, the models can simulate the functioning of the system and calculate outputs, in terms of resource consumption, cross-sectoral demands, and so on.

Optimization models normally perform dynamic optimization that minimizes or maximizes a specific utility function and find the optimal solution of the system under exogenous inputs and constraints, which could mimic specific policies. Such models tend to find the 'optimal' system configuration as a unique solution and are often used to assess possible capacity expansion portfolios, investment costs, and also assess resource used across sectors.

Several solution methods and algorithms exist, are used and changed by the developers' teams. However, it does not seem to be a major issue of discussion among the modelling limitation of CLEWs models. Various approaches are therefore interchangeable and often compared in literature (see column *Structure* in Table 2.1 [37]). One limitation for large optimization models that process a large amount of data, might be to find free advanced solvers that also guarantee reduced solution time.

A different aspect that can be related to uncertainty and limitations, especially in the CLEW system, is the way different sectors are connected. Here, the majority of cases differ between soft-linked separate models, fully integrated models, or a hybrid of the two (see column *Nexus integration* in Table 2.1).

Having soft-linked models allows the use of pre-existing models, likely one-sector models, that might also have a high level of sectoral detail. However, to make different models work together, an exchange of information is required through an iterative process to convergence. For instance, a hydrological model would pass information, probably in aggregated form, to a crop-growth model, which would take water availability and evapotranspiration as input, and would determine crop production. These results would then need to iterate back to the water model to update the previous runs with the new water demand assumptions, which would then give new hydrological output. This iterative process can become particularly complicated when more than two models are linked, such as energy system or climate models, and requires substantial work in setting up the input-output exchange

and the iterative procedure.

Integrated models, on the other hand, incorporate all the possible representations in one unique large system, with the advantage of reducing effort and simplifications related to transferring information across modules and avoiding iterations. This also reduces particularly the uncertainty around the connection between different modules, which is in this case endogenized. However, integrated models might become very large models, heavy to work with and requiring high multi-disciplinary competencies. This limitation might result in a more simplified or unbalanced representation of each module. This is for instance noticeable in some of the global IAM models, historically energy-climate models, which have later added water and land features, initially simplified, and then further improved. This trade-off of integrated models is less of an issue in CLEW models where the focus is more on the cross-sectoral dynamics than on the detailed processes within each sector.

#### 2.4.6 Availability, accessibility and usability

In recent years the scientific community and modelling teams have pushed significantly toward open-access information, both in terms of publications and making the tools available for free to external users. This has allowed spreading the use of models to different teams without the need to dedicate new funds and time to re-develop complex models. These spillovers sometimes resulted in new versions of the models (e.g. COFFE and BLUES are modified version of the MESSAGE-GLOBIOM model, and from those, the model ELENA was developed [4]) or the creation of proper international communities that also contribute to the development of the tools (an example of the OSeMOSYS energy system model, part of the CLEWS framework that has been adopted and developed in numerous country studies [43]).

For this article we consider only models that are currently available, maintained, or still actively used, so to better focus on the factors that could contribute to further development.

The rationale for more open-access research and tools is to make them available, accessible, understandable and reusable. In the modelling world, this means having an easy-to-find online repository where the model is downloadable and having clear documentation that explains the model in detail and how to use it. Additional tutorials, testing infrastructure and community forums to engage with developers are also assets that make a significant difference. In fact, the open-access trend has often lead to simple online repositories where code and data are stored without thorough documentation and therefore not particularly useful for external users. This is an issue in particular in small projects or early research, where time and resources are scarce [3].

Scanning through the models considered in the review, it is noticeable that several models completely lack online repository and documentation (Figure 2.4 ). Only a few are fully accessible, documented and usable for free. One of the main limitations, especially for large global models, is the lack of public model data, which shareability is often constraint by third parties. Modelling teams that can afford it (mostly teams maintaining global models), find solutions like graphic interfaces (IMAGE, GCAM) or data and results explorers (MESSAGE , CLEWs) to enable the users to run the models or access data stored on the developers' servers.

Considering the number of publications and the number of applications of those nexus models to different scopes, we notice that actually open-access is not the primary factor for widespread utilization. Although Figure 2.4 shows that open-access models (mostly global models, with the exception of CLEWs) are also quite well known and utilized (last two columns on the right). It must be noted that in most of the case the modelling teams have moved to open-access only in the last couple of years. Or, in the case of the CLEWs framework, not all model configurations associated with individual studies are openly shared, and a large amount of the resulting research is not peer-reviewed but is rather *grey literature* [81]. For these reasons, the correlation between model scale and accessibility might change in the future as small-scale models spread more widely. Nonetheless, those models that grant high visibility, and that have been utilized widely around the world can be probably associated with the large community support that has been promoted over years, together with capacity building activities, and engagement with stakeholders. In conclusion, while open-access is important and need to be promoted with adequate time and resources, other factors like stakeholder engagement and capacity building are driving forces in connecting modellers groups, and shaping existing model into new prototypes, or case studies.






## 2.5 Discussion: emerging gaps and way forward

The comparison of the thirteen CLEW models (or family of models) presented above allows identification of areas that would most benefit from new developments, while providing a transparent assessment of usability and availability for scientists and non-scientist users.


The survey of CLEW models at different scales also highlighted some of the main limitations regarding methodology, sectoral coverage and nexus interlinkages, and socioeconomic components.

### 2.5.1 Methodological limitations

The major methodological limitation among CLEW models are the following.

Model	Model description/ doc	model code (and doc)	Free Software	Public data	User interface	Nexus publications	Nexus different scopes
	N/Y	N/Y/Y+D	N/Y	N/Some/Y	Graphic/API	≤2/3-5/>5	1/2-5/>5
CLEWs	Y	Y*	Y	Some	API+ result explorers	>5	>5
GCAM	Y	Y+D 	Y	Some	Graphic interface	>5	2-5
MESSAGE-GLOBIOM	Y	Y+D 	N	N	API+ result explorer	>5	2-5
COFFEE	Y	N	N	N	API	>5	2-5
Nexus Tool 2.0	Y	Y "	Y "	N "	API "	3-5	2-5
IMAGE	Y	N	N	Some	Graphic interface	>5	1
REMIND-MAgPIE	Y	Y+D 	Y	Some	API	>5	1
ECHO	Y	N	N	N	API	3-5	1
NEST	Y	Y 	N	Some	API	3-5	1
WHAT-IF	Y	Y + D 	Y	N	API	≤2	1
NexSym	Y	N ^	Y	N ^	Graphic interface "	≤2	1
WEAP-nexus	Y	N	N	N	Graphic interface "	≤2	1
BLUES	Y	N	N	N	API	≤2	1

\* framework of different models, referred to OSeMOSYS  
 " information could not be validated  
 ^ available upon author request

 available on Github




 room for improvement  
 accessible for scientists  
 user friendly for the most

Figure 2.4: Summary of accessibility aspects.

- Soft-linked modules suffer mostly from the simplification of the data and scope of information exchanged between models, often reduced to one or two variables (e.g. price) and from long iteration time.
- Integrated models, particularly at the global scale, tend to simplify some nexus interlinkages and/or the sectoral representation; although continuous progress in computing power has allowed increasingly higher model complexity.
- Boundary conditions are a critical source of uncertainty for country, basin and local-scale models.

The trend for integrated models is to increase detail in each sector with more detailed spatial data and increased resolution.

### 2.5.2 Sectoral representation and nexus interlinkages

Depending on the scale of representation we noticed that the details of the sectoral representation or nexus interlinkages vary, sometimes rationally with the model scope and questions that can be addressed, but in other cases in a relatively ad-hoc approach to address complexity issues. Below follows a list of the major simplifications in sectoral representation.

- Local models tend to neglect or simplify interactions with climate and focus only on the main nexus feedbacks relevant to the system.
- At the basin and national scale all CLEW interactions become relevant. In fact models at these scales include the largest number of interconnections and allow for detailed spatial representation of water and land systems.
- Full CLEW representation is also highly relevant for global models, but to make the models tractable complexity trade-offs that complicate the modelling are necessary. Only a few teams can have the necessary coverage of expertise, data and computing power to build and run such large integrated models.
- Major gaps in sectoral implementation are in hydrology assessment (particularly groundwater), and in primary energy linkage to natural resources. The water-energy nexus is represented quite adequately in most of the models.

### 2.5.3 CLEW linkage to Sustainable Development Goals (SDG) and challenges

Several studies in the literature show how models on climate, land, energy and water nexus can inform planning, policy exploration and risk assessment in regards to the water,

food, energy and climate SDGs [65, 81]. Depending on the specific model, some have a stronger focus on water or food scarcity, environmental protection, or soil and air pollution. Therefore, linkages to other SDGs such as industry and infrastructure, poverty, economic growth and life on land can also be explored with existing tools.

Social aspects such as equity, health and human rights, as well as economic aspects, e.g. governments and finance, are not included in any of the existing CLEW models, although there is some evidence these are also related to the CLEW sectors. Other types of models already explore some of these dimensions, but they are not yet linked to proper geophysical assessment tools like the CLEW models discussed here.

In terms of heterogeneity of CLEW model applications, most of the recently developed models focus on an area where climate change impacts are projected to be high and CLEW interlinkages are highly relevant. Several models explore case studies in Africa (ECHO, CLEWS, WHAT-IF), south Asia (NEST) and South America (BLUES, ELENA [4]). Moreover, current global models do now provide tools to zoom in the analysis to single countries or basins (IMAGE, GCAM).

#### **2.5.4 The lack of common assumptions**

To better address socioeconomic and climate uncertainty, the IAM community has agreed on common scenarios called Shared socioeconomic Pathways (SSP)[83]. Originally the SSPs defined five storylines with different trends of population and GDP growth, and assumptions concerning technologies in the energy sector. The SSPs represent different challenges for mitigation and adaptation to climate change. Almost all the studies mentioned in this article refer to SSPs, providing a multi basis for result comparisons.

The same community has subsequently introduced assumptions on global land use [80] with the intention of homogenizing assumptions on other sectors besides energy. Similarly, some teams have proposed SSP assumptions for water technologies [34]. But a holistic CLEW shared nexus perspective remains to be formulated within the SSPs. For example Momblanch et al., 2019 make assumptions for cropland and environmental flows that are not agreed upon within a community (as is for example the case for GDP and other indicators); this complicates the comparison of results with other models [72]. In addition, the SSPs provide publicly available databases with population and GDP trends that were originated at the macro-regional level. When focusing on national or regional scales, downscaling and further assumptions are required. Some recent work addresses this issue and proposes approaches in this direction [30]. Nonetheless, there is a need for high-resolution database for all SSP assumptions that cover all water, energy and land sectors that can be formally approved/agreed upon and referenced by all researchers working in this area.

### 2.5.5 Way forward for scientists and modellers

Both global models and those focusing at smaller scales are increasingly reaching higher levels of detail in representing CLEW systems and cross-sector interlinkages. Parallel efforts should be directed to the reduction of existing uncertainties related to geographical boundary conditions, interactions between sub-modules and downscaling.

socioeconomic aspects need to be better incorporated or connected to CLEW models to improve assessment of the feasibility and impact of policies and understanding of the social implications of future investments. Stakeholder engagement during scenario development and results analysis is currently used for validating scenarios analyzed with CLEW models. Further linkings with social-science experts, ABM representing household-companies-governments interactions, or finance risk models would be avenues to be explored in the future and provide further assets to the relevance of CLEW models.

### 2.5.6 The right model for the right user

There is not a better or worse model but, based on research questions or spatial scale, some models are more suitable to be used. In this review we discussed models at different scales, highlighting the scope applications they can be used for. We also surveyed public availability in terms of source code, data, open-access software and appropriate documentation, as well as the strength of the online community supporting maintenance and new developments (Figure 2.4). It is clear that open access and transparency are important factors for model dissemination and use. However, other factors, such as a strong community and stakeholder engagement network can help spread the use of models and frameworks. Since CLEW models are new and in undergoing continuous development, it might be hasty to draw conclusions largely on accessibility visibility.

These are important considerations for scientists looking for state-of-the-art models to use or compare. These considerations could also help decision makers, governments institution, and other research and development institutions identify useful opportunities to pursue new climate land energy and water analyses to face regional, national, or global challenges and possibilities.

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## Chapter 3

# The Nexus Solutions Tool (NEST) v1.0: An open platform for optimizing multi-scale energy-water-land system transformations<sup>1</sup>

### Preamble

The energy-water-land nexus represents a critical leverage future policies must draw upon to reduce trade-offs between sustainable development objectives. Yet, existing long-term planning tools do not provide the scope or level of integration across the nexus to unravel important development constraints. Moreover, existing tools and data are not always made openly available or are implemented across disparate modeling platforms that can be difficult to link directly with modern scientific computing tools and databases. In this Chapter, the Nexus Solutions Tool (NEST) is presented: a new open modeling platform that integrates multi-scale energy-water-land resource optimization with distributed hydrological modeling. The new approach provides insights into the vulnerability of water, energy and land resources to future socioeconomic and climatic change and how multi-sectoral policies, technological solutions and investments can improve the resilience and sustainability of transformation pathways while avoiding counterproductive interactions among sectors. NEST can be applied at different spatial and temporal resolutions, and is designed specifically to tap into the growing body of open access geospatial data available through national inventories and the earth system modeling community. A case study analysis of the Indus River Basin in South Asia demonstrates the capability of the model to capture important interlinkages across system transformation pathways towards the United Nations' Sustainable Development Goals, including the intersections between local and regional transboundary policies and incremental investment costs from rapidly increasing regional consumption projected over the coming decades.

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<sup>1</sup>The body of this chapter was published in Vinca et al. *The NEXus Solutions Tool (NEST) v1.0: an open platform for optimizing multi-scale energy-water-land system transformations*, Geoscientific Model Development, 13, 1095–1121, 2020 [85]. The material reproduced here is in line with the journal's copyright policy

### 3.1 Introduction

The United Nations' Sustainable Development Goals (SDGs) provide 17 broad targets and diverse indicators for guiding humanity and the environment towards prosperity. Many of the SDG indicators are interdependent, and thus implementation strategies should be based on a broader systems perspective [46, 52, 57]. The concept of nexus thinking has gained traction, and is increasingly applied within the context of the linkages among energy, water and land (EWL) resources [3, 37, 48]. A nexus approach balances EWL interactions across multiple sectors and livelihoods to better understand the synergies and trade-offs associated with meeting future resource demands in a sustainable way [4, 7, 47].

A number of previous studies address nexus challenges with computational modeling. Generally, these studies demonstrate that co-optimization, in the sense that decisions for EWL sectors are made simultaneously and incorporate the interlinkages, can identify strategies that avoid trade-offs and achieve synergies [9, 15, 31, 36, 43, 51, 59, 64, 72]. Similarly, previous analyses integrated water, energy and food systems across multiple temporal and spatial scales, and quantified the economic benefits that joint water-energy planning can provide by reducing the investment and operational costs of future infrastructure systems [6, 17, 29, 38, 45, 61, 80, 89, 94]. Land-use impacts of energy decisions, including bioenergy supply-chain interactions, are also increasingly integrated into long-term energy planning models to provide improved estimates of biomass availability and cost [2, 14, 54]. Analysis of decarbonization pathways for the United States demonstrates that multi-scale modeling is crucial for assessing the EWL nexus because of the diverse constraints on EWL resources at high spatial resolution, and the interaction with policies impacting different sectors and administrative levels [27, 73]. Similarly, other recent global analysis with an integrated assessment model highlights important differences between spatial scales relevant for energy, water and food supply [8]. In this context, some large-scale hydro-economic and integrated assessment models increasingly take a multi-scale perspective and consider water infrastructure investments across multiple basins, sectors and end-uses [35, 40, 60, 70].

Energy, water and land systems optimization models are thus important sectoral tools that inform utility and national planning towards the sustainable long-term development of natural resources. Yet, models used to develop long-term pathways consistent with the fundamental transformational changes called for under the SDGs do not represent simultaneously re-allocation of resources and capacity expansion decisions across tightly linked EWL sectors. Cross-sector interactions are crucial to consider when resource availability is limited and infrastructure expansion is expensive. Unforeseen constraints could lead to stranded assets and vulnerable water, food and energy supplies. More integration across EWL systems and resource planning decisions is required to capture important interactions in an explicit way, so that least-cost nexus solutions can be identified using

engineering-economic tools such as optimization.

Leveraging open source tools will promote end-user accessibility and should be prioritized for long-term system optimization models to enable validation and re-use in future research [13, 28]. Previous analysis combines different energy, water and land sector planning tools to achieve open-access integration [90]. The results of each sectoral planning tool are passed between tools as boundary conditions until the models reach an acceptable level of convergence. This process can take time and the decision solution obtained is not necessarily optimal across sectors. Moreover, the individual resource planning models require specific expertise to develop and run, and it can be time-consuming to design and implement a robust database for the model inputs and results, as well as online systems for sharing and merging model changes across different users. Other recent model developments are focusing mainly on water infrastructure [63] or city-scale scenarios [6, 53], leaving room for improvement in terms of the sectoral and geographic scope for solutions.

In this Chapter, the Nexus Solutions Tool (NEST) is presented: a new open platform for integrated EWL systems analysis under global change. The framework links a high-resolution distributed hydrological model to an engineering-economic modeling scheme that integrates multi-scale decisions impacting long-term EWL transformations. We mapped the output variables from NEST to the SDG indicators enabling integrated modeling of coordinated implementation and quantification of the investment costs. The new decision-making and open modeling platform provides a flexible framework for identifying and assessing EWL nexus solutions that can be applied to different geographic regions and multiple spatial and temporal scales.

The following section describes the NEST implementation. Sections 3.3 and 3.4 demonstrate the enhanced approach using data collected and processed for integrated policy analysis and capacity building in the Indus River Basin. Section 3.5 presents the conclusions and opportunities for future research.

## 3.2 Modeling framework

NEST links databases, processing scripts and state-of-the-art models covering multiple disciplines (Figure 3.1). The core framework consists of a distributed hydrological model (CWatM) and a resource supply planning model (MESSAGEix), both capturing the historical period and a future time horizon. NEST is used to generate future scenarios, where a scenario represents the technological and earth system transformation pathway under a given set of input data assumptions. In this context, the Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP) act as coupled scenario narratives framing climate and human development trajectories and driving exogenous demand profiles for specific sectors [58, 83]. Sectoral coverage is harmonized between CWatM

and MESSAGEix so that demand profiles can be translated between models. CWatM is initially run under baseline conditions to inform MESSAGEix of dynamic constraints on water availability, hydropower potential and irrigation water requirements. In future work elements of the resulting MESSAGEix pathway will be passed back to CWatM to simulate the expected human impacts under adaptive management at a high spatial resolution (Figure 3.1).

### 3.2.1 Community Water Model (CWatM)

The Community Water Model (CWatM) provides a grid-based representation of terrestrial hydrology, applied in this instance at a spatial resolution of 5 arc-minutes (grid-cells approximately 8 km wide near the equator) and daily temporal resolution [10]. CWatM distinguishes between six land cover types, including forest, irrigated non-paddy cropland, irrigated rice paddy, impervious surface, water bodies, and other land cover in simulating the water balance of each grid cell. CWatM includes processes relevant for high altitude implementations, including snow, glacier, and permafrost. Potential evaporation is calculated using the Penman-Monteith equations. Processes within soil layers include frost, infiltration, preferential flow, capillary rise, surface runoff, interflow, and groundwater percolation.

The model simulates river streamflow using the kinematic wave routing approach, and can simulate either naturalized streamflow or streamflow impacted by human activities including reservoirs, irrigation demand, and water withdrawals and return flows by industrial and domestic sectors. Reservoir outflow in the model is a function of the relative filling of the reservoir, storage parameters, and outflow parameters [11]. Irrigation demand is a function of crop water demand, water availability, and crop type (paddy or non-paddy) [86]. Parameter calibration uses an evolutionary algorithm that optimizes a modified version of the Kling-Gupta Efficiency (KGE) between the simulated and observed discharge [5, 20].

### 3.2.2 MESSAGEix

MESSAGEix is an open-source, dynamic systems-optimization model developed for strategic energy planning [32]. MESSAGEix is based on the original MESSAGE model that has been developed and applied widely over the past three decades to analyze scenarios of energy system transformation, both globally and in different geographic regions, under technical-engineering constraints and political-societal considerations, e.g., [39, 55, 68, 82]. A defining feature of MESSAGEix that distinguishes it from other energy models in its class (e.g., OSeMOSYS [28] and MARKAL [50]), and that leverages its widespread use as a nexus solutions tool, is that it incorporates the ix modeling platform (ixmp): a back-end database and version control system that enables users to collaboratively develop,

solve and visualize models using the open-source R and Python programming environments [32]. This feature complements with the philosophy and design of CWatM, which utilizes similar open access software (Python) as the main interface for collaborative model development and calibration. In this context, the NEST framework employs the *reticulate* package to integrate R and python work environments [79].

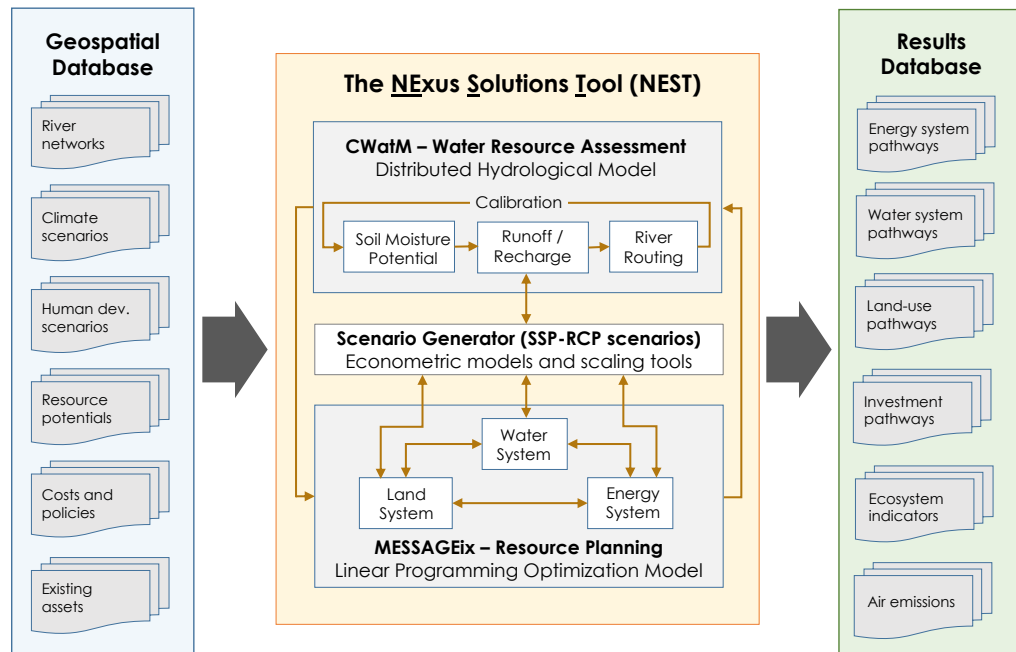


Figure 3.1: The NEST modeling scheme integrates the Community Water Model (CWatM) with a unified EWL technological system implemented in MESSAGEix. A scenario generator harmonizes data across the models and generates exogenous demand profiles aligned with coupled climate-human development narratives from the Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP).

As a bottom-up systems optimization model, MESSAGEix includes resource consumption and capacity limitations at the technology-level. Each technology modeled in MESSAGEix is defined and characterized by input/output efficiencies (the rate at which a particular commodity is consumed or produced during technology operation), economic costs (investment, fixed and variable components), and environmental impacts (e.g., greenhouse gas emissions, water consumption, etc.). A technology in this context can represent any process that transfers or transforms commodities, including natural systems such as rivers, aquifers and crops. By solving the following deterministic inter-regional and inter-temporal linear programming (LP) problem, MESSAGEix minimizes the total cost for system capacity and operation over a future time period while meeting user-specified levels of demand

and technical/policy constraints:

$$\min f(\mathbf{x}) = \sum_{r,t} \mathbf{c}_{r,t}^T \mathbf{x}_{r,t} \delta_{r,t} ; \mathbf{A} \mathbf{x} \geq \mathbf{b} \quad (3.1)$$

In the above system of equations, the time period index is given by  $t$  and the region index is given by  $r$ . The solution vector containing the capacity and activity of the technologies is given by  $\mathbf{x}$ . Economic costs are described in the cost coefficient vector of the objective function  $\mathbf{c}$ . The discount rate associated with future cash flows is represented by  $\delta$ . The set of constraints including the supply-demand balances, capacity limits, technology retirements and capacity additions, activity bounds and additional policies addressing environmental impacts are contained in the technical coefficient matrix  $\mathbf{A}$  and right-hand side constraints vector  $\mathbf{b}$ . The full set of equations is summarized in the online model documentation (<https://messageix.iiasa.ac.at>). The single-objective LP formulation can also readily be transformed to handle multiple objectives, such as minimum total investments, emission level or other environmental indicators [62].

By linking the inputs and outputs of individual processes, energy, water and land decisions can be represented as a single system using the MESSAGEix modeling scheme. Thus, decisions impacting system design and operation over the planning horizon are made understanding the nexus interactions, and will adapt the transformation pathways for each sector to avoid constraints and reduce trade-offs from the perspective of the objective function. Moreover, MESSAGEix supports spatially-distributed systems modeling using a node-link representation, where commodities can be transferred between nodes based on the definition of dedicated technologies. It is therefore possible to explicitly represent the interplays between up- and downstream water users. Commodities are distinguished by the location (level) within the supply-chain enabling explicit accounting of associated efficiency losses and costs for grid and conveyance infrastructures. The temporal representation enables users to select the investment periods (e.g., annual) and sub-investment periods (e.g., sub-annual) over which supply, demand and system capacity must be balanced [32].

### 3.2.3 Reference system

The reference system is the user-defined bottom-up representation of the technological system and its spatio-temporal delineation in MESSAGEix that defines interactions between technologies and the balance of commodity flows across the system [55]. The reference system contains the portfolio of possible technologies and interventions (existing and future) and does not typically change across scenarios; the parameterization of data, including the constraints, are varied to compare how the system reacts to certain inputs, policies and objectives. Two broad categories of data are used to characterize the NEST reference system: (1) historical data on resource use and availability, existing and planned technology capacities; and (2) parametric data for technologies used in the optimization model,

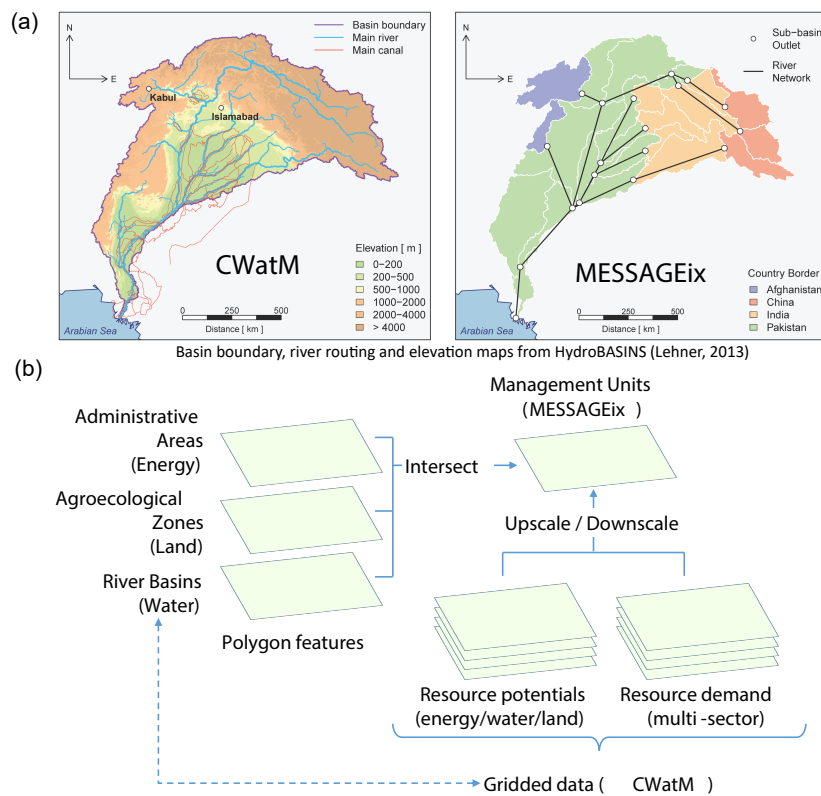
expressed as costs or consumption of resources per unit of production. These data are based on assumptions and can vary spatially and temporally.

### **Spatial delineation**

River basins are defined as fundamental spatial units in the reference system because they indicate how surface runoff (discharge) is directed across space and towards a single outlet downstream to the sea or an inland lake. River basins are disaggregated into sub-basins (tributaries) in NEST to improve accounting of within-basin surface water flows and impacts of upstream water use on downstream water availability. To enable a transboundary perspective, the approach further intersects the sub-basin boundaries with country administrative units; sub-national administrative units and regions covering multiple basins could be considered. The framework does not represent countries entirely, unless countries completely fit within the basin delineation or multiple basins covering a country's borders are included. Optionally, the units can be further intersected with agro-ecological zone boundaries to support diverse climatic characteristics within each sub-basin. The intersection of the administrative, agro-ecological and sub-basin units results in a new classification of management units defined as Basin Country Units (BCUs) (Figure 3.2) [23].

Each BCU is defined as a management unit (or node) in MESSAGEix. The nodes are an aggregated representation of the embedded resources and infrastructure assets that supply demands in the model, and are the fundamental spatial scale over which supply and demand are balanced. Infrastructure connections that move resources outside the region are included as boundary conditions. A reduced-form network for guiding surface water flows between the BCUs is derived based on high-resolution flow-direction data consistent with CWatM [35]. An example for the Indus River Basin in South Asia is depicted in Figure (3.2). The approach is leveraging flow direction data at 15 arc-seconds from HydroSHEDS, which provides hydrographic data layers that allow for the derivation of watershed boundaries for any given location based on the high-resolution Shuttle Radar Topography Mission (SRTM) digital elevation model [44].

Renewable surface water and groundwater inflows into each BCU are represented by aggregating (upscaling) the gridded run-off and recharge projections simulated with CWatM under current land-use patterns (Figure 3.2). This approach is likely to overestimate the available freshwater for human use within each BCU, because water users are distributed and do not have uniform access to the aggregate BCU-level water resources. Grid-cells in CWatM are mapped to specific management units in MESSAGEix by overlaying the polygons and identifying the grid-cell centroids that fall within a given polygon boundary. Daily run-off sequences from CWatM are converted to decadal inflow scenarios by averaging monthly volumes over a 30-year time period; inflow percentiles can alternatively be



22

Figure 3.2: Delineation of spatial units in NEST. (a) The Indus River Basin elevation changes, river system in CWatM (left), and the basin delineated into Basin Country Units (BCUs) with a reduced form node-link river network for implementation in MESSAGEix (right); (b) the methodology intersecting basin boundaries, administrative regions and agro-ecological zones to converge on a common spatial scale, and linkage to gridded resource potentials and demands.

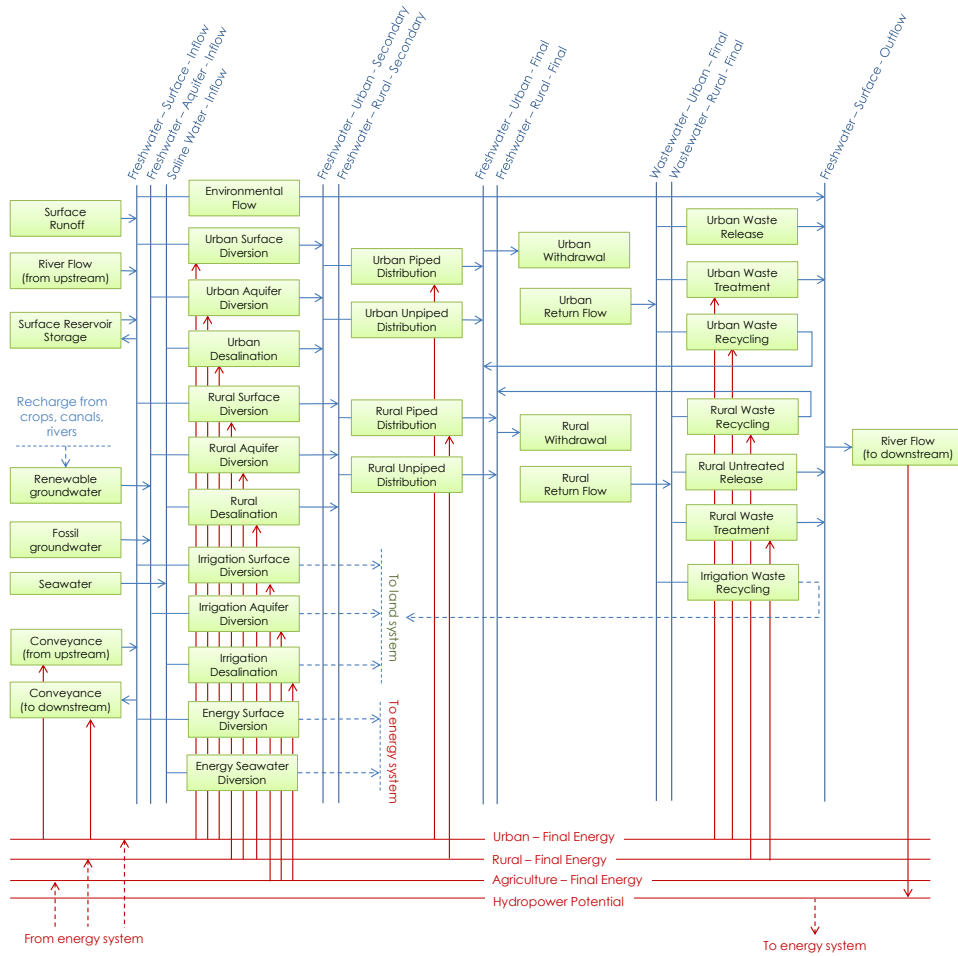
stipulated to consider extreme flow conditions. Similarly, other gridded resource potential and demand projections detailed in the following subsections are harmonized to the CWatM spatial grid to facilitate upscaling and downscaling between models.

### Water sector

The scheme for water management within each BCU is depicted in Figure 3.3. Different water resources (surface, aquifer and saline) are accounted for and allocated across sectors (urban, rural, energy and agriculture). Internal runoff, regulation of reservoirs and water flowing from adjacent nodes through rivers or canals, all contribute to available surface water in each BCU. Renewable and non-renewable groundwater use is distinguished using groundwater recharge scenarios from CWatM and the efficiency losses from irrigation [92]. Simultaneously, return-flow volumes are managed, including opportunities to recycle wastewater streams within and between sectors. River flow and conveyance technologies move water between BCUs. Sectoral water withdrawals and return flows 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. Interactions across sectors are included in the model decision-making, including the energy required for pumping and treating water, and the water needed for crops and electricity generation. Average elevation changes between major urban areas are used to estimate energy intensities for specific conveyance routes [61], whereas average water table depths are used to estimate energy intensities for lifting groundwater to the surface [35].

Figure 3.3 depicts an explicit linkage enabled between nodal outflows and the production of hydropower potential in the model. The potential is passed to the energy system representation described in the following section, and limits the maximum monthly hydropower generation in each BCU. An important challenge surrounds the aggregation of distributed hydropower potential that varies within each BCU both spatially and temporally. We estimate a linear transformation coefficient between modeled flows in the reduced-form basin network and the BCU-level hydropower potential calculated using the gridded data from the hydrological model. Hydropower projects off the main river tributary do not depend on upstream flows in the BCU river network and are identified based on the gridded flow direction data. Separate technologies and linear transformation coefficients are defined for these projects, where the linear transformation coefficient is estimated using the internal BCU runoff. In NEST, we map the CWatM runoff data onto the 15 arc seconds flow accumulation grids from HydroSHEDS to estimate discharge at scales that preserve elevation differences governing hydropower potential [24, 41]. Potential hydropower capacity  $hp$  is calculated with the following equation:

$$hp = \eta \cdot \rho \cdot g \cdot q \cdot (h_i - h_o) \quad (3.2)$$



22

Figure 3.3: The water sector representation in each BCU using the MESSAGEix reference system scheme. The water sector is hard-linked to the energy and land sector representations using the indicated interactions.

where  $\eta$  is the turbine efficiency,  $\rho$  is the density of water,  $g$  is the gravitational acceleration,  $q$  is the design discharge (taken to be the 70th percentile of the inflow sequence),  $h_o$  is the outlet elevation and  $h_i$  is the inlet elevation. Individual projects are identified along 5 km reaches of the 15-arc second river system based on their estimated annual production level and a set of exclusion zones including the distance to existing infrastructure, land-use and population density [24]. We assume that new projects can only utilize 10% of the total flow to ensure a high level of ecological security [69], and limit the canal lengths to a maximum of 3 km based on observed historical trends in installations. We do not consider dam storage or transfers of water between rivers in the assessment of hydropower potential due to additional planning challenges that are associated with these projects not readily monetized in the framework. Alternatively, new dam projects are considered on a case-by-case basis based on published information on planned projects and stakeholder engagement.

## Energy sector

The energy system representation for EWL nexus analysis using the MESSAGEix framework is depicted in Figure 3.4. The approach mimics closely conventional energy systems modeling with MESSAGEix, but integrates directly interactions with the novel implementation of the water and land systems. A diverse range of fossil and low-carbon energy resource extraction, processing and power generation technologies can be included in the framework. Water system interactions are enabled through the definition of water withdrawal and consumption intensities for each energy technology and connection to water diversion technologies constrained by the availability of water resources. Thermal power plants are also distinguished by cooling technology, with the choice of cooling technology impacting the plant's economics and efficiencies. Alternative formulations may disaggregate the cooling technology choice from the prime mover technology in order to enable retro-fitting of cooling systems directly [60].

Wind and solar potential is estimated by linking NEST to the Renewables.ninja application programming interface (<https://www.renewables.ninja/>). Renewables.ninja estimates hourly capacity factors for wind and solar technologies covering most terrestrial locations in the world, and generated based on calibrated resource data and technology representations [65, 77]. In NEST, the grid-cell centroids from CWatM are passed to Renewables.ninja which then generates hourly production times series at each location. Exclusions zones are used to limit the areas where wind and solar can expand. The gridded potential in each management unit is categorized into capacity factors for representing diverse performance characteristics within each BCU.

A simple energy transfer scheme is considered for electricity transmission between adjacent BCUs, with distinct costs for each route estimated based on the average distances between

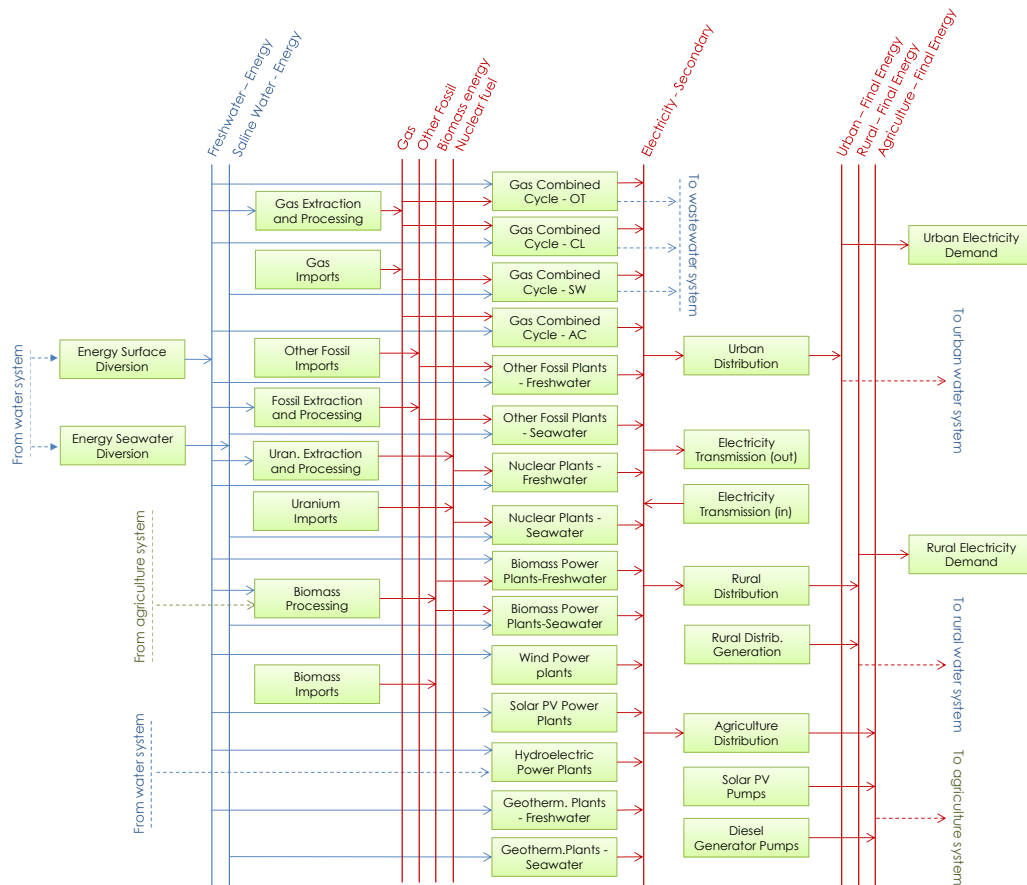


Figure 3.4: The energy sector representation in each BCU using the MESSAGEix reference system scheme. The energy sector is hard-linked to the water and agriculture sector representations using the indicated interactions.

the most populated urban area within each BCU [61]. Fuel trade with areas outside the delineated study region are defined using consistent fuel price projections from the MESSAGEix-GLOBIOM global integrated assessment model [21]. The energy system interacts directly with agriculture systems through the inclusion of bioenergy technologies that consume crop yields. Included are categories of dedicated bioenergy power plants providing electricity to grid-connected and distributed consumers, as well as categories for existing plant-types that can be co-fired using a limited fraction of bioenergy feedstock (e.g., crop residues). The current version of the model does not account for the direct land footprint of energy system technologies. Energy demands from the agriculture and water sector activities are accounted for to ensure sufficient power generation capacity and to account for associated air pollution and greenhouse gas emissions.

### **Agriculture sector**

An important feature of the reference system that bridges decision-making across the nexus is an agriculture sector representation integrated with the water and energy sectors presented previously. Diverse crop types and management strategies can be included in the approach, with the model selecting the cropping area and management method. The latter enables representation of alternative irrigation technologies, land preparation methods, and/or fertilizer application intensities, and importantly incorporates the spatial re-distribution of crops as a management strategy. We adopt a similar approach for integrating land-use into the reference system to that proposed in Köberle (2018) [14], so that when the model selects a specific land-use it must balance the decision with the available land area within each BCU. Land-use is categorized into specific types (forest, pasture, crop, natural, etc.), with dedicated land-use change processes defined in the reference system to convert land-use between types. The maximum cropping area is constrained based on the suitability of land within each BCU to support specific crop-types due to topographic and climatic conditions, as well as the total area available for cropping across all crop types. Non-CO<sub>2</sub> emissions as well as on-farm energy requirements besides that used for water pumping are tracked for different crops based on data from the literature [66]. The model does not currently include dynamic growth and harvest of short-rotation forest crops, but this feature could be added in future work through appropriate definition in MESSAGEix using, e.g., the interannual stock and storage variables (Section 3.2.4). In Figure 3.5 we show an example for a system containing rice and wheat crop types with rain-fed, canal and drip irrigation options.

For crop process modeling, each BCU aggregates crop parameters into coarser spatial units with average land-use parameters [26]. Crop yields are calculated aggregating spatial historical data at the BCU-level. This results in different yield coefficients for each crop, unit area and water supply (irrigation or rain). Similarly, crop water requirements vary across types and the intensity per unit area is estimated for each BCU using consistent

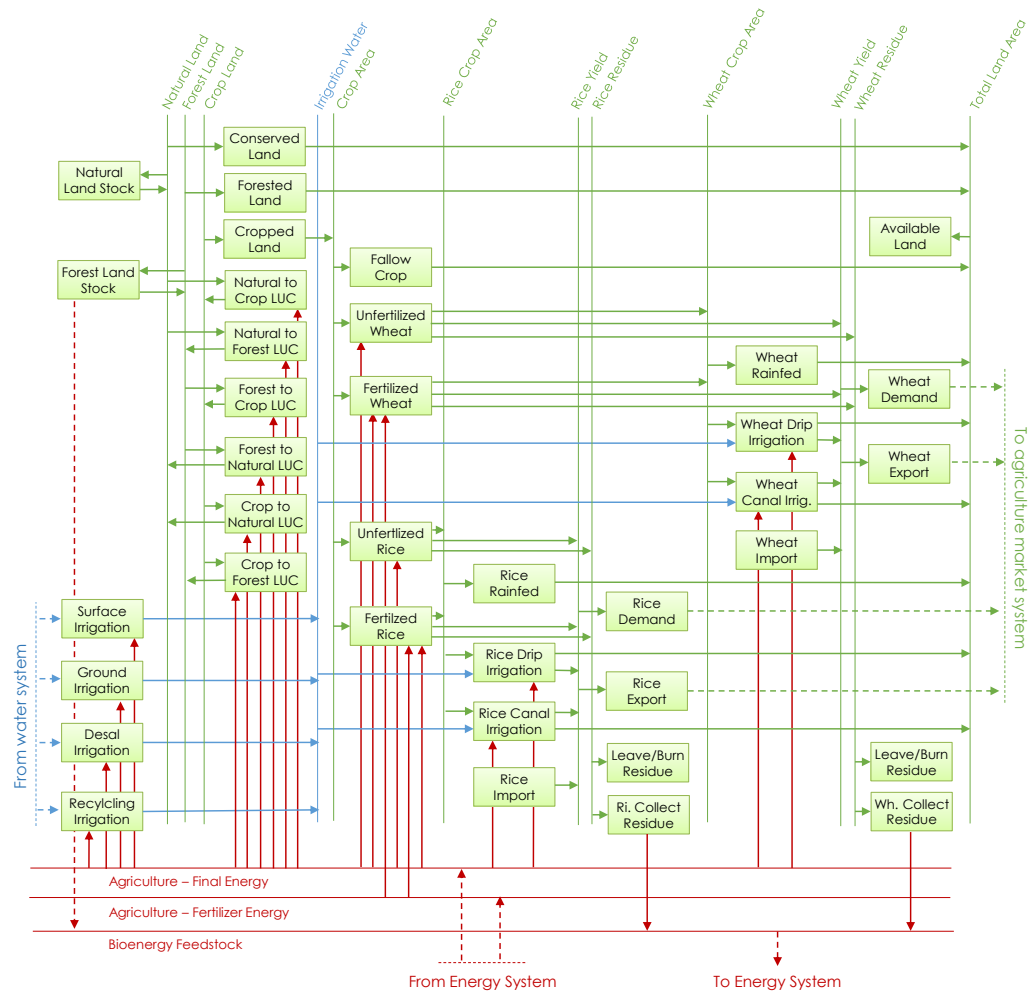


Figure 3.5: The agriculture sector representation in each BCU using the MESSAGEix reference system scheme. The agriculture sector is hard-linked to the water and energy sector representations using the indicated interactions.

water resource projections from the hydrological model. The irrigation per unit area for each crop  $w$  is calculated using the CROPWAT approach [76]:

$$w = \max \{ (k \cdot e - p^*), 0 \} \quad (3.3)$$

In the above equation,  $k$  is the crop coefficient,  $e$  is the reference evapotranspiration and  $p^*$  is the effective precipitation. The reference evapotranspiration is calculated with CWatM using the Penman-Monteith method. The effective precipitation accounts for soil water storage and is estimated following the CROPWAT approach: [76]:

$$p^* = \begin{cases} p \cdot (4.17 - 0.2 \cdot p) & p < 8.3\text{mm/day} \\ 4.17 + 0.1 \cdot p & \text{otherwise} \end{cases} \quad (3.4)$$

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 [16]. Irrigation intensities can optionally be calibrated such that, when aggregated across a given BCU, reproduce annual historical irrigation withdrawals when multiplied by the historical cropping area.

Similarly to the other sectors, the model defines the infrastructure portfolio to meet an exogenous demand for crop yields. Additionally to internal production, import and export of crop yields are allowed and demands can be defined and aggregated across multiple regions to simulate national accounts. Moreover, crop residues are tracked as by-products of agriculture activities. The residues can be burnt resulting in air emissions or transported and processed to have solid or liquid biofuel for electricity production.

### Multi-sector demands and return-flows

Despite the endogenous representation of interactions between energy, water and land systems, there remains the need to exogenously define consumption profiles for the different sectors of the economy categorized in NEST but not specifically modeled at the technology-level. This currently includes the municipal and manufacturing sectors. Baseline demands for freshwater and cropping pattern are also required for the hydrological modeling. A demand scenario generator incorporated into NEST combines gridded climate and socio-economic data from the coupled SSP-RCP scenario framework with econometric models fit to historical data. The SSP-RCP scenario data is harmonized at 7.5 arc-minutes and includes urban and rural populations, income-level and climatic indicators. Sector specific econometric models convert the gridded demand drivers into consumption profiles (water and electricity) and water infrastructure access rates for each sector [60, 61]. For regions lacking universal electricity access and transmission data, gridded electrification rates are estimated using satellite derived night-time light intensity combined with recent maps of population changes [18], and used to parameterize historical grid capacities and downscale

national electricity projections from econometric models.

Food and fiber demands are represented as constraints on yields from specific crops aggregated to the national-scale. Import and export demands are included using variable prices, which might be calibrated in future work by optimizing parameter settings so that the model is able to reproduce prices observed historically [30]. Transport of agricultural products is not considered in the modeling, but might be added as a feature in future work by integrating geospatial and economic indicators for existing and future transport options including road networks [56]. Land and surface water resource availability is also added as an exogenous inflow into the system that must be continuously balanced by technologies and processes included in the model. This supports accounting for conservation measures that preserve land and move water downstream (environmental flows).

### 3.2.4 Enhancements to the MESSAGEix model

The existing MESSAGEix core model does not represent sub-annual storage dynamics and associated capacity constraints. Previous work demonstrates specific approaches for integrating short-term (i.e., daily) storage dynamics into long-term energy system models similar to MESSAGEix [33]; yet, sequential seasonal storage dynamics are most critical to represent from the perspective of water resources management, because of the important role reservoirs play in balancing seasonal hydrologic and demand variability, and the potential for future reservoir development to compete with other water uses during filling. To enable inclusion of seasonal reservoirs in NEST, sequential monthly sub-annual time steps are included in the MESSAGEix implementation and the core model is enhanced with the following set of equations merged into the existing technical coefficient matrix and right-hand constraints vector:

$$\begin{aligned}
 \Delta S_{n,c,l,y,m} \cdot \Delta t_m + S_{n,c,l,y,m+1} - (S_{n,c,l,y,m} \cdot \lambda_{n,c,l,y,m}) &= 0 \\
 S_{n,c,l,y,m}^- &\leq S_{n,c,l,y,m} \leq S_{n,c,l,y,m}^+ \\
 S_{n,c,l,y,m} &\leq Z_{n,c,l,y} \\
 \Delta S_{n,c,l,y,m} &\leq \Delta Z_{n,c,l,y}
 \end{aligned} \tag{3.5}$$

In the above equations,  $n$  is the node where the storage is located,  $c$  is the commodity stored,  $l$  is the level in the supply-chain the storage interacts with,  $y$  is the investment period (annual), and  $m$  is the operational periods (sub-annual). The storage level is given by  $S$ , whereas the change in storage is given by  $\Delta S$ . The first set of inequality constraints is used to limit the storage level to within a specific range ( $S^-$  is the lower bound and  $S^+$  the upper bound), for example to include operating rules for reservoirs used for multiple purposes. The second and third inequality constraints are the capacity limitations both in terms of system size ( $Z$ ) and rate of commodity transfer ( $\Delta Z$ ). Storage losses (i.e. evaporation and seepage) are given by the factor  $\lambda$ , and computed as a function of the

estimated evaporation from the hydrological model and a linear area-volume relationship [49]. The sub-annual time period duration  $\Delta t$  converts the storage change calculated as a rate into a volume consistent with the storage level. To account for filling behavior and interannual variations we ensure: (1) the start and end levels are the same across years when no new storage capacity is added; and (2) when new storage capacity is added, it must be filled uniformly throughout the first 10 years, thus presenting an additional freshwater demand. Capacity additions are exogenously defined based on reported data; future work will consider the capacity limitations as control variables that can be expanded through increased investment in storage capacity.

To avoid integer (binary) decision variables associated with the choice of whether or not to plant a specific crop in a specific area, an additional set of minimum utilization constraints are defined for crops included in MESSAGEix. This forces the optimization to maintain the growing schedule over the course of the year, while balancing the total land area across crop types. Further adjustments to the core model are needed to ensure the physical balance of EWL resources. Specifically, the existing MESSAGEix core model constrains resource supply to be greater than or equal to resource demand. This setup enables the model to spill excess resource production when beneficial to the overall operating costs of the system. However, this configuration poses challenges when accounting for inflows into the system to effectively size infrastructure capacity. For example, when considering wastewater return flows as a specific commodity that should be managed using wastewater treatment technologies, it is crucial to ensure a complete commodity balance across all time periods. Otherwise, the model would be able to exclude inflows to avoid building wastewater treatment capacity. To reconcile inconsistencies and to ensure a physical balance of EWL resources, we define a new set of supply-demand balance equality constraints in the enhanced MESSAGEix core model used in NEST.

Finally, for computational efficiency we developed a set of tools in the R programming interface that enable users to rapidly prototype new models during the testing phase by selectively managing interactions with ixmp. We found that for the case study described in Section 3.3 that the new approach cuts model instance generation time by an order of magnitude. Importantly, the ixmp utilities can be optionally used so that once debugging is complete, models can readily be shared and modified using the powerful database utilities enabled with ixmp. All of the enhancements to the MESSAGEix model implemented in this paper can be obtained from the online repository for NEST (<https://github.com/iiasa/NEST>).

### 3.3 Modeling SDG implementation in the Indus River Basin

As a first application of NEST, we focus on the Indus River Basin (IRB). The setup is meant to demonstrate the capabilities of the model, with ongoing work dedicated to the

integration of local data and understanding of the policy implications for the region, and to be summarized in a future publication. The IRB, located in South Asia, is home to an estimated 250-million people (Pakistan 61%, India 35%, Afghanistan 4%, and China less than 1%) and has the highest density of irrigated land in the world [42, 93]. In recent years, the region experienced rapid population and economic activity growth, and this is expected to continue in the next decades leading to reduced poverty and growing demands for water, energy and food. With no surface water left in the basin for expanded use and accelerating exploitation of fossil groundwater as a result, long-term management of systems dependent on water is fundamental for the sustainable development of the region [88].

There have been a number of previous analyses of EWL challenges in the IRB, including integrated modeling of the systems in Pakistan’s portion of the basin to understand the cost of climate change [92, 93]. Other recent analysis has quantified existing and future gaps in water supply caused by projected socioeconomic and climate change or gaps in estimating electricity demand variation due to groundwater pumping for agriculture [75, 91]. Previous work on the IRB does not provide a full assessment of EWL adaptation options or long-term pathways for the IRB as a whole. Specifically, there remains a need to link long-term capacity expansion decisions across EWL systems to understand the best strategies for developing the region’s infrastructure into the future while accounting for existing transboundary policies. Crucially, there are important interplays between irrigation efficiency, land-use change and groundwater recharge that need to be reconciled to ensure water saving policies have the intended effect [25]. The NEST framework is ideally positioned to tackle these research questions because of its explicit representation of EWL capacity expansion and land-use change across spatially distributed regions and features basin wide water accounting for surface and groundwater systems.

### **3.3.1 Model setup**

To parameterize the model in terms of resources, technologies and demands, we used the data sources outlined in Table 3.1. Importantly, much of the data needed to run NEST can be obtained from open access geospatial datasets with global coverage. Thus, NEST is readily adapted to other regions of the world. Nevertheless, it is important to emphasize the prioritization of approved local data, as well as use of the calibration steps that can be embedded in the framework that improve the performance of the model in terms of reproducing historical conditions. Moreover, it is important to stress the use of multiple climate models and RCP-SSP scenarios to bridge the range of uncertainties in the hydrological modeling and demand drivers.

We calibrated CWatM for the IRB at 5 arcmin resolution using the monthly streamflow data during 1995-2010 at the Besham station, in northern Pakistan. The Besham station

Parameter(s)	Dataset	Spatial Resolution	Latest Year
Country administrative boundaries	Database of Global Administrative Areas (GADM)	polygon	2008
Basin and sub-basin boundaries	HydroBASINS database	polygon	2012
Climate forcing	Intersectoral Impact Model Intercomparison Project (ISIMP)	$0.5^\circ \times 0.5^\circ$	2015
Urban and rural population	[34]	$0.125^\circ \times 0.125^\circ$	2010
Urban and rural GDP	Byers et al. (2018)	$0.125^\circ \times 0.125^\circ$	2010
Elevation, flow-direction, basin/lake boundaries	HydroSHEDS Database	$0.004^\circ \times 0.004^\circ$	2008
Non-hydro power plant capacity, age and location	World Electric Power Plant (WEPP) Database	asset-level	2017
Power plant cooling technologies	[67]	asset-level	2014
Hydro power plant capacity, age and location	[81]	asset-level	2017
Reservoir capacity, age and location	Global Reservoir and Dam (GRaND) Database	asset-level	2014
Crop areas, yields and location	Global Agro Ecological Zones (GAEZ) Database	$0.1^\circ \times 0.1^\circ$	2005
Protected areas	World Database on Protected Areas (WDPA)	polygon	2014
Forests	Global Forest Change (GFC) Database	$0.004^\circ \times 0.004^\circ$	2014
Depth to groundwater	Fan et al. (2013)	$0.01^\circ \times 0.01^\circ$	2012
Historical energy supply and demand by sector	International Energy Agency (IEA)	national	2017
Historical water supply and demand by sector	Information System on Water and Agriculture (AQUASTAT)	national	2015
Historical irrigation water supply by source	[12]	$0.1^\circ \times 0.1^\circ$	2015
Historical non-irrigation groundwater use	[87]	$0.5^\circ \times 0.5^\circ$	2005
Historical transmission capacity and roads	OpenStreetMap	asset-level	2017
Historical on-farm energy use incl. pumping	[75]; [66]	provincial	2015
Historical water conveyance capacity	Estimated from technical reports	asset-level	2018
Historical crop prices, fertilizers and crop coefficients	Food and Agriculture Organization (FAO)	national	2018
Planned reservoir and power plant capacity	Estimated from technical reports	asset-level	2030
Power plant cost and performance	[61]; [21]	technology-level	2014
Surface and groundwater performance	[35]	technology-level	2010
Irrigation cost and performance	Local data collected	technology-level	2010
Wastewater cost and performance	[61]	technology-level	2014
Desalination cost and performance	[61]	technology-level	2014

Table 3.1: Data sources leveraged to parameterize the NEST implementation of the IRB.

is chosen because of its coverage of historical years, it incorporates the runoff from both glacial and seasonal snowmelt. However, multiple stations would be necessary to better represent regional heterogeneity (in particular lower versus upper basin). Future work will incorporate spatially distributed observations to improve the calibration. It is important to emphasize the complexity of the hydrology in the IRB and the difficulties in calibrating to observed data due to extreme elevation changes [19]. For calibration, the CWatM simulations included human impacts on streamflow and a spin-up period of 5 years to allow long-term storage components to stabilize. Analysis of the initial calibration results showed that the calibration was mainly impacted by the ice melt coefficient and empirical shape parameter of the ARNO model for infiltration [11, 78]. Therefore, we ran a second calibration that searched for optimal values for only these two parameters. The calibrated parameter values are given in Table 3.2. The performance of the model after the two calibration runs is in Figure 3.6. We then used the calibrated CWatM for the IRB for historical (1956-2005) and future (2006-2099) simulations using the downscaled meteorological inputs of the ISI-MIP2b project from four global climate models (GCMs: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5) [22]. The streamflow in CWatM were naturalized because human activity, and water withdrawals in particular, are represented and accounted for in the MESSAGEix framework. The resulting ensemble mean monthly runoff profiles for each riparian country's basin area and the Indus as a whole are depicted in Figure 3.7. The total basin runoff matches closely with other reported data [42].

For implementation in MESSAGEix, the IRB is delineated into 24 Basin Country Units

Parameter	Value
Snow melt coefficient	0.003597
Crop factor correction	1.211
Ice melt coefficient	0.5366
Soil preferential flow constant	5.4
ARNO b	1.259
Interflow part of recharge factor	1.807
Groundwater recession coefficient factor	3.823
Runoff concentration factor	1.492
Routing Manning's N	8.104
Reservoir normal storage limit	0.5257
Lake alpha factor	1.154
Lake wind factor	1.205

Table 3.2: Calibration parameters values for convergence of CWaTM.

(BCUs) using the basin and country administrative boundary datasets (Figure 3.2). Further disaggregation into the agro-ecological zones is not pursued in this case because of limited spatial variability in crop potential within the delineated BCUs. The planning horizon considers investment periods spanning 2020 to 2060 in 10 year time steps, and 2015 is parameterized as the base historical year (i.e., the initial starting point). Monthly sub-annual time steps are considered.

CWaTM is run with fixed spatial and temporal resolution as mentioned in previous sections. Therefore, performances are not affected by the final scale of the optimization model. Running times are in the order of few hours on personal computers. The MESSAGEix component is instead scale sensitive, increasing the number of BCU or the temporal resolution increases the size of the matrix of the LP optimization significantly. In the current configuration, the *cplex* solver in the GAMS model reduces the system of equations to a LP matrix of approximately 1 million x 1 million elements and solves in less than 30 minutes on personal computers. For each policy scenario described in the following sections, CWaTM is only run once for each SSP and RCP combination, while additional policies are only implemented and run in the optimization model.

With most of the land area dedicated to crop production, we simplify the reference system by limiting the land-use options to crop land choices and limit the crop types to fertilized options. The SSP2 (middle-of-the-road) socioeconomic scenario is explored in the analysis and the *ensemble* mean climate scenario across the RCP climate models is used for climate forcing.

Urban and rural population and per capita income for SSP1, 2 and 5 projected for 2050 are compared to 2010 values for each riparian country's part of the IRB in Figure 3.8. It can be seen that rapid urbanization and growth in income levels is projected in the scenarios, and these changes translate into increased consumption of water, energy and crops in the modeling framework. Figure S1 depicts the corresponding sectoral exogenous

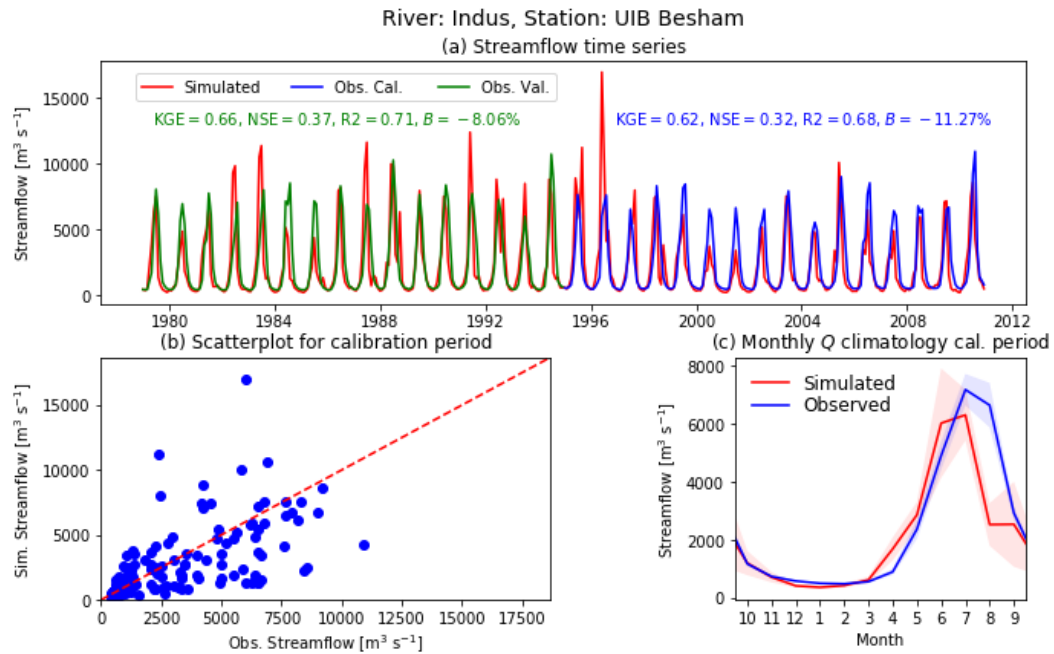


Figure 3.6: Comparison between the simulated streamflow by the calibrated model and the observation. KGE: Kling-Gupta Efficiency. NSE: Nash-Sutcliffe Efficiency. R-sq: R-square. B: mean bias.

demands for the SSP2 scenario. Note that results for China are not included because the existing and projected population growth in this region is very low and thus the consumption has negligible impact on the downstream resources. Electricity demands increase most dramatically across countries due to the rapid increases in GDP and the assumption that electrification is supporting economic development. Water demands increase more gradually due to less influence of economic growth, although for India the manufacturing sector water uses increases significantly due to the existing water intensity. Corresponding projections of the population with and without access to pre- and post-treatment of freshwater are generated based on the GDP projections.

Canals play an important role in enabling the Indus Water Treaty, and are mapped to specific BCUs using the data in Table S1. Operational constraints are also added to force the linkages to transfer water between routes, in line with the Indus Treaty. The Indira Gandhi canal is considered as a constraint on flows originating from the particular BCU where the inlet is found. Similarly, an urban water transfer to Karachi near the Indus Delta is included as an additional demand. The capacities of other water diversion infrastructures (surface and groundwater) for each sector are estimated from the historical withdrawals. The energy source for groundwater pumping is also identified, where diesel generators dominate in Pakistan and Afghanistan, and electricity is used predominately in India.

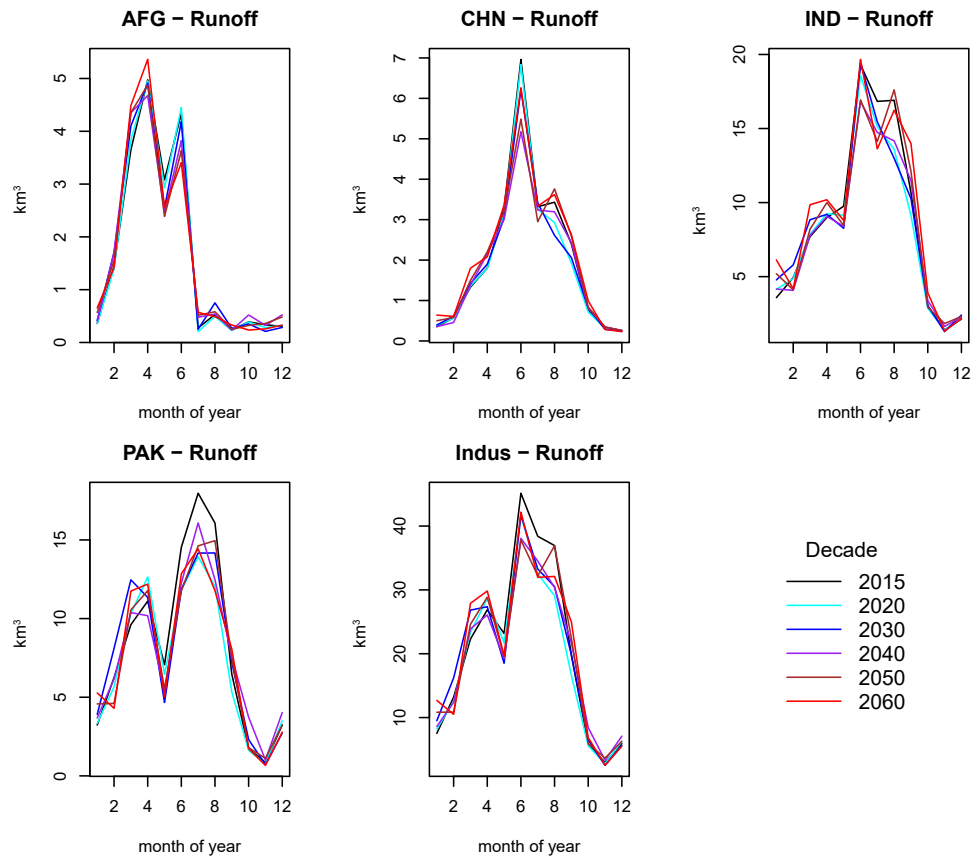


Figure 3.7: Ensemble mean monthly runoff in each country and the IRB as a whole. Daily run-off sequences from CWatM are converted to decadal runoff scenarios by averaging monthly gridded volumes over a 30-year time period. Outputs from four global climate models are included in the ensemble: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5.

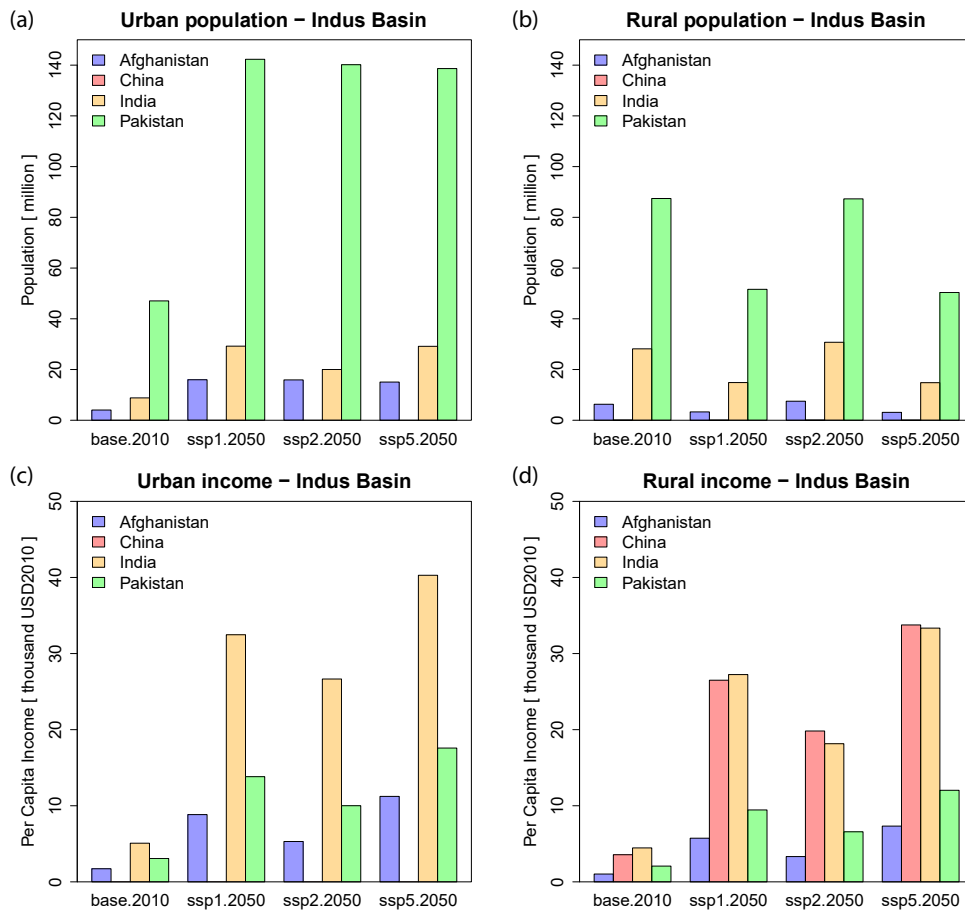


Figure 3.8: Urban and rural population (a),(b) and per capita income (c), (d) for SSP1, 2 and 5 in 2050 and 2010 for each riparian country's part of the IRB.

The existing and planned capacity of power generation in the IRB is depicted Figure S2. Hydropower is the main source of generation capacity in the basin, with the basin regions of Pakistan also hosting significant amount of fossil generation. A number of large-scale hydropower projects are also planned in the region (Table S2) that were not found in the global databases, and these projects have also been included in the model. For projects with an opening date before 2025, it is assumed they are operational in 2020; all other projects are assumed to be operational in 2030. For hydropower projects with storage, the storage capacity is added to the BCU level storage in the year it becomes operational, with the filling of the reservoir averaged over the first 10 years of operation, as described previously. Existing storage capacity includes 26.4 km<sup>3</sup> in Pakistan, 22.2 km<sup>3</sup> in India and 0.6 km<sup>3</sup> in Afghanistan. Operating rules are derived for the largest existing dams based on the historical reported releases for 2016 and 2017. Approximately 45 GW of additional hydropower potential is estimated using the approach described in Section 3.2.3, mainly in the Upper Indus Basin. The assessed solar and wind potential greatly exceeds the electricity demand, with most of the wind potential focused mainly in the Indus Delta region. Tapping the solar and wind potential, however, requires investment in transmission and flexible assets (e.g., storage). In the Supplementary Information we provide variable capacity factor of solar and wind aggregated for each BCU (*Variable\_capacity\_factor.xlsx*).

The performance of the different crop types considered in the model in terms of yields are presented in Figure S3 for irrigated and non-irrigated options. Crop categories are set according to the main types of crops grown in the region, with some aggregation of crop types occurring to simplify the number of decision variables. The maximum productivity on a per hectare basis demonstrates that irrigation significantly boosts crop productivity in many locations, enabling less land to be used. As mentioned previously, land for each crop type in each BCU is constrained based on suitability and total area. Certain crops also are performing better than others in some regions, while some crops are not available entirely in some regions. The historical crop yields are harmonized to historical irrigation water use by calculating the required irrigation to support the historical crop areas using Eq. 3.3, and then calibrating the irrigation intensities such that the withdrawals match with the reported irrigation deliveries in [12] aggregated to the BCU-scale.

### 3.3.2 Scenario analysis

The parameterized NEST model of the IRB is applied within a scenario analysis in which a baseline (business as usual) scenario and a multi-objective scenario achieving multiple SDG indicators by 2030 are compared. The SSP2 information is used to parameterize population and economic indicators in each scenario. The business as usual scenario assumes the continuation of existing policies (e.g., Indus Water Treaty), and is aiming at cost minimization with limited environmental constraints such as emission or infrastructure access targets. Conversely, the SDG implementation pursues a vision of economic

growth (poverty eradication) jointly combined with reducing resource access inequalities and the environmental impacts of infrastructure systems. It is important to emphasize the SDG scenario is not exploring all of the individual targets and indicators, but instead a limited set relevant for water, energy and land systems that are also well represented in the NEST framework. The main features of the baseline and multiple-SDG scenarios are summarized in Table 3.3. The scenarios are simulated by solving NEST under the different implementations. Additional sensitivity analysis is performed to highlight uncertainties in the modeling framework.

Target	Description	Modeling: SDG vs baseline
Climate action		
Global Greenhouse gas (GHG) Emissions	SDG 13.a Implement the commitment undertaken by to the United Nations Framework Convention on Climate Change	Set GHG emission budget and climate scenario accordingly. Baseline: no emission targets
Clean and affordable energy development scenarios		
Clean energy access	SDG 7.2 By 2030 50% share of renewable energy in the global energy mix	Set targets on share of renewables (wind, solar, geothermal). Baseline: no targets
Power plant cooling	SDG 7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all	Phase out of once-through cooling, imposing capacity constraint. Baseline: no targets
Water sector development scenarios		
Sustainable water withdrawals	SDG 6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes	Minimum of 20% of monthly natural flow left in rivers and aquifers by 2030. Set sustainable levels of groundwater extractions (also in baseline)
Wastewater treatment	SDG 6.3 By 2030, improve water quality by reducing pollution, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	Treat half of return flows treated by 2030, recycle one quarter of return flows. Baseline: no targets
Sustainable agriculture scenarios		
Food & agriculture infrastructure access	SDG 2.4 By 2030, 100% implementation of modern so-called smart irrigation technologies that increase productivity and production relative to 2015	SDG 2.4 constraint technologies with low efficiency to have zero capacity in 2030. Baseline: no smart irrigation technologies adopted before 2030

Table 3.3: Policy scenarios embedding specific SDG targets, [74]

## 3.4 Results and discussion

### 3.4.1 Role of water storage and seasonal effects

Figure 3.9 shows the balance of surface water in the model for a specific sub-catchment (BCU) in Pakistan with planned storage expansion in 2030. Inflows in the region from upstream river flows or from internal runoff are subject to strong seasonal variations (a).

Urban, rural and industry water demands are assumed to be constant through the year (therefore not shown in Figure 3.9), while water requirements for agriculture and power plants' cooling are instead endogenous and thus variable during the year (c). Supply and demand are not constrained to specific water sources, Figure 3.9 depicts a case in which water requirements for agriculture are supplied by groundwater (b). Most surface water is indeed outflowing from the region to downstream nodes (d) due to environmental flow requirement and it is in turn used for hydroelectric generation (e). Noticeably, storage absorbs the high inflow peaks in the months of April and June, and releases high outflows in July (f). However, it is not straightforward to directly link the reservoir level changes to hydropower generation or other regional water requirements under the conjunctive management strategy. Storage regulation appears in this case to mostly be serving downstream water demands as opposed to supporting hydropower potential.

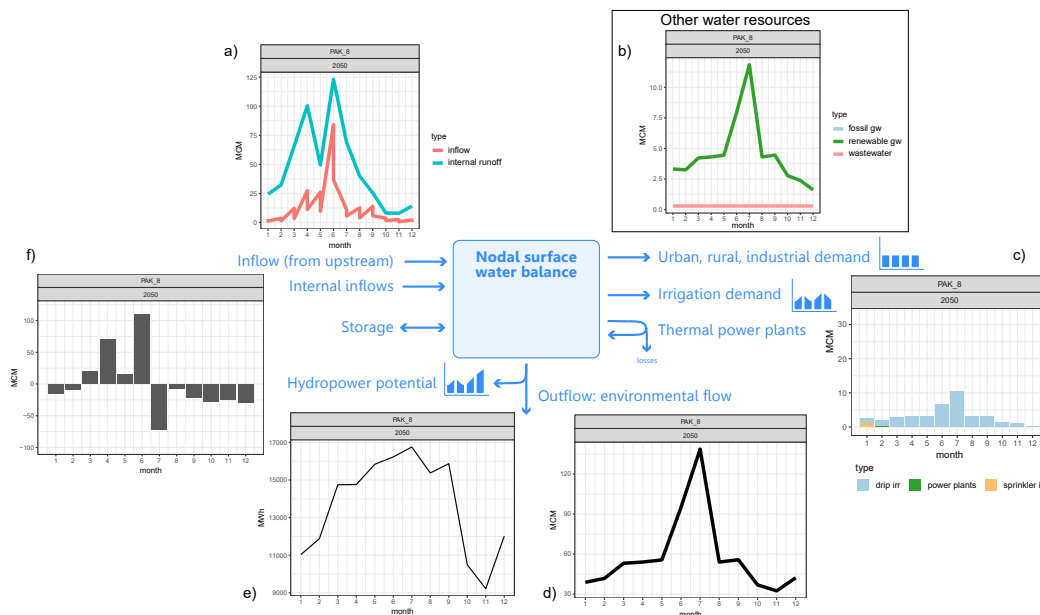


Figure 3.9: Surface water balance for a specific BCU (PAK\_8) in 2050 (a) surface water inflows (b) supply from other water sources (c) variable water demand (d) surface water outflow (e) hydroelectric generation (f) storage level changes, recharging if positive, discharging if negative.

Seasonality effects embedded in the model input are mostly related to water availability, renewable energy capacity factors and crop water requirements and productivity. Figure 3.10 shows outputs of the model that are affected by the above mentioned seasonal variations. Electricity generation fluctuations in hydropower generation are mostly compensated by nuclear, imports or natural gas. Similarly, the time for crop cultivation, growth and yield is season specific, taking into account precipitation and crop coefficients seasonality. Other studies have looked at the role of hydropower in the region with a nexus perspective, considering both electricity production and water management [92]. Whilst the results from the Indus Basin Model Revised (IBMR) and NEST could be compared,

if similar scenarios were run, it must be noted that IBMR only focuses on a sub-region of the basin network with higher spatial detail, while NEST includes a more complete representation of energy demands, supply and water-energy linkages.

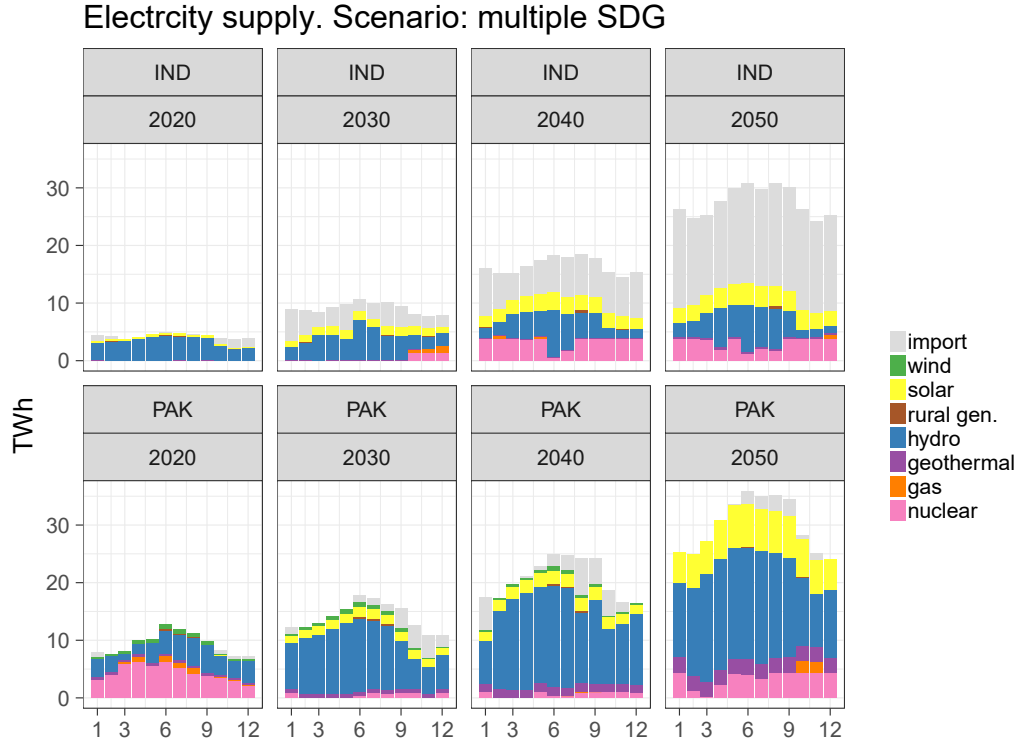


Figure 3.10: Monthly electricity generation under the *multiple SDG* scenario

### 3.4.2 Quantifying investments to achieve the SDGs

We present a comparison between the baseline and the multiple SDG scenarios. Figure 3.11 (a) depicts the yearly average new investment portfolio and associated average operational costs for each scenario. To achieve the sustainability goals, investment costs approximately double, while operational costs increase by about 30% (these include fixed costs, variable costs of operation and costs of electricity imports). To meet the targets for wastewater treatment and the share of renewable energy (solar and wind and geothermal), a large portion of the new investments are dedicated to technology development and a shift in power plant type. Hydropower emerges as an important option in the baseline because of the planned expansions and unexploited potential quantified in the assessment.

As a consequence of the environmental flow policy in SDG6, multiple sectors need to adapt to lower water availability. The agriculture sector is particularly impacted due to its high share of total water demands and expands to non irrigated areas to avoid water withdrawals. However, this implies lower yields and so more area is needed to support the same production and at higher operational costs due to the lower productivities. Addi-

tionally, there is increased investment into more efficient irrigation technologies, especially where most of the available arable land is cultivated and production still needs to be boosted to maintain agricultural supplies.

Figure 3.11 (b) compares the nexus interactions at the basin-scale for each scenario. The multiple SDG scenario displays an almost fivefold increase (from 500 GWh to 2500 GWh per year) in energy requirements for water management (mostly pumping, treatment and arrangement of new canals). This is to support increased water access in the municipal sector and massively expanded wastewater treatment capabilities in urban areas, but still represent less than 2% of total electricity generation projected in 2020. A combined GHG emission target ensures the increased demands are met without increasing carbon emissions.

These results demonstrate the value of interconnection across EWL sectors in terms of chain reaction in investments (i.e. expanding piping distribution also require expansion in electricity production and distribution), synergies (investing in irrigation efficiency implies saving in water distribution for irrigation) and trade-offs, as it is clearly not possible to minimize costs and resource use across all sectors to achieve the SDGs.

### 3.4.3 Synergies and trade-off among SDG targets

The sustainability scenario includes multiple policy objectives across different sectors, which are considered simultaneously by the model. Specific policy objectives can thus be analyzed individually or in combination. Cross-sectoral implications are not necessarily the same when assessing multiple policies at the same time or individually. However, to additionally understand the implication of each single SDG policy on the water, energy and land systems, we tested each policy independently (as in Table 3.3).

Figure 3.12 depicts the electricity generation, water withdrawal by source and the land use for agriculture in India and Pakistan from 2020 to 2050 in all the scenario permutations tested. The baseline scenario assumes that enough water is present in the basin to meet increasing energy, water and food demands, while fulfilling the Indus Water Treaty allocations, but neglecting the additional environmental flow standards, water efficiency guidelines and infrastructure access constraints present in the SDG6 case. The second row of plots depicts the sectoral changes induced by the multiple sustainability policies. Intuitively, constraining the use of surface water for environmental purposes has most impact on cross-sectoral activities in Pakistan because it is the most downstream country and thus faces the greatest challenge in meeting increasing water demands while concurrently allocating more flow to ecosystems when water is already scarce. In fact, its hydroelectric potential is significantly reduced and the main water source left is renewable groundwater. This has a large impact on the agriculture system, where both India and Pakistan expand

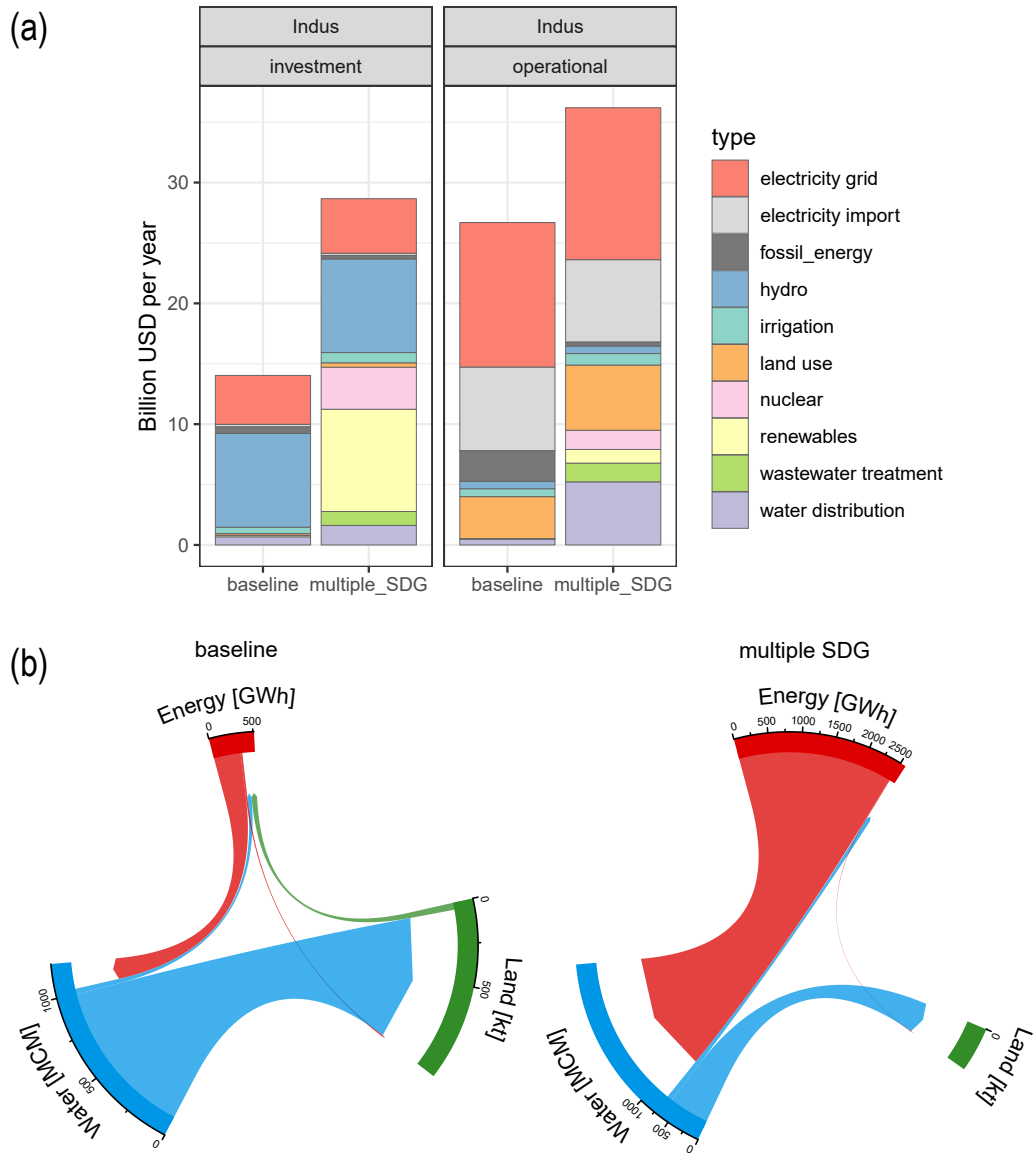


Figure 3.11: (a) Comparison of investment and operational cost (yearly average) for the entire basin. (b) Representation of water for energy (excluding hydropower) and irrigation [MCM], energy for water management technologies and for agriculture [GWh] and biomass used for energy production [kt].

cultivated land with rain-fed crops, to adapt to water scarcity<sup>2</sup>.

It is crucial to note that in India the total available land for agriculture is already utilized in the base year in most of the modeled regions due in part to the Indus Water Treaty obligations (which allows India to use a limited amount of western river waters for irrigation). Thus, to fulfill increasing food demand and reduce the water consumption per hectare in the SDG scenario, an uptake in more efficient irrigation technologies is observed. Importantly, the basin-wide water accounting framework enables the applied water efficiency policies to account for the complex interactions between irrigation water losses and groundwater availability, to ensure that a combination of surface and non-renewable groundwater sources are conserved.

Looking at single scenarios separately helps to understand what policy drives the specific changes and what sector is mostly affected.

- SDG2. Most of the existing flood irrigation systems are substituted by drip and sprinkler technologies. This reduces the water demand for irrigation. For further analysis the authors intend to add other SDG2 related targets concerning changes in food demand, import, export and shifts to different types of crops.
- SDG6. The environmental flow policy represents one of the major constraints for the resource management in the region. Indeed, we notice how, particularly in Pakistan, electricity and water supply systems would require complete restructuring, as well as management of land for agriculture. The main water resource for Pakistan becomes renewable groundwater, which is recharged from via infiltration including losses from irrigated fields. One important difference to the multiple SDG scenario is the role of hydropower and the consequences on the remaining surface water availability in Pakistan. In fact, as the SDG6 scenario is not bound by emission constraints, fossil fuel generation (gas and oil) is rapidly deployed. When adding CO<sub>2</sub> emission and renewable energy shares consistent with SDG7, results show it can be optimal for Pakistan to exploit all the possible hydropower potential, while meeting environmental flow minimum requirements. This reduces the surface water availability both for irrigation and other demands. As a consequence, less irrigation technologies are adopted in the multiple SDG scenario in favor of more rain-fed crops. However, this leads to a vicious circle where less irrigated land means less water recharging groundwater aquifers, but at the same time the model accounts for the interaction and finds an optimal balance.
- SDG7. This policy imposes specific targets for solar, wind and geothermal electricity production in terms of the share in the entire energy mix. We set the share target of 30% by 2050, which is achieved gradually starting with 10% in 2020. In addition,

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<sup>2</sup>For this case study we do not consider land use change to other types of land, such as forests

a phase out of coal and once through cooling technologies after 2030 are also considered. One consequence of this policy is a more rapid transformation away from fossil fuels. Nonetheless, this is not necessarily the most economically optimal way of achieving CO<sub>2</sub> emission reduction (see SDG13). When compared to the multiple SDG scenario, nuclear plays a more significant role, despite higher water consumption. Since nuclear is currently a critical issue in both India and Pakistan, further research will investigate the feasibility of nuclear with more detail and interacting with local stakeholders.

- SDG13. To understand what are the possible pathways towards a carbon neutral electricity system, the SDG13 results show how nuclear electricity generation can be an important option due to cost and reliability, and is complemented well by the available hydropower potential. Importantly cost and policy barriers difficult to monetize in the framework could cause development constraints for nuclear systems in the region.

In summary, this overview of the single policy objectives shows that constraints on land and water availability push the system to make transformational changes to the development pathway for each sector, and can drastically alter the structure of the energy and water supplies and land-use pattern. Considering multiple target simultaneously shows different results than summing individual analysis. As mentioned above, the electricity mix changes when considering water constraints and climate targets. Similarly, land use is different when efficiency policies are in place together with environmental targets. This clearly shows the importance of an integrated multi-sectoral analysis to highlight synergies and barriers among objectives. The authors intend expand this topic in upcoming research.

#### 3.4.4 Uncertainty and sensitivity

Integrated assessment models are subjected to different types of uncertainty, which can cumulate and therefore require particular attention. Uncertainty can be broadly divided in data or parametric uncertainty, which is given by data sources, often represented as distribution or numerical ranges; and assumption uncertainty, occurring when dealing with future scenario in the scope of policy analysis [71].

Here we present an example of scenario uncertainty propagation between the two different models in NEST and a simplified parametric sensitivity analysis to demonstrate the need for a more thorough study.

Figure 3.13 (a) shows different level of monthly total runoff from the CWaTM using different climate models and under two different climate scenarios (RCP 2.6 and 6.0). We notice major diversity in trend given by different climate models, while climate scenario implies changes mostly in the eighth and ninth months of year 2020. When running the

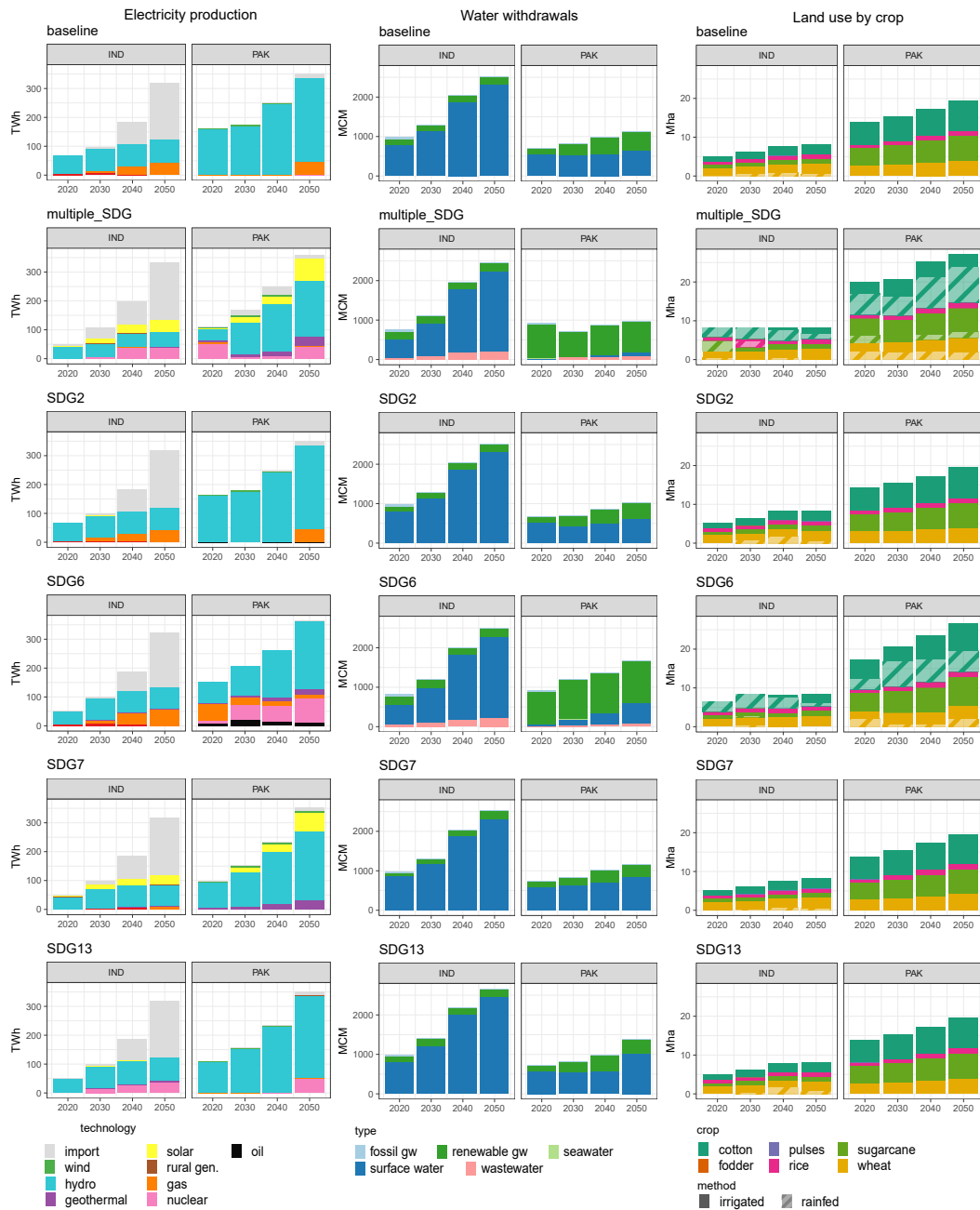


Figure 3.12: Comparison among different scenarios of yearly values for Pakistan (PAK) and part of India in the Indus basin (IND) of: electricity supply mix [TWh], water withdrawals from different sources [MCM], total land used for farming different crops [Mha], distinguishing between irrigated (dark color) and non irrigated area (semi-transparent)

optimization model in NEST, outcomes carry the uncertainty from the hydrological model and cumulate it with other types of uncertainty. Figure 3.13 (b) shows total cost for the Indus region where the uncertainty of different SSP assumptions is added the previous set of climate scenarios. We notice how SSP assumptions more greatly affect total cost compared to either climate model or RCP (each bundle of same-color lines includes runs with all climate scenario and RCP assumptions). However, looking at SSP 2 and 1, with reduced stress caused by population growth, climate uncertainty is more significant than for SSP 5.

Figure 3.14 illustrates different output changes under the BAU scenario in response to an arbitrary variation in input parameters (-25%,+25%). Intuitively, some outputs as groundwater extraction and energy production are strongly affected by the variation of sector-related parameters, irrigation and power plants' efficiency respectively. The plot also shows some significant cross-sectoral feedbacks. For instance, changes in energy efficiency and investment cost impact groundwater and surface water withdrawals by up to 5% and irrigation efficiency strongly impact fossil-fueled energy production. Land use seems not to be sensitive to the input parameters here considered. Looking at total cost alterations, multiple parameters induce variations comparable with the scenario uncertainty described above. This preliminary analysis suggests that further and more thorough study is needed, adopting more realistic uncertainty ranges or data distributions.

Structural uncertainty also typically characterizes complex models such NEST [1]. We expect that omitting some feedbacks or expanding some modules could distort some of the model responses. Further work will focus on exploring this type of uncertainty.

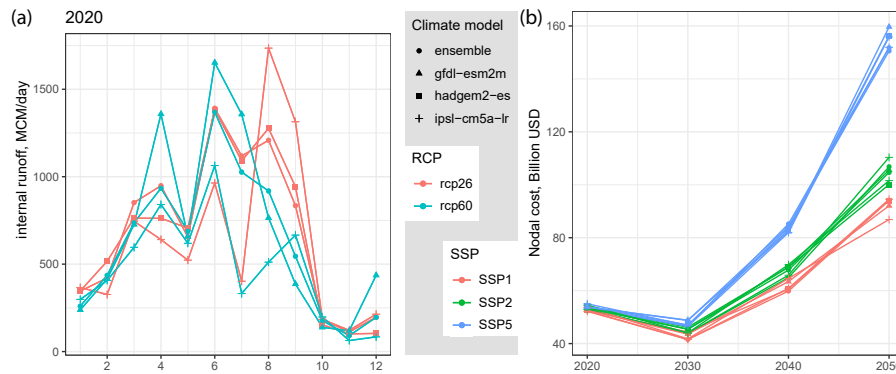


Figure 3.13: Total monthly runoff availability in 2020 under different RCP and climate models (a). Total costs under different climate model, RCP and SSP assumptions (b)

### 3.4.5 Structural limitations and further developments

Increasing spatial and temporal resolution might be helpful to focus on sub-regions and identify possible critical areas with higher detail. However, it brings greater computational challenges associated with using classical mathematical programming methods. In

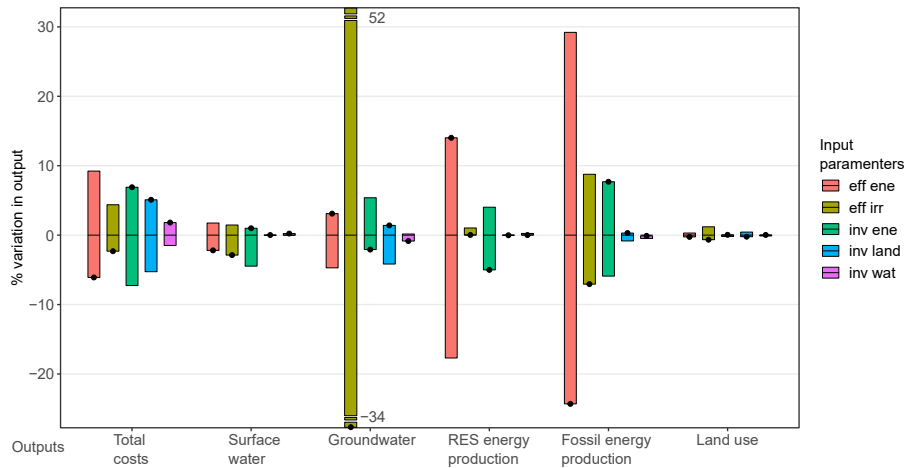


Figure 3.14: Changes in model outputs in response to a variation (-25%,+25%) of input parameters, namely power plants' efficiency (eff ene), irrigation technologies' efficiency (eff irr), investment costs of power plants and transmission lines (inv ene), irrigation and land management (inv land) and water distribution/treatment (inv wat). The outputs refer to average yearly values for basin's total system costs, surface and ground water withdrawals, energy production from renewable or non-renewable sources and land use for agriculture. The black dots show the outputs corresponding to +25% variation in inputs.

this context, scaling of the input-output coefficients to ensure fast solution times can be challenging for nexus models, because many cross-sector interactions require definition of input-output coefficient ranges covering multiple orders of magnitude. Future work may need to explore heuristics or other emulations as an alternative approach to classical optimization methods in order to integrate and optimize the vast amounts of geospatial data increasingly available and promoting the use of ultra-high resolution models for infrastructure planning.

From a hydrological perspective, some limitations of the current NEST formulation include the use of static land-use maps in the development of the water resource potentials. Dynamic land-use maps could be used in future work using the optimal solutions from MESSAGEix. An important next step involves downscaling water- and land-use results to the spatial scale used in the hydrological model, improving the visualization and analysis of results, as well as enabling spatially explicit calculation of water availability and demands to represent dynamic changes of water and land-use consistently across the two models in NEST. The assessment of groundwater could also be improved by including lateral groundwater flows and by changing the representation of aquifer recharge to a non-linear model. A major constraint in modeling hydrological processes is the linear formulation of the optimization model which limits dynamic representation of key sustainability indicators as continuous model decision variables (e.g., water quality).

Finally, assumptions on boundary conditions, such as costs of imports (of food, electricity or water), are important for simplistic assumptions (e.g. electricity imports in Figure 3.12). Future work could improve the representation of boundary conditions with supply-

cost curves or by linking with market models representative of the system outside the study area. Linking with global and regional integrated assessment models through the common commodity markets could improve the expected import-export response in NEST under scenarios of global change and explore different scenarios of basin self-sufficiency and resilience to external shocks.

### 3.5 Conclusions

The NExus Solution Tool (NEST) links a distributed hydrological model with a multi-sector infrastructure optimization model, the framework of which described in this paper in detail and applied to the Indus River Basin's energy, water and land systems. The framework is flexible and can be adapted to other regions of the world. NEST is designed to produce indicators relevant to the SDGs for water, energy, land and climate and to tap into the increasing volumes of geospatial data openly available through national inventories and the earth system modeling community. Comparing results for a business as usual scenario to one where multiple SDGs are enforced highlights the framework's capability to capture clear differences in the optimal investment portfolio and cross-sector interactions characteristic of the SDGs.

A key innovative feature of the NEST framework is the dynamic linking of the distributed hydrological and infrastructure optimization tools through a combination of geospatial analytics and scenario generation algorithms. The underlying CWatM and MESSAGEix open source modeling tools could be interchanged with other similar tools in use by national and basin planning agencies. NEST incorporates detailed representation of the EWL sectors and linkages among them. The representation of these sectors builds mostly on open global data, facilitating transferability to other geographical regions and the definition of Basin-Country-Units (BCUs) embedding geopolitical borders. Among these data, we make use of 3-D cross-sectoral resource flows and potentials, such as water availability, hydropower and renewable capacity. Additional local data can substitute or complement global data in empowering the model, facilitating calibration and validation and for building stakeholder trust.

The application of NEST to the Indus River Basin demonstrates the usefulness of such a tool in highlighting cross-sectoral policy impacts. An example are the implications of water treatment and recycling policies on energy consumption and the consequences for agriculture when attaining river environmental flow standards. Moreover, the delineation of the model into spatial units and the parametrization based on spatial data, enables results interrogation for single countries or BCUs within the basin boundaries. In this context, results for Pakistan and India are very different for water supply, electricity generation and agriculture.

Finally, critical areas for possible future improvement include: increasing spatial resolution and capability to deal with ultra-high resolution data; iterating MESSAGEix and CWatM to obtain a dynamic solution and better representing the non-linear interactions between groundwater and surface water; and, the improving assumptions at the geographical (and model) boundaries, for instance with cost curves or market models for food and electricity to represent the options of international trade.

### 3.6 Code availability

Code and processed data for NEST v1.0 is made available in Vinca et al., 2020 [84] (<https://doi.org/10.5281/zenodo.3625776>) . The associated development repository with continuous updates can be found at <https://github.com/iiasa/NEST>. The code and documentation for CWatM can also be found at: <https://cwatm.iiasa.ac.at>. Documentation and code of MESSAGEix is available at: <https://messageix.iiasa.ac.at>.

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## Chapter 4

# NEST case study: Transboundary cooperation a potential route to sustainable development in the Indus Basin <sup>1</sup>

### Preamble

To feed a rapidly growing population of 250 million, the Indus river basin in South Asia is one of the most intensively cultivated regions on Earth, highly water stressed and lacking energy security. Yet, most studies advising sustainable development policy have lacked multi-sectoral and cross-country perspectives. This chapter shows how the Indus countries could lower costs for development and reduce soil pollution and water stress, by cooperating on water resources and electricity and food production. According to this analysis, Indus basin countries need to ramp up investments to 10 billion USD/year to mitigate water scarcity issues and ensure improved access to resources by 2050. These costs could shrink to 2 billion USD/year, with economic gains for all, if countries pursued more collaborative policies. Downstream regions would benefit the most, with reduced food and energy costs and better water access, while upstream regions would benefit from new energy investments. Using integrated water-energy-land analysis, this study quantifies the potential benefits for novel avenues to sustainable development arising from greater international cooperation.

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<sup>1</sup>The body of this chapter was published in Vinca, A., Parkinson, S., Riahi, K. et al. Transboundary cooperation a potential route to sustainable development in the Indus basin. *Nature Sustainability* (2020) [62]. The material reproduced here is in line with the journal's copyright policy

## 4.1 Introduction

The Indus river basin is home to about 250 million people of which 61% live in Pakistan, 35% in India, 4% in Afghanistan and less than 1% in China [34, 63]. The basin encompasses the largest glacier area in Asia, covering over half a million square kilometers of mountains and providing, together with precipitation a precious water resource of about 287 km<sup>3</sup>/year [5]. Agriculture is the main economic activity, employing half the population to generate a quarter of the basin GDP [7]. With the most extensive irrigation canal system in the world, agriculture is responsible for up to 95% diversion of available freshwater in the basin [3, 30, 34].

Water scarcity has long been a critical problem, causing river dry-out in the Indus Delta, soil salinization and exploitation of groundwater; consequences that local administrations struggle to manage [14, 58, 68]. Agricultural practices, namely crop-type shift, crop rotation and water and energy-use efficient irrigation technologies can help reduce water stress, but require investment, education and organizational resources. Fresh water availability is also tightly related to the operation of hydropower plants and reservoirs, which must balance prescribed allocations of the Indus Water Treaty (IWT) with challenges in controlling seasonal droughts and floods [1, 45].

In the coming decades, population and water, energy, food and land demand will grow and climate change is already altering water availability, posing multi-dimensional challenges to development and sustenance in the region [6]. Additionally, political tensions related to resources within and across countries in the region further adds to the challenges.

River flow allocation to the six main tributaries of the Indus river between Pakistan and India is currently governed by the Indus Water Treaty, which is considered one of the most enduring international agreements for water resources [26]. But new challenges are now emerging. For instance, the IWT has provisions for dispute resolution and arbitration, but lacks trust-building mechanisms such as adequate data-sharing. As the impacts of climate change manifest, the issue of trust, allocation, and co-operation will gain new saliency for Pakistan and India in particular, but also for Afghanistan and to a limited extent, China [44, 45].

Other large basins around the world deal with challenges of large scale river diversions, food and energy security and international cooperation similar to the Indus basin (i.e. Nile and Ganges) [20, 31, 65]. The United Nation Sustainable Development Goals (SDGs) provides a framework to help governments and stakeholders tackle such challenges and inform policy intervention in individual sectors [9, 51]. However, climate, land, energy and water (CLEW) systems are highly coupled and qualitative methods need to be complemented with integrated approaches to understand and assess multiple cross-sector feedbacks [11, 22, 35].

CLEW studies and Indus-basin applied research to date have been mostly water-centric and with gaps in either energy, climate or land cross-sectoral feedbacks [4, 27, 52, 57]. Furthermore, current analyses focus on local or national solutions, without accounting for the transboundary nature of basins or the opportunities that international collaboration could offer in basin-wide solutions [67, 68].

Here, we present a quantitative scenario-based analysis that captures synergies and trade-offs within the water, energy, land and climate systems of the Indus Basin. Uniquely, we offer a perspective that focuses on the entire basin beyond national borders, exploring the possibility of joint investments in food and electricity production, as well as open market of shared resources. We show how improved cross-border cooperation on electricity, water trade and crop shift among riparian countries has the possibility of bringing economic, social and environmental benefits for regional development. Previous studies address transboundary cooperation issues between CLEWS sectors within the context of the Water Convention [16, 64]. However, Indus countries lack a framework to promote transboundary discussion on sensitive topics as shared-resource management.

The approach also advances existing research on cooperation issues, in which water and energy resources, electricity market and greenhouse gas (GHG) emission mitigation are considered as segregated areas with disparate scales in time and space (i.e. water conflicts involve riparian countries, energy and food markets are global) [21, 42, 54]. Connection between sectors are particularly evident in the Indus basin, for example linkages of virtual water involved in food trade, and flood management, food production and electricity generation that are linked through multi-purpose and nationally-administrated dams [15, 29]. This study explores what maybe be possible with transboundary cooperation in these sectors.

We use a modelling framework that links hydrological modelling with engineering-economic capacity planning (NEST [61]), and we study a set of long term scenarios to 2050 (see Table 4.1). By comparing the developments of water, energy and agriculture sectors in a Business-as-usual (*BAU*) pathway with a scenario with sustainability targets (*SDG*), we assess the investment gaps to achieve the targets, and we quantify several associated socio-environmental co-benefits. The investment gap for the basin (summing new investments in some sectors and disinvestment in others) amounts to only 13% of total annual expenditures. In the case of the *SDG* scenario, we investigate the additional benefits of increased cooperation (*SDG-coop*). The *SDG-coop* scenario explores the pathways to achieve the same targets as the *SDG* scenario with specific cooperative mechanisms: cross-border electricity trade driven by electricity market prices; basin-wide food market to meet demands, as opposed to domestic production assumed in the *BAU* and *SDG* scenarios; and river flow allocation to guarantee environmental flow targets, water access and lowest cost for agriculture production across the whole basin.

We find that cooperation, in all the analyzed scenarios, is the most beneficial solution

to all Indus countries, even when taking into account uncertainties through a sensitivity analysis. Therefore, it would be worth for regional policy makers to explore and pursue more cooperative strategies.

## 4.2 Towards Sustainable Development Goals (SDGs)

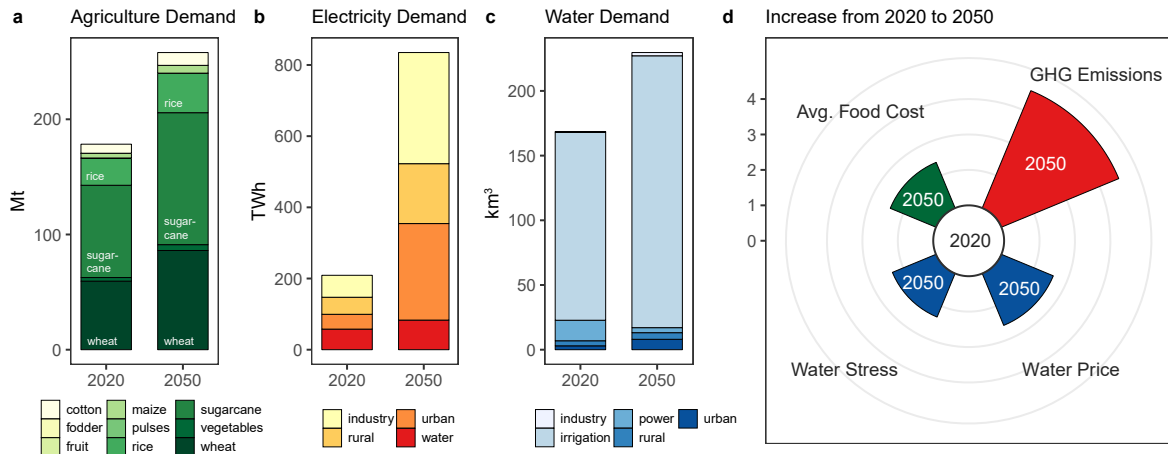


Figure 4.1: Expected Indus basin demands growth from 2020 to 2050 in, agriculture products (a); electricity (b) and water (c). X-fold increase from 2020 to 2050 in cumulative GHG emissions, freshwater prices, water stress (as calculated in Figure 4.2, and average food cost (d).

Although all nations committed to the SDGs in 2015, first we consider the case that might occur in absence of progress on the SDGs – Business As Usual. Currently, about 55% of electricity in the basin is produced from fossil fuels, hydropower production is underexploited and renewable energy generation is less than 5% of total production [40, 61]. We estimate a fourfold rise in electricity demand in the basin by 2050 compared to 2020 driven by population growth and improved electricity access. The *BAU* scenario with a continuation of historical trends and current energy policies (expansion of hydropower and phase out of coal, Supplementary Fig. C.3), would result in a fourfold increase in GHG emission related to oil and gas consumption, augmenting the regional contribution to climate change (Figure 4.1b and d). Simultaneously, based on FAO projections, demand for agricultural products will rise by 45% between 2020 and 2050 (Figure 4.1a). In the absence of water efficiency measures in agriculture, the withdrawals will exceed 220 km<sup>3</sup>/year (versus the current 180 km<sup>3</sup> [34]), and water prices, food production costs and water stress will more than double (Figure 4.1c and d). The regions of Punjab (both Indian and Pakistani) and the lower regions (Sindh in Pakistan), which already struggle with water scarcity [14], would overexploit renewable water sources by up to 250% in 2050 (Figure 4.2). This poses challenges not only to farmers, but also to urban areas that will

suffer from reduced water access [2]. Improvements in irrigation efficiency with subsidies to drip, sprinkler and smart monitoring technologies can significantly reduce water losses related to unproductive evaporation. Water consumption can be consequently lessened if irrigation efficiency policies are supported by withdrawals regulation [19, 50]. In addition, achieving the SDG targets will entail improved clean water and sanitation accessibility for about 127 Million people [8].

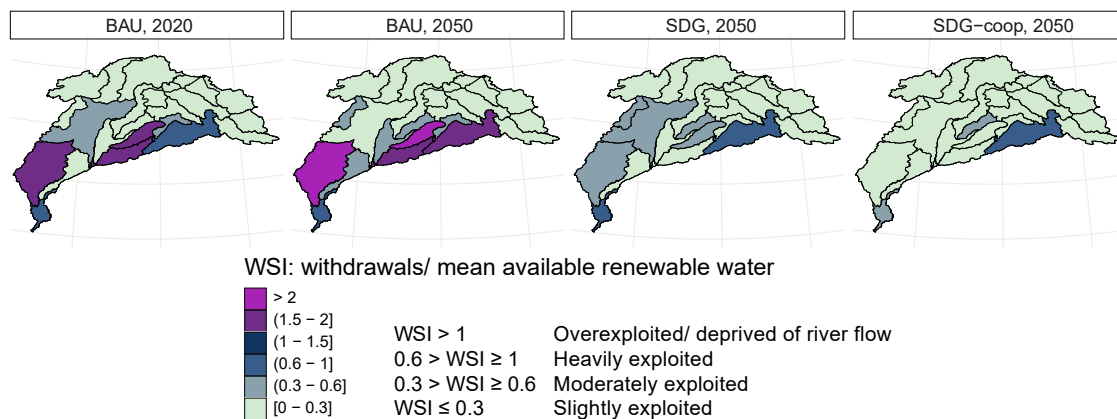


Figure 4.2: Maps of annual Water Stress indicator (WSI) in the Indus basin in the *BAU* in 2020 and 2050, and values for 2020 for *SDG* and *SDG-coop* scenarios. A map with region's names is shown in Supplementary Fig. C.1. Basin delineation from HydroSHEDS [24]

To meet and sustain progress on the SDGs through to 2050, will mean coping with the rapid increase of access to limited resources and the growing demands across all sectors. Thus, we defined a set of ambitious targets for each sector (summarized in Table 4.1), based on scientific information and informed by direct consultation with local stakeholders, along with co-producing a compatible modelling framework (see Supplementary Methods, Section C.4). Starting from the most urgent problem of controlling water withdrawals –to ensure domestic water access and minimum river flows required to protect the rich ecosystem of the Indus Delta [58]– we constrain future agriculture withdrawals to not exceed current levels (about 150 km<sup>3</sup> per year). We set minimum environmental flow requirements (in average 10 km<sup>3</sup>/year, [18]) and set a reasonable goal of 95% access to sanitation in the whole region [8].

We characterized the remaining targets by consulting local experts (see Supplementary Methods, Section C.4), setting at least 50% deployment of efficient irrigation, and 90% carbon-free electricity generation, this would entail incentivizing decentralized electricity production with solar PV or mini-hydro to reduce energy poverty [13].

Pursuing these targets requires a set of long-term measures, namely increased investment in efficient irrigation; crop relocation within countries to maximize yields while minimiz-

ing water consumption; expansion of piped water distribution and increase of wastewater recycling; shift from fossil fuel-based electricity generation to more distributed renewable sources; and management of large storage to concurrently meet energy demand and minimum river flow requirements.

The net basin cost change (investments and operational costs) induced by these measures amounts to 10 billion USD/year (see cost assumptions in Methods and Supplementary Tables B.3 and B.4). This is 13% more than the overall system costs of 75 billion USD/year in Business-as-usual (as a reference, this is one quarter of Pakistani GDP in 2017, which is for 80% included in the basin [17], Figure 4.3a).

In particular, Pakistan needs to invest 4 and 0.6 billion USD/year in water distribution and treatment respectively. Internal crop relocation could save the country 3 billion USD/year while reducing water withdrawals. The energy measures would require a shifting 4 billion USD/year in oil and gas to 7 billion USD/year investments in more distributed renewable energies, which could save more than 1 billion USD/year in electricity transmission. India would need to invest in water distribution and treatment (1.3 and 0.4 billion USD/year respectively) and about 3 billion USD/year in efficient irrigation technologies, but require only marginal changes in the energy sector. Afghanistan requires similar investment trends, although proportionally smaller, namely 313 and 84 million USD/year in water distribution and treatment, but also 540 million USD/year in renewable energy, which is 40 % of the total cost increase in the region (Figure 4.3b).

A number of socio-environmental co-benefits are direct consequence of new measures and investments (Figure 4.3c). Increased irrigation efficiency and optimal crop shift lower irrigation surface and groundwater use per ton of crop product in 2050 by 30%. Land pollutants drop by 40% due to reduced cultivated land and fertilizer use. Investments in water distribution and treatment policies enable sanitation access to 127 million people by 2050 and increase availability of water that can be re-used for domestic purposes. Water saving measures help reduce river depletion and water stress across the whole basin (Figure 4.2). The shift from fossil-fueled electricity to renewable sources has clear impacts on air pollution and GHG emissions (85% and 65% reduction respectively), as well as on water consumption for power plant cooling (Figure 4.3c).

Some socio-economic benefits are not directly embedded in our modelling framework, for example the positive effect of decentralized electricity production with solar PV or mini-hydro on energy poverty [13]. Therefore, we can state that some advantages of achieving sustainability goals may be here underestimated. Also, socio-environmental benefits are heterogeneous across countries. Extended Data Fig. 4 shows overall positive trends across all Indus countries and indicators when achieving the goals in the *SDG* scenario.

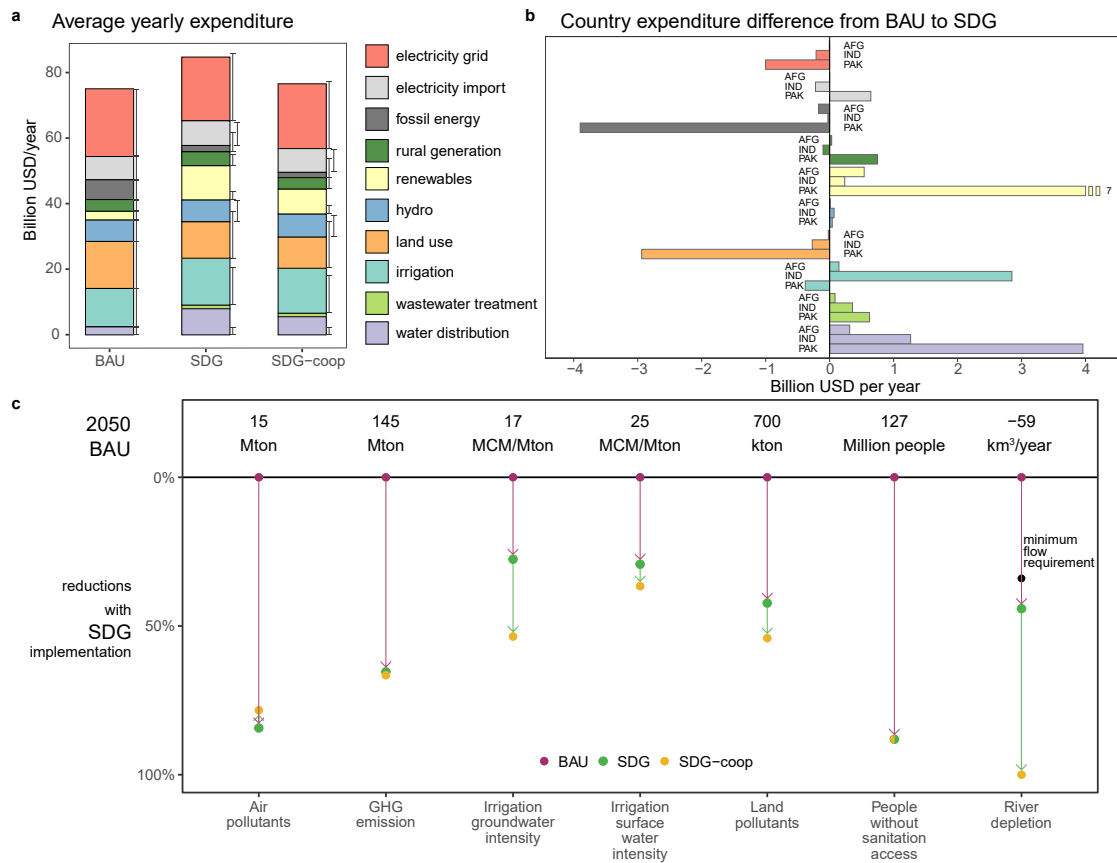


Figure 4.3: Total basin average yearly costs (investments + Operational and Maintenance), USD2010 are used in this analysis. Sectors: electricity transmission and distribution; domestic electricity import from regions not included in the basin, fossil-fueled energy generation; rural diesel or solar energy production; solar, wind or biomass generation; large and small hydropower; land cost, machinery and fertilizers; irrigation technologies (flood, drip, sprinkler and canals); wastewater treatment; water extraction, diversion and distribution. Error bars show *BAU* values (a); Total cost changes between *SDG* and *BAU* scenario by country, changes refer to areas within the basin boundary (b); Sectorial socio-environmental benefits of *SDG* and *SDG-coop* scenarios with respect to *BAU* in 2050. The 0% axis and labeled values refer to *BAU*, arrows and other dots represent the reductions for other scenarios. Indicators: cumulative air pollutants' emissions from electricity generation and land use ( $\text{SO}_2$ ,  $\text{CO}$ ,  $\text{NH}_3$ ,  $\text{VOC}$ ); cumulative  $\text{CO}_2$  equivalent emitted; average surface and groundwater use per unit of crop product; cumulative release of pollutants from fertilizers ( $\text{K}_2\text{O}$ ,  $\text{N}$ ,  $\text{N}_2\text{O}$ ,  $\text{P}_2\text{O}_5$ ,  $\text{VOC}$ ); number of people without access to sanitation and clean water; difference between lowest and highest discharge river level across scenarios (c).

Sector/area	BAU	SDG	SDG-coop
Water treatment and access to sanitation (SDG 6.3)	Projection of current rates with GDP growth	~50% water treatment	~95% access to sanitation
Water efficiency (SDG 6.6)	BAU constrained by water availability (287 km <sup>3</sup> /year) and seasonality	Constraint future agriculture water withdrawals to historical levels	
Environmental flows	BAU	Minimum Indus river level in Delta area of 46 MCM/day (Kharif) and 12 MCM/day (Rabi)	
Agriculture (SDG 2.4)	Continuity of flood being the main irrigation technique	~50% of agriculture water use from efficient irrigation	
Energy & GHG emissions (SDG 7.2 and 13a)	National Determined Contributions (NDCs) to Paris agreement	NDC; 90% carbon-free electricity generation in 2050; coal phase out	
Electricity trade	National electricity transmission within and outside the basin border	National electricity transmission within and outside the basin border	Electricity trade market among riparian countries
River flow allocation	In line with the Indus Water Treaty	In line with the Indus Water Treaty	Improved allocation alternative to IWT to optimize other sustainable objectives
Agriculture production/trade	National production; historical crop allocation	National production and crop relocation to maximize yields and minimize water withdrawals	Basin-wise production and crop relocation to maximize yields and minimize water withdrawals

Table 4.1: Scenario assumptions for *BAU*, *SDG*, and *SDG-coop*, in addition to common assumptions for all scenarios, Supplementary Table C.1.

### 4.3 Role of cooperation

From a systemic point of view all countries gain when pursuing the cooperation strategies identified in this study. Total basin costs for achieving the targets in the *SDG* scenario would be 9% lower (8 billion USD/year less) if cooperation on energy, agriculture and water management was implemented. Thus, the additional system costs for sustainability targets would be only 2 billion USD/year above *BAU*, instead of 10 billion USD/year (Figure 4.3a, see Extended Data Fig 3 for country differences). Overall, the changes embedded in the cooperation scenario clearly lead to environmental and efficiency benefits. Surface and groundwater intensity in irrigation, as well as land pollutants and river depletion will further reduce compared to the *SDG* scenario, augmenting the benefits of achieving sustainability targets (Figure 4.3c). On the other hand, the improvements in energy-related indicators, such as GHG emission and air pollutants, remain similar with or without cross-country cooperation.

The electricity generation portfolio in 2050 and electricity trade between countries suggests that about 66 TWh of solar energy produced in lower Pakistan would be replaced by less costly electricity from hydropower, geothermal and solar PV in India in the *SDG* and *SDG-coop* scenarios (Figure 4.4a). Also, abundant hydroelectric energy available in upper Pakistan, normally only used domestically, is provided to the nearest regions of Afghanistan and India in the *SDG-coop* scenario. This might pose challenges for Pakistan energy security, especially in case of climate change affecting water resources, and will be

further explored with sensitivity cases. This shift would also require new investments in energy production in the Indian part of the basin. As a consequence of these changes, and accounting for the different average expenditure net of trade costs ( $inv + O\&M + \Delta trade$ ) in the two scenarios, Pakistan would save 5 billion USD/year. Electricity production costs for India would increase of 1.3 billion USD/year, but the country would attract new investments and build a more robust power sector.

Enhancing cross-border food trade reveals that if production of 23 Mt of wheat and 16 Mt of rice from lower Pakistan is shifted to India, where water costs are lower, there would be overall improved utilization of water (Figure 4.4b). This strategy would result in trade-net savings for all the riparian countries, with Pakistan and Afghanistan benefiting the most (1750 and 300 million USD/year respectively) and very marginal savings for India. This also raises political acceptability concerns addressed in more detail in the following section.

From a water conveyance perspective, the alternative water allocation resulting from the above-mentioned production shifts (which differs from IWT allocations, as in Figure 4.4c) could save significant investment in Indian canals than internally redistribute water to match domestic demand (overall more than 2.4 billion USD/year savings for India). At the same time, this would reduce water costs for the other riparian countries, allowing significantly higher inflows to Pakistan and reducing water stress in the whole basin (Figure 4.4c and d).

In summary, taking a transboundary, cooperative approach that relies on increased electricity and food production on the upper parts of the basin, is demonstrably a win-win strategy: being both cost effective and delivering environmental benefits across the board (Figure 4.4d). From a country by country perspective, Pakistan and Afghanistan see an overall economic benefit of cooperation across all sectors of about 7.75 and 0.43 billion USD/year respectively (around 15% of total cost to achieve SDG targets for both countries). But India could also save 1.15 billion USD/year (3.2% of Indian annual costs) by redistributing costs from water distribution to energy production (Figure 4.4d). Also in this case, the actual economic benefits would be higher than what estimated here, if the beneficial environmental impacts were to be monetized. Finally, we also notice that the *SDG-coop* scenario yields improvements in the environmental indicators for the entire region and across all countries, except for GHG emissions and land pollutants in India related to cooperative shift in energy and food production (Extended Data Fig 4).

## 4.4 Discussion

This study demonstrates that cross-boundary cooperation among riparian countries in the Indus basin could enable sustainable development at 9% lower costs than without coop-

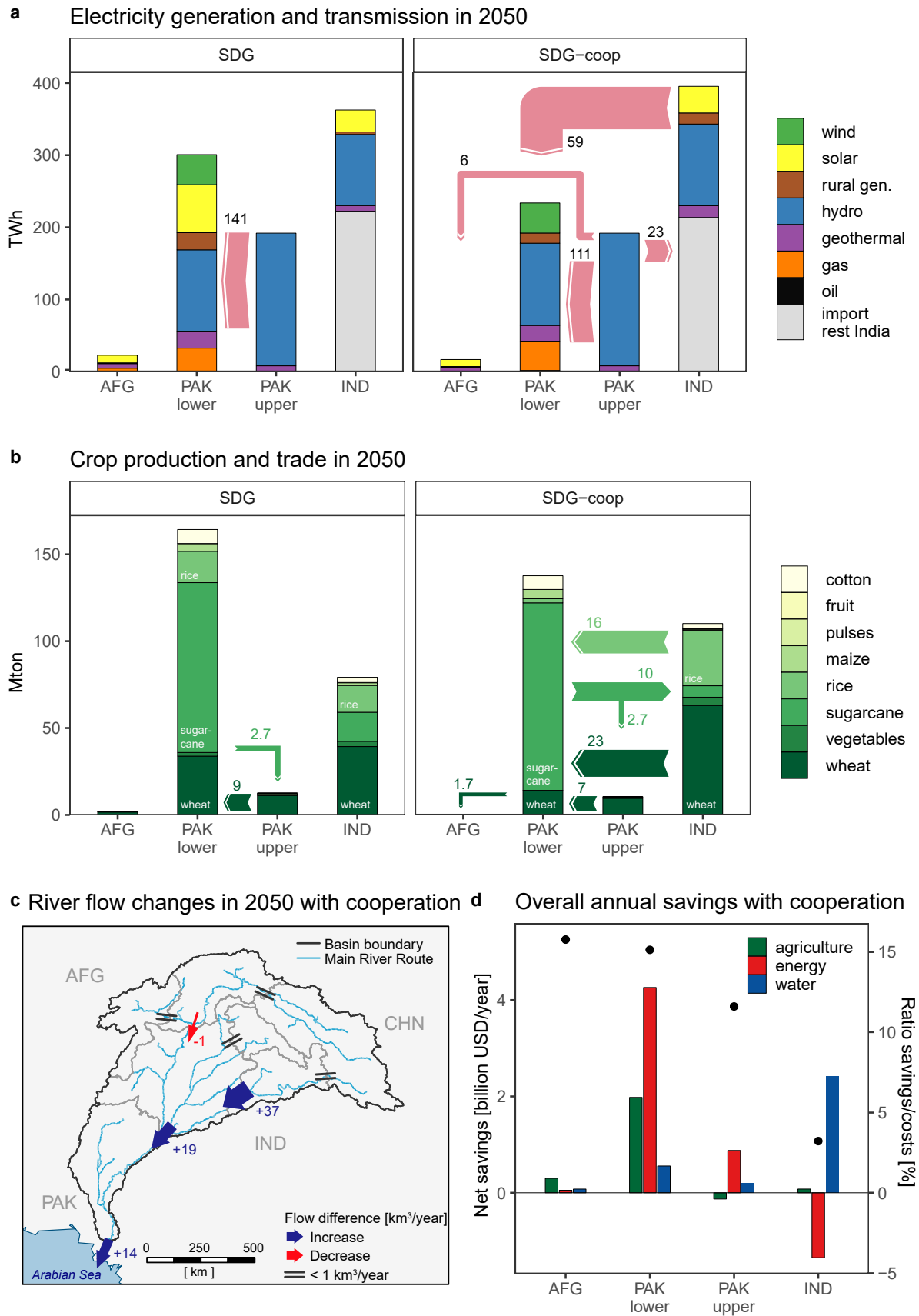


Figure 4.4: Comparison of electricity generation and transmission (pink arrows) in 2050 in by region for *SDG* and *SDG-coop* scenarios (a); Comparison of agriculture production and trade (b); Differences in river flow changes in 2050 in the *SDG-coop* scenario (c); Sectoral annual savings (cost ± trade) implied with cooperation (bars) and the ratio savings/costs per each region (black dots, right axis) (d)

eration and with additional socio-environmental benefits, primarily lowering water stress in the regions of Kabul, Punjab and Sindh from heavily-moderately to slightly exploited water resources. The various benefits are of major importance for policy making and incentive planning. All can gain, if the management of shared resources and investment planning would go beyond country-centric visions.

While water agreements are currently in place and electricity trade plans have also been discussed between Indus countries [53], the idea of large de-localization of food production might be politically difficult, since policy makers are mainly focused on food self-sufficiency and security. A cooperative scenario without basin-wide food market cooperation (*SDG-NL-coop*, Supplementary Table C.4) is still cheaper than the *SDG* scenario, albeit only 7%, instead of 9% and, at the same time, would lead to more evenly distributed savings among riparian countries, see Supplementary Tables C.2 and C.3. We tested an additional cooperation scenario without basin electricity market (*SDG-NE-coop*). This could be the case in which downstream provinces were reluctant, due to climate uncertainty, to de-localize solar energy production in favor of importing hydro-electric energy from upstream regions or neighboring countries [46]. We notice the same changes in basin cost as in the *SDG-NL-coop* scenario, but with different distribution between regions.

Similarly, the Business-as-usual scenario with multi-sectoral cooperation (*BAU-coop*) but in the absence of sustainable development policies, has economic advantages even more significant than for the *SDG* scenario, with about 12% cost reduction and net savings ranging between 6% and 20% between countries (Supplementary Table C.2).

The results depend on climatic parameters for which there is a high uncertainty such as precipitation patterns and glacier melt. These uncertainties propagate to the prediction of water trends in the coming decades [36, 38]. For the Indus basin, climate change impact on water availability is particularly important but and yet highly uncertain [25]. Based on the knowledge that 60-70% of discharge in the Indus originates from mountain snow or glacier melt [10], we test the system robustness to a hypothetical extreme scenario of reduced water availability with (*SDG-GM-coop*) and without cooperation (*SDG-GM*, Supplementary Fig. C.2). A system robust to extreme reductions in melt-water availability requires additional cost to achieve the SDGs (+7 billion USD/year). Nevertheless, cooperation can still help reduce costs by 13% (Supplementary Table C.2). Climate change uncertainty in the Indus basin is a complex topic that requires further analysis and testing of a broader range of sensitivity cases.

Although several policy limitations have been considered to explore main uncertainty dimensions (see also the parametric sensitivity analysis in Supplementary Discussion Section C.3), possible implementation requires further assessment and planning. In particular, in a transboundary context, large scale crop shift, while not a novelty in Punjabi and Indian agriculture [37], have implications on employment, food market and land use change which need to be reflected in any negotiation process. Socio-cultural aspects such as employ-

ment, wages and education –with the exception of water access and energy poverty level– are not included in the modelling framework and deserve ad hoc analysis to complement the economic results of this paper.

In conclusion, increasing cooperation around water allocation, energy and food trade appears to always be cost optimal and also environmentally beneficial than non-cooperative strategies. This finding is robust to various levels of cooperation, future scenarios and climatic uncertainty, as well as to changes in crops water requirements and crop yields (see sensitivity analysis, Supplementary Tables C.2 and C.3). Cooperation has the potential to usher important changes in the economic balances and relationships between countries. In this case of the Indus basin, our results show for example how increasing trade and sharing of resources have the potential to improve production while also providing higher river flow to regions that suffer water scarcity for the benefit of all. Policies paving the way for such cooperation should be pursued even with limited crop shift that are politically and socially challenging to implement.

## 4.5 Methods

This analysis is done with the NExus Solution Tool (NEST), an integrated model for Water-energy-land-climate systems analysis under global change. The framework links a distributed hydrological model (CWatM, [12]) to an engineering-economic resource supply planning and capacity expansion model (MESSAGEix, [23]), both capturing the historical period and a future time horizon. A detailed and comprehensive description of the model, data requirements and online availability is provided in Vinca et al. 2020 [61]. A brief summary of the main framework is as follows.

The Community Water Model (CWatM) provides a grid-based representation of terrestrial hydrology, applied in this instance at a spatial resolution of 5 arc-minutes (grid-cells approximately 8 km wide near the equator) and daily temporal resolution. The model can simulate either naturalized streamflow or streamflow impacted by human activities including reservoirs, irrigation demand, and water withdrawals and return flows by industrial and domestic sectors. Sectoral coverage is harmonized between CWatM and MESSAGEix so that demand profiles can be translated between models. CWatM is initially run under baseline conditions to inform MESSAGEix of dynamic constraints on water availability, hydropower potential and irrigation water requirements.

MESSAGEix is a bottom-up systems optimization model that includes resource consumption and capacity limitations at the technology level. MESSAGEix is based on the original MESSAGE model that has been developed and applied widely over the past three decades to analyze scenarios of energy system transformation, both globally and in different geographic regions, under technical-engineering constraints and political-societal consider-

ations, e.g., [32, 39, 47, 59]. Each technology modeled in MESSAGEix is defined and characterized by input/output efficiencies (rate of commodity consumptions/production during technology operation), economic costs, and environmental impacts (e.g., greenhouse gas emissions, water consumption, etc.). A technology can represent any process that involves resources and commodities, such as power production, energy consumption and irrigation, but can also represent natural systems such as rivers, aquifers and crops. MESSAGEix minimizes the total cost for system capacity and operation over a future time period while meeting exogenous and endogenous demands and technical/policy constraints, as a deterministic inter-regional and inter-temporal linear programming (LP) problem:

$$\min f(\mathbf{x}) = \sum_{r,t} \mathbf{c}_{r,t}^T \mathbf{x}_{r,t} \delta_t ; \mathbf{A} \mathbf{x} \geq \mathbf{b} \quad (4.1)$$

where  $\mathbf{x}$  is the solution vector containing the capacity and operation of any water, energy or agriculture technology in the time period  $t$  and region  $r$ . Economic costs are described in the cost coefficient vector of the objective function  $\mathbf{c}$ . The discount rate associated with future cash flows is represented by  $\delta$ .  $\mathbf{A}$  right-hand side constraints vector  $\mathbf{b}$  include the supply-demand balances, capacity limits, technology retirements and capacity additions, and all constraints that express specific policies.

By linking the inputs and outputs of individual processes, energy, water and land decisions can be represented as a single system using the MESSAGEix modeling scheme. Thus, decisions impacting system design and operation over the planning horizon are made understanding the nexus interactions, and will adapt the transformation pathways for each sector to avoid constraints and reduce trade-offs from the perspective of the objective function. Moreover, MESSAGEix supports spatially-distributed systems modeling using a node-link representation, where commodities can be transferred between nodes based on the definition of dedicated technologies. It is therefore possible to explicitly represent the interplay between up- and downstream water users.

For implementation in MESSAGEix, the Indus River Basin is delineated into 24 Basin Country Units (BCUs) using the basin and country administrative boundary datasets. This is a common method in spatial water assessment, however it is worth noting that different spatial aggregation choices, in particular those taking into account agro-ecological zones, might impact results [49]. Further disaggregation into the agro-ecological zones is not pursued in this case because of limited spatial variability in crop potential within the delineated BCUs. The planning horizon considers investment periods spanning 2020 to 2050 in 10 year time steps, and 2015 is parameterized as the base historical year (i.e., the initial starting point). Monthly sub-annual time steps are considered. However, a different temporal scale could be used. For instance a daily representation of energy demand and supply could help capture renewable energy variability, but would on the other hand significantly increase running time.

The NEST model adds to a number of similar CLEW models that have been applied to river basins for policy assessment [16, 28, 33, 43, 48, 56, 66]. Among these models, only few integrate multiple sectors in one optimization framework, instead of soft linking different optimization tool for each sector [56]. NEST stands out as one of these models that also includes spatial explicit river flow representation, essential to assess upstream and downstream river basin dynamics. The representation of CLEW sectors builds mostly on open global data, facilitating transferability to other geographical regions and the definition of Basin-Country-Units (BCUs) embedding geopolitical borders. Additional local data can substitute or complement global data in empowering the model, facilitating calibration and validation and for building stakeholder trust. A detailed representation of alternative water options, as well as standards of water sanitation is a feature mostly missing in the above-mentioned CLEW models.

Critical areas for possible future improvement include: testing different spatial resolutions and capability to deal with ultra-high resolution data; iterating MESSAGEix and CWatM to obtain a dynamic solution and better representation the non-linear interactions between groundwater and surface water; and, improved assumptions at the geographical (and model) boundaries, for instance with cost curves or market models for food and electricity to represent the options of international trade. Static cost and efficiency assumptions would ideally also be replaced by reasonable projection to capture system learning and improvements. Finally, as mentioned in previous sections, a thorough discussion of socio-cultural policy and implementation aspects deserve assessment with ad hoc methods, as these aspects are often not well addressed in IAMs.

#### 4.5.1 Cost calculations and assumptions

The sectoral investment and Operational & Maintenance costs (in USD2010) discussed in this analysis are calculated in MESSAGEix as multiplication of investment, fixed and variable unit cost by the capacity and utilization factors of each technology/process, which are decision variables of the optimization model.

More details on MESSAGEix formulas are available in [23], while a comprehensive description of all the technologies and processes in NEST is reported by [61]. From this paper, the main cost assumption of all the technologies represented in the model are reported in Supplementary Tables B.3 and B.4.

The mean annual costs presented in this article and Figure 4.3a and Supplementary Table C.2 are the average between 2020 and 2050 of total annual investments and O&M costs.

The net savings presented in Figure 4.4d and Supplementary Table C.3 refer to the total cost summed with the net costs (or earnings) of food products and energy trade. The saving is then the difference in this value between non-cooperative and cooperative scenario.

The associated ratio between the total saving and the total cost in the non-cooperative scenarios gives an idea of the relative economic benefit.

#### 4.5.2 Water-energy-land indicators

##### Water Stress Index (WSI)

The annual Water Stress Indicator (WSI) compares the overall withdrawals (from any water source) to the Mean Annual Runoff (MAR), which includes the total freshwater inflow. This gives a sense of sustainability of the withdrawals and reliance on non-renewable sources of water [55].

$$WSI = \frac{Withdrawals}{MAR} \quad (4.2)$$

##### Average Food Cost

The indicator shown in Figure 4.1d in incremental terms is the annual mean of rice and wheat prices for the whole basin. These are calculated as average of regional prices weighted on the regional production (both outputs of the supply demand balance of the optimization model).

##### Water Price

Figure 4.1d shows water price in incremental terms, this is calculated as the yearly average basin price as output of the model freshwater supply and demand balance.

##### Greenhouse Gas Emissions

The GHG emission indicator displayed in Figures 4.1d and 4.3c represent the basin cumulative GHG (CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O) emission from 2020 in CO<sub>2</sub> equivalent terms for the electricity sector and land use.

##### Air Pollutants

The Air Pollutants indicator assesses the basin cumulative air pollutants' emissions from electricity generation and land use (SO<sub>2</sub>, CO, NH<sub>3</sub>, VOC) from 2020.

##### Irrigation Groundwater and Surface Water Intensity (IWI)

The IWI indicators show the surface and groundwater withdrawals use per unit of crop product, as annual mean of values from each region:

$$IWI_{s,g} = mean \left( \frac{IW(r)_{s,g}}{tot\_prod(r)} \right) \quad (4.3)$$

where  $IW(r)_{s,g}$  for region  $r$  is the overall annual irrigation water withdrawal by source;  $tot\_prod$  is the sum of all crop regional production  $s$  and  $g$  refer to surface and groundwater.

### **Land Pollutants**

The Land Pollutants indicator assesses the basin cumulative release of pollutant ( $K_2O$ ,  $N$ ,  $N_2O$ ,  $P_2O_5$ ,  $VOC$ ) during agriculture activity from 2020 average.

### **People Without Sanitation Access**

Number of people in the basin that do not have access to sanitation in their household in a specific year.

### **River Depletion**

The River Depletion indicator in Figure 4.3c shows the difference between the minimum river flow level (basin annual mean) and river flow of other scenarios, including the reference point of the minimum environmental flow requirement. The reported value is the largest difference.

## **4.5.3 Modelling scenarios assumptions**

The future scenarios considered in this article represent the technological and earth system transformation pathway under given input data assumptions. In line with the scenario narratives framing climate (Representative Concentration Pathways (RCP)) and human development trajectories (population, GDP, demand profiles for specific sectors from the Shared Socioeconomic Pathways (SSP)) for this analysis we consider SSP2, also called 'middle of the road' and RCP 6.0, which consider warming in 2100 up to three Celsius degrees [41, 60]. Other important assumptions in common among all scenarios are listed in Supplementary Table C.1.

## **4.5.4 Full results consultation and visualization**

The results presented in this article explore only a small portion of the model outputs from our scenario analysis. The ISWEL Nexus Basin Scenario Explorer hosted by IIASA provides access to a database of all variables of interest, defined for each scenario and broken down to sub-basin catchments spatial resolution (<https://data.ene.iiasa.ac.at/nexus-basins/>). The Scenario Explorer is a versatile open access tool to browse, visualize and download data and results. User can freely create a private workspace where customized plots can be saved and shared.

## 4.6 Data availability

Processed input data used for model runs that support the findings of this study, and associated model code, is publicly available online (in the .RData format) at <https://github.com/iiasa/NEST>. Raw data availability is in some cases subjected by third party restrictions. Data are however available from the corresponding author upon request, upon third party permission, when applies.

## 4.7 Code availability

Model code updated to the scenarios described in this publication is also available for download at <https://doi.org/10.5281/zenodo.4037884>

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# Chapter 5

## Conclusions

Water, energy, food and eco-systems are all interconnected with each other and with the climate system. The formulation of policies to face the coming challenges of increased population and climatic variability needs to take into account climate, land, energy and water (CLEW) interactions. This dissertation presents a new modelling framework (NExus Solution Tool) that links a hydrological model to a newly developed optimization model with multi-sector representation of long-term energy, water and food demand, and supply chains. The model, applied here to the Indus River basin, can address policies related to electricity generation, water allocation and access, crop production and irrigation in an integrated way. The results show that an integrated approach yields different solutions in terms of water allocation, electricity generation and type of crops and irrigation when multi-sector policies are considered simultaneously rather than individually. The experience of developing and using NEST with several stakeholders, together with a comparison of other recent CLEW models, seek to shed light on the current limitations and potential of state-of-the-art nexus modelling, particularly in relation to spatial and temporal scales.

### 5.1 Key insights and contributions

The main outcomes of this thesis are a newly developed framework, the NExus Solutions Tool and novel insights into the potential of transboundary cooperation in attaining sustainability goals more cost-effectively. The framework links a high-resolution distributed hydrological model to an engineering-economic modeling scheme that integrates multi-scale decisions impacting long-term EWL transformations.

- The application of the NEST model presented in the thesis shows an example of co-development with stakeholders, that helps define and prioritize features to be developed, and complemented data collection with local datasets. High-resolution spatial data have been used when available (hydrology, crops and variable renewable energies), together with downscaling of global or national data.

- NEST innovates by integrating CLEW sectors, spatially resolved river and canal routing and electricity transmission lines, wastewater technologies and water access indicators under a unique framework.
- NEST can be used to address long-term planning requirements to achieve environmental flow standards or water withdrawal limitation policies; targeting location for the best type of irrigation and crops, or renewable energy to meet increasing demands.
- The application of NEST offers a novel perspective on transboundary cross-sector cooperation in the Indus basin, which has never been studied in the region, showing that:
  - Multi-sector analysis is needed to thoroughly assess implications of SDG targets, even when only related to a single sector (e.g. river water allocation)
  - The countries in the region would need to increase their annual investments in renewable energies, irrigation technologies and improved water distribution by 13% until 2050 to achieve local WEL SDGs.
  - This cost would reduce by 9% if countries cooperated on sharing water resources, and electricity and food market. In addition, cooperation would guarantee other benefits, such as better air and soil quality, reduced water stress and sufficient environmental flows.

Developing a new CLEW model triggered thinking on the relation between model scale and scope with the level of detail of data (e.g. spatial and temporal resolution) and sector representation. Particular attention and effort were also given to making NEST open-source, accessible and supported by a graphic interface to explore results. From this experience, combined with the literature review and a detailed comparison of CLEW models, some insights emerged on technical limitations, research gaps and accessibility of state-of-the-art models.

- From the methodological point of view, soft-linked modules might have a long iteration time and might suffer from the simplification of the data often reduced to one or two variables (e.g. price) and loss of important information during the exchange between models. On the other hand, integrated models, tend to simplify some nexus interlinkages and/or the sectoral representation; although continuous progress in computing power slowly help overcome this limitation.
- Boundary conditions are a critical source of uncertainty for country, basin (i.e. in NEST food and electricity import and exports) and local scale models.
- The scale impacts the level of detail. Local models tend to neglect or simplify interactions with climate and focus only on the main nexus feedbacks relevant to the

system. At the basin and national scale, all CLEW interactions become relevant and models tend to include the largest number of interconnections and allow for detailed spatial representation of water and land systems. In global models complexity trade-offs that complicate the modelling are necessary to make the models tractable. Only a few teams can have the necessary coverage of expertise, data and computing power to build and run such large integrated models.

- Major gaps in sectoral implementation are in hydrology assessment (particularly groundwater), in the crop yield change in response to climate change, and the primary energy linkage to natural resources. The water-energy nexus is represented quite adequately in most of the models.

## 5.2 Future directions

Concerning the NEST model, critical areas for possible future improvement include: increasing spatial resolution and capability to deal with ultra-high resolution data; iterating MESSAGEix and CWatM to obtain a dynamic solution and better representation of the non-linear interactions between groundwater and surface water; and improving the assumptions at the geographical (and model) boundaries, for instance with cost curves or market models for food and electricity to represent the options of international trade. The representation of the land system could be improved by linking on the one hand to food production chain and dietary choices and, on the other hand, to a better assessment of land allocation, including forestry and other types of land. The optimization criteria of the objective function, currently cost minimization, could be modified to include other dimensions, such as water availability and access to resources, possibly in a multi-objective approach.

In the context of the Indus River Basin, improvement of climate change impact estimates on water availability is particularly important. By interacting with stakeholders and scientific partners, it became evident that the resolution and scope of NEST needed to be improved in order to address some specific questions. For instance, farmers' behavior in response to increasing irrigation efficiency or water allocation restriction could not be simulated and it might need consideration when developing policies. In addition, the spatial resolution adopted in the case study was adequate to address national and cross-boundary challenges, but did not allow stakeholders to corroborate results at the urban or sub-provincial level. To improve the relevance of our findings, spatial resolution could be improved in future applications, and the feasibility of scenario results (i.e. crop shift plans) could be carefully examined with local stakeholders.

Both global models and those focusing at smaller scales are increasingly reaching higher levels of detail in representing CLEW systems and cross-sector interlinkages. Parallel

efforts should be directed to the reduction of existing uncertainties related to geographical boundary conditions, the interaction between sub-modules, and downscaling, particularly relevant at the national/basin scales. One way to achieve this could be improving public high-resolution databases. Most models dealing with population growth and economic projections refer to the Shared Socioeconomic Pathways (SSPs) [3]. Nonetheless, there is a need for high-resolution database for SSP assumptions that cover all water, energy and land sectors that can be formally approved/agreed upon and referenced by all researchers working in this area. This would prevent divergence in important data assumptions and could promote CLEW model inter-comparison.

Other socio-economic aspects need to be better incorporated or connected to CLEW models to improve assessment of the feasibility and impact of policies and understanding of the social implications of future investments. Stakeholder engagement during scenario development and results analysis is useful to validate scenarios analyzed with CLEW models. However, further links with social-science experts, ABM representing household-companies-governments interactions, or finance risk models would be assets to be explored in the future to make CLEW models more comprehensive. As mentioned previously, the macro-economic assumptions are often simplified or do not include emerging discussions on alternative economic thinking, such as circular economy or de-growth.

Including many of the above mentioned aspects might appear to lead to onerous model complexity. One question that arises is whether this is worthy or needed. For climate mitigation assessment, several studies availed of limited nexus linkages, neglecting important possible side-effects, but allowed effectively assessment of the potential and cost of decarbonization options. However, when studying climate adaptation strategies, the multi-sector impact of climate change cannot continue to be omitted [1, 2]. Trade-offs in land allocation and water management become central at guaranteeing food, water and energy security. The complexity of CLEW models might seem discouraging. However, similarly to how most current models have increased in complexity in the last decades, supporting nexus approaches by constructing ad-hoc teams could lead to the establishment of a well needed discipline.

Comparing multiple models, it is clear that open access and transparency are important factors for model dissemination and use. However, other factors, such as a strong community and stakeholder engagement network can help spread the use of models and frameworks. Since CLEW models are new and undergoing continuous development, it might be hasty to draw conclusions largely on accessibility visibility. However, the NEST framework, while fully available and downloadable online, could benefit from more detailed code documentation and a more user-friendly interface.

In conclusion, IAMs and CLEW models are increasingly required to be more flexible to adapt their scope and scale to address policy implementation questions. This requires on the one hand the tools to incorporate high-resolution data and specific stakeholder

specifications. On the other hand, this also means that models need to be more accessible and offer intuitive interfaces so that stakeholders can fully interact with input and better understand the results.

These are important considerations for scientists looking for state-of-the art models to use or compare. These considerations could also help decision makers, governmental, and other research and development institutions identify useful opportunities to pursue new climate land energy and water analyses to address regional, national or global challenges and possibilities.

# Appendix A

## A.1 Model references

### IMAGE 3.2

Model web page, with links to documentation and publications: [https://models.pbl.nl/image/index.php/Welcome\\_to\\_IMAGE\\_3.0\\_Documentation](https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation)

Model and nexus related publications: Bijl *et al.*, Bijl *et al.*, Van Vuuren *et al.*, van Vuuren *et al.*

### REMIND-MAgPIE

Model web page, with links to documentation and publications: <https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind>

Github: <https://github.com/remindmodel/remind>

Model and nexus related publications: Luderer *et al.* 2015; Bauer *et al.* 2020

### MESSAGE-GLOBIOM

Model web page, with links to documentation and publications: <https://docs.messageix.org/projects/global/en/latest/>

Github: [https://github.com/iiasa/message\\_ix](https://github.com/iiasa/message_ix)

Model and nexus related publications: Krey *et al.*, Parkinson *et al.*

## GCAM

Model web page, with links to documentation and publications: <http://www.globalchange.umd.edu/gcam/>

Github: <https://github.com/JGCRI/gcam-core>

Model and nexus related publications: Calvin *et al.*, Graham *et al.*, Graham *et al.*, Snyder *et al.*

## COFFEE

Model web page, with links to publications: <http://www.cenergialab.coppe.ufrj.br/tools> <https://www.iamconsortium.org/uncategorized/computable-framework-for-energy-and-the-environment/>

Model and nexus related publications: Oshiro *et al.*, Rochedo

## CLEWs framework

Model web page, with links to publications and case studies: <http://www.osimosys.org/> <https://unite.un.org/sites/unite.un.org/files/app-globalclews-v-1-0/landingpage.html>

Github: <https://github.com/OSeMOSYS/OSeMOSYS>

Model and nexus related publications: Ahjum & Stewart, Howells *et al.*, Miralles-Wilhelm *et al.*, Ramos *et al.*, Sridharan *et al.*

## WEAP-nexus

No online page directly linkable with the below mentioned case study. WEAP model web page: <https://www.weap21.org/>

Model and nexus related publications: Momblanch *et al.*

## ECHO

Model web page, with links to publications: [https://iiasa.ac.at/web/home/research/researchPrograms/water/Global\\_Hydro-economic\\_Model.html](https://iiasa.ac.at/web/home/research/researchPrograms/water/Global_Hydro-economic_Model.html)

Model and nexus related publications: Kahil *et al.*

## Nexus Tools 2.0

Model web page: <http://wefnexusstool.org/login.php>

Model and nexus related publications: Daher & Mohtar, Schull *et al.*

## BLUES

Model web page, with links to documentation and publications: <http://www.cenergi.alab.coppe.ufrj.br/tools> [https://www.iamcdocumentation.eu/index.php/Model\\_Documentation\\_-\\_BLUES](https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_BLUES)

Model and nexus related publications: [12]

## NEST

Model web page, Github: <https://github.com/iiasa/NEST/>

Model and nexus related publications: Vinca *et al.*, Vinca *et al.*

## WHAT-IF

Model web page, with links to documentation and publications:

Github: <https://github.com/RaphaelPB/WHAT-IF>

Model and nexus related publications: Payet-Burin *et al.*

## NexSym

Model web page, with links to documentation and publications: <https://process.innovation.ox.ac.uk/software/p/16137a/nexsym-academic/1>

Online repositories and User Guide: <https://drive.google.com/drive/folders/1tGdzZ-J9nqYKshaQD>  
<https://drive.google.com/drive/folders/17ywxZKn-RgmrvszaNwlgNz6xnJC8CM1C>

Model and nexus related publications: Martinez-Hernandez *et al.*

**IM3**

Model web page, with links to documentation and publications: <https://im3.pnnl.gov/>

Github: <https://github.com/IMMM-SFA>

Model and nexus related publications: Hyun *et al.*, Vahmani *et al.*, Voisin *et al.*, Yang *et al.*

## A.2 Additional tables

Table A.1: Criteria and sectoral coverage to assess sectoral gap in Figure 2.2a

<b>Model</b>	<b>Water</b>	<b>Energy</b>	<b>Land</b>	<b>Climate</b>
	1) assessment of consumption/demands	1) electricity/energy consumption and need, only hydropower	1) land area assessment, or biomass	1) emission accounting; impact on hydrology only
	2) exogenous hydrology inputs	2) electricity/energy supply, distribution	2) crop models, irrigation water needs and technologies	2) climate impacts on many sectors, climate scenarios
	3) integrated hydrology, distribution technologies, groundwater, water quality	3) full primary to final energy demand and supply; transport; buildings; industry	3) forest growth, crop growth model, livestock, pollution	3) full dynamic linkage with climate model for atmosphere balance
IMAGE	3	3	3	2
REMIND-MAgPIE	1	3	3	2
MESSAGE-GLOBIOM	2	3	1	2
GCAM	3	3	3	2
COFFEE	0	3	3	2
CLEWs	3	3	3	2
WEAP-nexus	3	1	1	1
ECHO	3	2	2	1
Nexus Tool 2.0	3	3	3	2
BLUES	3	3	3	2
NEST	3	2	2	2
WHAT-IF	3	2	2	2
NexSym	3	2	2	2

Table A.2: Criteria and thematic inclusion to assess thematic gap in Figure 2.2b

<b>Model</b>	<b>Social</b>	<b>Economic</b>	<b>Ecological</b>
	1) energy poverty, water stress, hunger, pollution 2) equity, income inequalities, human health 3) employment, migration, gender, human rights	1) GDP, rest of economy 2) Income distribution, household choices, companies, governments 3) country financial governance (dept), financing policies	1) emission, pollution 2) existing CC impacts, glacier, SLR, afforestation 3) ecosystem protection, biodiversity, floods, fires
IMAGE	2	1	3
REMIND- MAGPIE	1	1	2
MESSAGE- GLOBIOM	1	1	2
GCAM	2	1	3
COFFEE	1	1	2
CLEWs	1	1	3
WEAP-nexus	1	1	3
ECHO	1	1	2
Nexus Tool 2.0	1	1	2
BLUES	1	1	2
NEST	1	1	2
WHAT-IF	1	1	2
NexSym	0	0	2

Table A.3: Discrete assessment of Interlinkages visualized in Figure 2.3

Model (yes, basic linkage) (multiple linkages (multi) )	wat 2 ene cooling or hydro or storage	wat 2 land irrigation use	wat 2 clim impact of water management on climate	ene 2 wat pumping or desalination or other	ene 2 land energy choices impacting land, or energy use in land and food processing	ene 2 clim GHG emission	land 2 wat irrigation techs. or canal, water reservoir	land 2 ene biomass for energy use or crop residues	land 2 clim de/afforestation or land GHG	cli 2 wat change in ET rates, or precipitations, or changes in demand	cli 2 ene power cooling, or energy efficiency	cli 2 land plant crop yields or other
(multiple linkages (multi) )	all those above	detailed ET impacting irrigation needs, river flow, storage	n/a	all those above	Both those above	GHG and other emissions	all those above	all those above	all those above	all those above	all those above	more than one aspect
IMAGE	multi	multi	no	yes	multi	yes	yes	multi	multi	multi	yes	yes
REMIN-MAgPIE	no	yes	no	yes	yes	yes	no	multi	multi	no	yes	yes
GCAM	multi	yes	no	yes	no	yes	no	yes	yes	yes	yes	yes
MESSAGE-GLOBIOM	yes	no	no	yes	no	yes	no	yes	no	no	yes	yes
COFFEE	no	no	no	no	multi	yes	no	multi	multi	no	yes	no
CLEW	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes
WEAP-nexus	multi	yes	no	yes	no	no	yes	no	no	multi	no	no
ECHO	yes	yes	no	yes	no	no	yes	no	no	yes	no	yes
Nexus Tool 2.0	yes	yes	no	multi	yes	yes	yes	no	no	yes	no	yes
BLUES	yes	multi	no	multi	multi	yes	yes	multi	multi	yes	yes	no
NEST	multi	multi	no	multi	yes	yes	multi	multi	no	multi	yes	yes
WHAT-IF	multi	yes	no	yes	yes	yes	yes	yes	no	multi	no	yes
NexSym	yes	yes	no	yes	yes	no	no	yes	no	yes	yes	no

The interlinkages express the changes in flows or condition from one sector to the following one. For example 'ene 2 wat' means there are additional energy flow needed in the water sectors. 'wat', 'ene' and 'clim' are abbreviations of 'water', 'energy' and 'climate' respectively.

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## Appendix B

### B.1 Exogenous demands

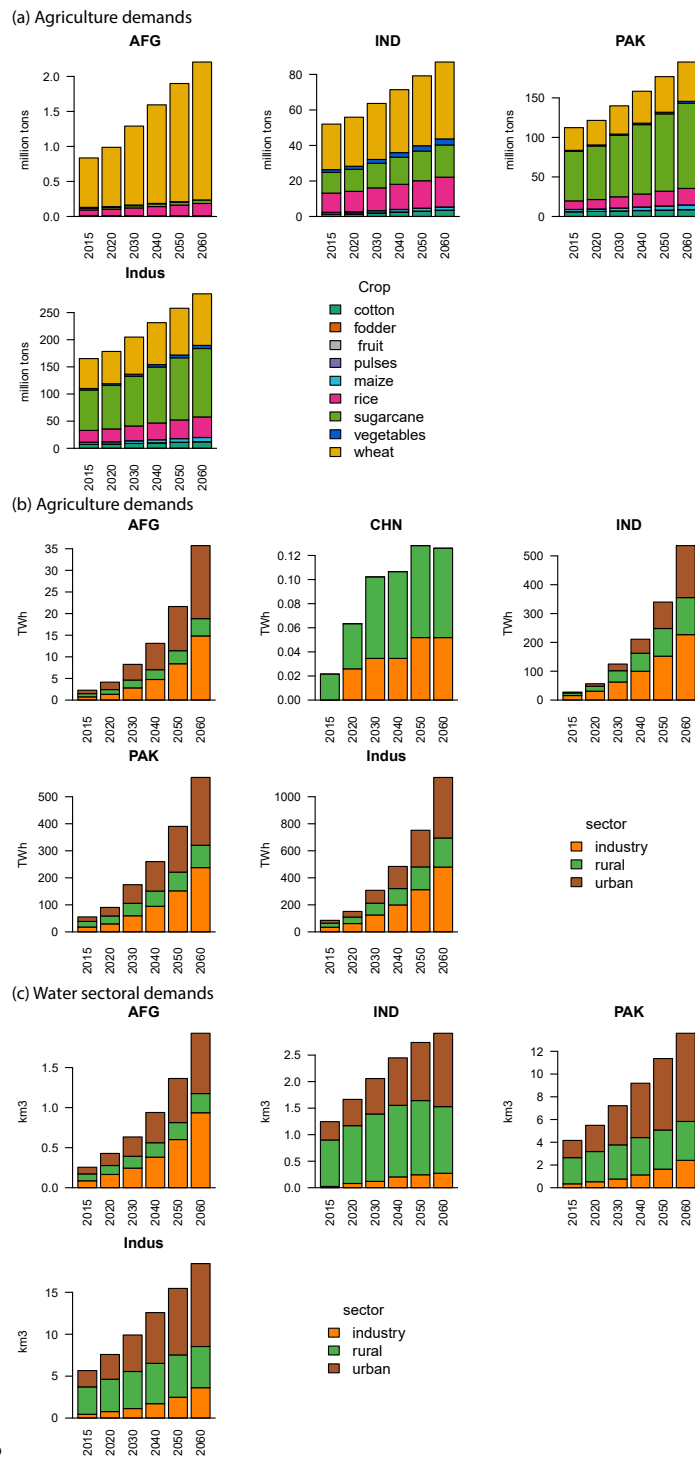


Figure B.1: Exogenous agriculture products (a), electricity (b) and water (c) demands. For each country and the whole Indus basin, from 2010 to 2060.

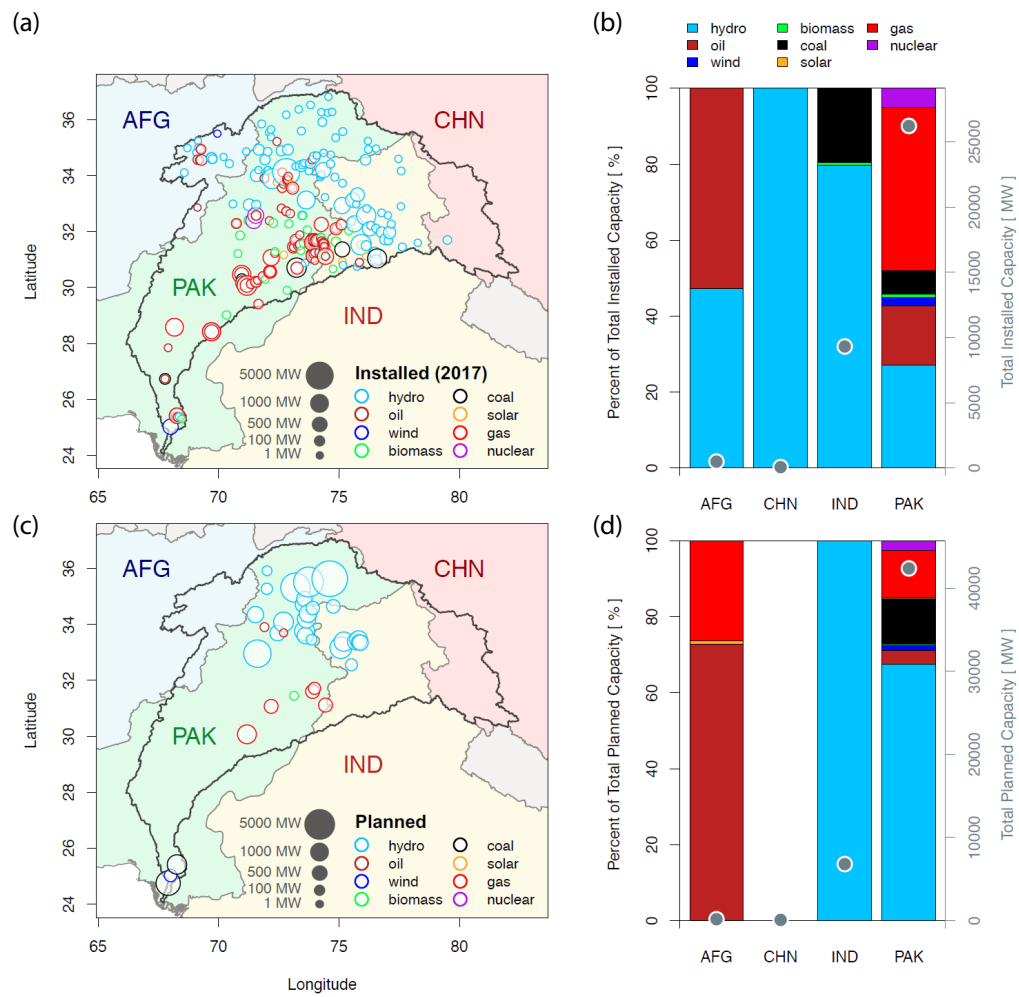
## B.2 Canals, hydroelectric projects and power plants data

Project	Capacity [ m <sup>3</sup> / sec ]	Length [ km ]	Long. In [ °E ]	Lat. In [ °N ]	Long. Out [ °E ]	Lat. Out [ °N ]
Rasul-Qadirabad	538	44	73.5187	32.6830	73.7135	32.3370
Qadirabad-Bulloki	527	129	73.6858	32.3228	73.9138	31.2982
Balloki-Sulemanki	524	87	73.8590	31.2226	73.9241	30.4953
Trimmu-Sidhnai	312	64	72.1462	31.1450	72.1933	30.5690
Sidhnai-Mailsi	283	94	72.1582	30.5713	72.2459	29.7278
Chashma-Jhelum	615	135	71.3837	32.4358	72.2214	31.9680
Taunsa-Panjnad	340	72	70.8505	30.5137	71.3677	30.2735
Marala-Ravi	622	97	74.4698	32.6699	74.6239	31.8966
Ravi-Bedian	142	82	74.4701	31.7212	74.1755	30.7265
Bambanwala-Ravi	142	82	74.2941	32.3609	74.4701	31.7212
Chenab-Bambanwala	453	28	74.4698	32.6699	74.2941	32.3609
Chenab-Ravi	311	44	74.2941	32.3609	74.0820	31.4142
Keenjhar-Karachi	31	44	68.0500	24.9500	-	-
Indira Gandhi	138	602	75.0111	31.1628	-	-

Table B.1: Major conveyance canals in the NEST implementation of the IRB that are linking river systems or for interbasin transfers. Locations, capacities and lengths are approximate and estimated by the authors based on reported technical data. Interbasin transfers are occurring where no outlet location is defined.

Project	Country	Longitude [ °E ]	Latitude [ °N ]	Capacity [ MW ]	Storage [ km <sup>3</sup> ]	Opening
Azad Pattan	Pakistan	73.5715	33.7678	700	-	2022
Patrind	Pakistan	73.4288	34.3440	150	-	2017
Gulpur	Pakistan	73.8625	33.4553	102	-	2019
Suki Kinari	Pakistan	73.5427	34.7231	870	-	2022
Kohala	Pakistan	73.6546	34.2023	1100	-	2025
Athmuqam	Pakistan	73.9107	34.5891	350	-	2020
Golen Gol	Pakistan	72.0143	35.9212	58	-	2018
Mahl	Pakistan	73.5667	34.9167	590	-	2025
Neelum-Jhelum	Pakistan	73.7189	34.3928	968	-	2018
Diamer-Bhasha	Pakistan	73.7370	35.5207	4500	10.5	2023
Tarbela Extension	Pakistan	72.6983	34.0897	1410	-	2018
Karot	Pakistan	73.6012	33.5998	720	-	2021
Kalabagh	Pakistan	71.6136	32.9564	3600	7.5	proposed
Munda	Pakistan	71.5330	34.3532	740	0.9	proposed
Bunji	Pakistan	74.6159	35.6358	7100	0.2	proposed
Dasu	Pakistan	73.1933	35.3173	4320	0.8	2021
Akhori	Pakistan	72.4528	33.6905	600	8.6	2025
Sharmai	Pakistan	72.0053	35.2766	150	0.3	2023
Kishanganga	India	74.7647	34.6475	360	-	2018
Sawalkote	India	75.0759	33.1691	1856	-	proposed
Kirthai I	India	75.1994	33.3868	390	-	proposed
Kirthai II	India	75.1994	33.3868	930	-	proposed
Pakal Dul	India	75.8136	33.4572	1000	0.1	proposed
Kwar	India	75.8280	33.3623	540	-	proposed
Kiru	India	75.8898	33.3518	624	-	proposed
Bursar	India	75.6956	33.3903	800	0.6	proposed
Ujh	India	75.5156	32.5590	212	-	proposed

Table B.2: Additional planned hydropower projects included in the NEST implementation of the IRB. Locations, capacities and dates are approximate and estimated by the authors based on reported technical data.



Basin boundary from HydroBASINS (Lehner, 2013). Country borders from the Geospatial Data Abstraction Library (GDAL)

Figure B.2: Existing (a), (b) and planned (c), (d) power plant capacity in the NEST implementation of the IRB. Sources: World Electric Power Plant (WEPP) Database, [5, 6]

### B.3 Costs and Capacity Factor assumptions

Tables B.3 and B.4 show costs and capacity factor values for a number of technologies in the model. Technologies like transmission lines or water canals are not included, as costs are dependent on the length and the region. The tables only include a subset of energy technologies with different cooling systems. Costs for gas plant in combined cycle (*cc*), single turbine (*gt*) and steam turbine (*st*) configurations are reported for all cooling systems, air cooling (*ac*), closed loop (*cl*) and once through cooling (*oc*). Although we model these different cooling systems also for oil, coal, geothermal and nuclear power plants, we only show costs for closed loop in Tables B.3 and B.4.

Solar and wind power plants are divided in three groups having same cost assumptions but different levels of capacity factor, attached in the Supplementary Information *Variable\_capacity\_factor.xlsx*.

Technology	$I_{cost}$ [unit]	$F_{cost}$ [unit]	$Var_{cost}$ [unit]	CF [-]
Crops	[\$/ha]	[\$/ha]	[\$/(ha month)]	
wheat	341	36	72	1
rice	716	15	22	1
cotton	416	9	13	1
fodder	130	3	4	1
sugarcane	849.6	17	25.5	1
pulses	1320	26.4	39.6	1
maize	1000	20	30	1
fruit	545.5	11.5	16.5	1
vegetables	1362.5	27.5	41	1
Energy Technolgies	[\$/kW]	[\$/kW]	[\$/kWh]	
coal st cl	6860	24	0.048611	0.9
electricity distribution industry	1120	36	0.034722	0.9
electricity distribution irrigation	1120	36	0.034722	0.9
electricity distribution rural	1120	36	0.034722	0.9
electricity distribution urban	1120	36	0.034722	0.9
electricity short strg	3000	16	0.020833	0.9
gas cc ac	1105	17	0.037264	0.9
gas cc cl	1064	16	0.036875	0.9
gas cc ot	1023	15	0.036111	0.9
gas gt	676	7	0.122222	0.9
gas st cl	1205	17	0.048611	0.9
geothermal cl	6343	135	0.025	0.9
hydro old	5000	15	0	0.95
igcc cl	4131	32	0.079167	0.9
nuclear cl	5751	97	0.029167	0.9
oil cc cl	1064	16	0.036875	0.9
oil gt	676	7	0.122222	0.9
solar pv 1	3873	15	0.004167	variable
solar pv 2	3873	15	0.004167	variable
solar pv 3	3873	15	0.004167	variable
wind 1	7000	8	0	variable
wind 2	7000	8	0	variable
wind 3	7000	8	0	variable

Table B.3: Investment, fixed and variable costs and capacity factor values for model technologies. Sources: [1, 3, 4] and local data

Technology	$I_{cost}$ [unit]	$F_{cost}$ [unit]	$Var_{cost}$ [unit]	CF [-]
Irrigation technologies	[\$/ha]	[\$/ha]	[\$/(ha month)]	
drip	2600	52	78	0.9
flood	460	10	14	0.9
sprinkler	1625	33	49	0.9
canal lining flood	3110	62	94	0.9
smart	2825	57	85	0.9
drip smart	3100	62	93	0.9
sprinkler smart	2125	43	64	0.9
Water diversion/treatment technologies	[\$/(mq /day)]	[\$/(mq /day)]		
industry gw diversion	20	8.5	0	0.9
industry sw diversion	57	3	0	0.9
industry wastewater recycling	1350	99	0	0.9
industry wastewater treatment	431	37	0	0.9
irrigation gw diversion	8.5	1	0	0.9
irrigation sw diversion	57	3	0	0.9
rural gw diversion	8.5	1	0	0.9
rural piped distribution	326	18	0	0.9
rural sw diversion	57	3	0	0.9
rural wastewater recycling	1350	99	0	0.9
rural wastewater treatment	759	77	0	0.9
smart irrigation sw diversion	62.7	3.3	0	0.9
urban gw diversion	20	8.5	0	0.9
urban piped distribution	1013	252	0	0.9
urban sw diversion	57	3	0	0.9
urban wastewater collection	785	251	0	0.9
urban wastewater irrigation	1350	99	0	0.9
urban wastewater recycling	1350	99	0	0.9
urban wastewater treatment	431	37	0	0.9

Table B.4: Investment, fixed and variable costs and capacity factor values for model technologies. Sources: [1, 3, 4] and local data.

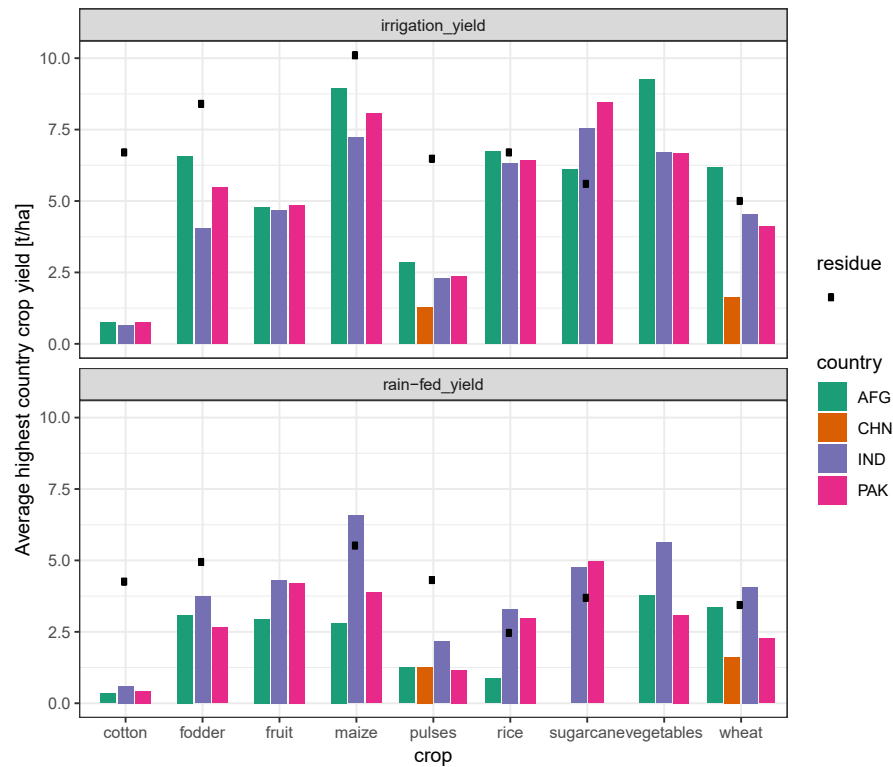


Figure B.3: Average highest irrigated and non-irrigated yield for each crop-country pairing in the NEST implementation of the IRB as well as the corresponding rates of residue generation. Sources: [2]

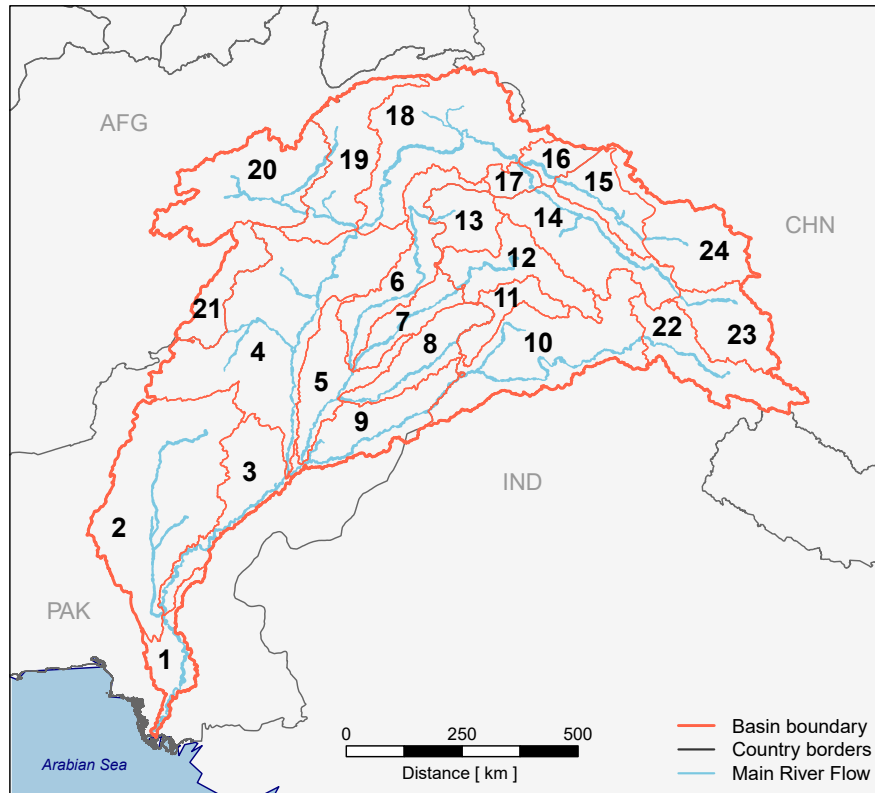
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# Appendix C

## C.1 Supplementary Figures



- |   |                         |
|---|-------------------------|
| 1. Sindh W                                  | 13. Jammu and Kashmir N |
| 2. Central Balochistan                      | 14. Kargil              |
| 3. Pakistani Punjab S -Sindh NW             | 15. Ladakh              |
| 4. Islamabad-Khyber Pakhtunkhwa S -Punjab W | 16. Gilgit-Baltistan SE |
| 5. Pakistani central Punjab                 | 17. Gilgit-Baltistan S  |
| 6. Jammu Kashmir-Jhelum Punjab              | 18. Gilgit-Baltistan    |
| 7. Gujrat Sargodha                          | 19. Khyber Pakhtunkhwa  |
| 8. Lahore-Punjab E                          | 20. Paktika - khost     |
| 9. Pakistan Punjab S                        | 21. Kabul               |
| 10. Indian Punjab-Himachal Pradesh          | 22. China rural 1       |
| 11. Indian Punjab N                         | 23. China rural 2       |
| 12. Jammu and Kashmir S                     | 24. China rural 3       |

Figure C.1: Map of the Indus river basin and the sub-regions represented in our modelling framework. Country maps from GADM database, basin delineation from HydroSHEDS [1, 2].

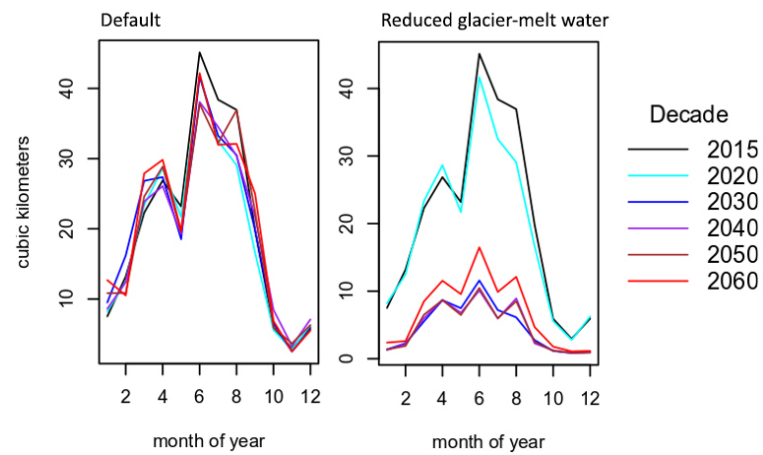


Figure C.2: Ensemble mean monthly runoff in the Indus river basin under default configuration (left panel, valid for all scenarios but *SDG-GM*) and glacier melt assumption (right panel, for the *SDG-GM* scenario).

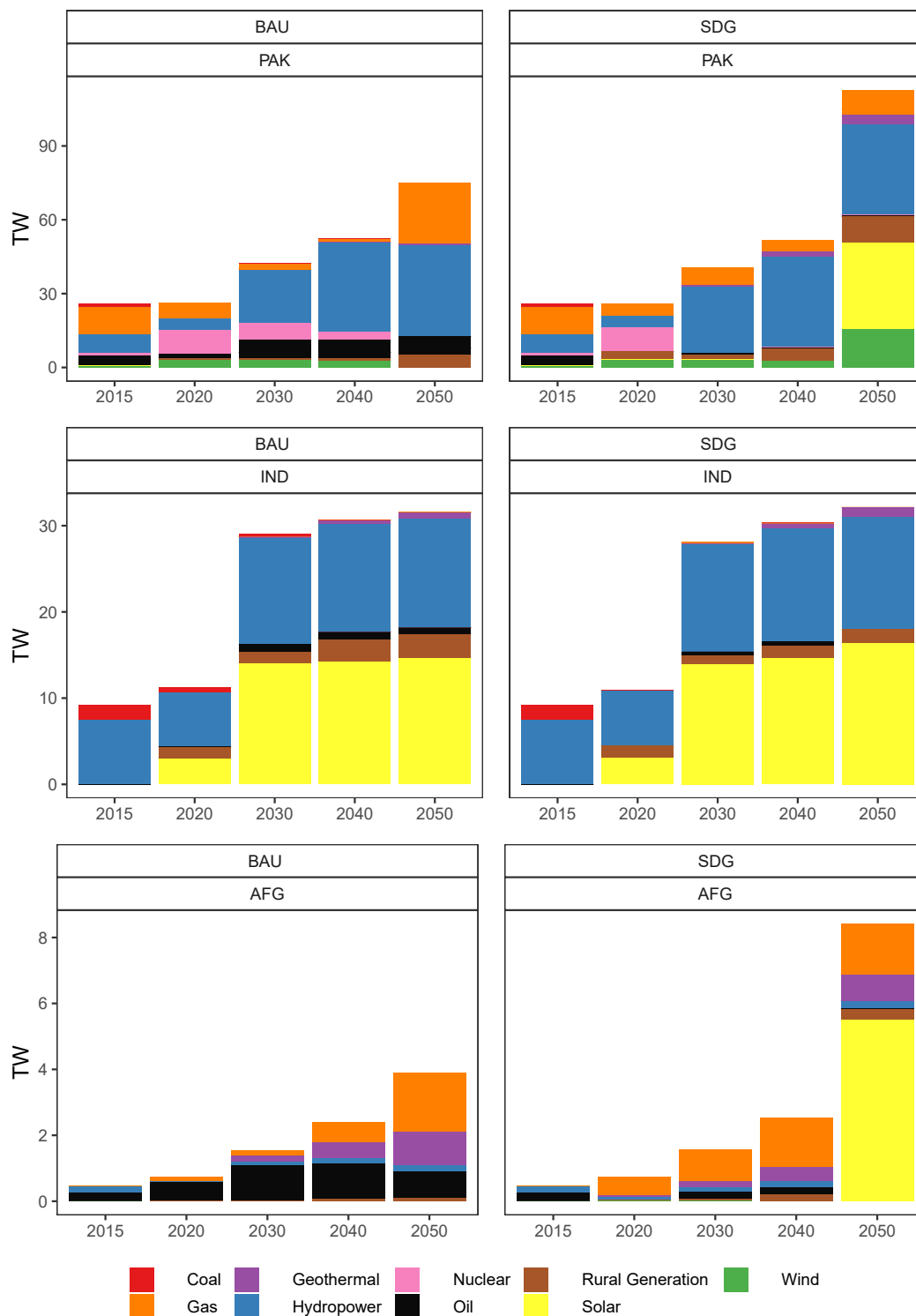


Figure C.3: Energy technologies' installed capacity for Indus countries from 2015 (historical) to 2050 under *BAU* and *SDG* scenarios. Hydropower refers to small and large power plants; rural generation includes diesel generators and solar panels not connected to the distribution grid.

## C.2 Supplementary Tables

Sector/area	Assumption
Population and GDP growth	SSP2 scenario assumptions
Energy demand: urban, rural and industrial	Exogenously calculated with population projections
Water demand: urban, rural and industrial	Exogenously calculated with population projections
Agriculture products' demand	Exogenously calculated with population projections
Energy demand for water distribution technologies, farming and irrigation	Endogenously calculated within the modelling framework
Water demand for power plants' cooling, hydro reservoirs and irrigation	Endogenously calculated within the modelling framework
Climate scenario assumption	RCP 6.0
Large hydropower planned projects	Planned dams by 2030 are included in energy/water planning for all scenarios

Table C.1: The main scenario assumptions with reference to IAM community standard. The parametric assumptions, such as technology costs, efficiencies, as well as the main outcomes from the hydrological model, as reported in Vinca et al., 2020 [4]

Scenario	Non-cooperative	Cooperative	Cost reduction (%)
BAU	75	66	9 (12%)
SDG	85	77	8 (9%)
SDG-GM	92	80	12 (13%)
SDG-NL	85	79	6 (7%)
SDG-NE	85	79	6 (7%)
SDG-WaterReq-	84	76	8 (10%)
SDG-WaterReq+	87	78	9 (10%)
SDG-CropYield-	89	80	9 (10%)
SDG-CropYield+	82	74	8 (10%)

Table C.2: Total average annual system costs (billion USD/year) for the entire Indus basin, for different scenarios, under cooperative or non cooperative assumptions. Scenario *SDG-WaterReq* (- and +) are sensitivity cases with respectively 10% decrease and increase in crop water requirement. *SDG-CropYield* (- and +) explore the cases of 10% variation of crop yields

Scenario	Region	Saving with cooperation			Total saving	Ratio savings/costs (%)
		Agriculture	Energy	Water		
BAU	AFG	243	64	66	372	20
	IND	318	-1049	2620	1890	6
	PAK lower	3363	3520	306	7189	18
	PAK upper	-82	564	-27	455	8
SDG	AFG	299	52	78	429	16
	IND	78	-1347	2416	1147	3
	PAK lower	1980	4261	556	6798	15
	PAK upper	-128	879	202	952	12
SDG-GM	AFG	344	-43	531	833	29
	IND	47	-706	1116	456	1
	PAK lower	3486	4100	10380	17965	35
	PAK upper	-363	384	1196	1217	14
SDG-NL	AFG	-3	-46	-9	-57	-2
	IND	457	-25	2624	3056	9
	PAK lower	-92	2371	-39	2241	5
	PAK upper	-15	827	32	843	10
SDG-NE	AFG	297	135	75	507	19
	IND	62	-738	2386	1710	5
	PAK lower	1845	2143	590	4578	10
	PAK upper	-117	-303	195	-224	-3
SDG-WaterReq-	AFG	297	67	55	419	16
	IND	-2	-1179	2483	1302	4
	PAK lower	1881	4127	279	6287	15
	PAK upper	-101	849	103	850	9
SDG-WaterReq+	AFG	271	79	81	431	16
	IND	373	-813	1903	1463	4
	PAK lower	2005	4253	1331	7589	16
	PAK upper	5	778	211	994	12
SDG-CropYield-	AFG	322	64	84	470	17
	IND	279	-1372	2379	1286	4
	PAK lower	2201	4408	623	7232	15
	PAK upper	-136	838	218	920	11
SDG-CropYield+	AFG	277	92	66	435	15
	IND	-27	-1292	2332	1013	3
	PAK lower	1707	4330	359	6395	15
	PAK upper	0	673	117	790	10

Table C.3: Average annual savings induced by cooperation strategies (million USD/year) for the entire Indus basin, for different scenarios, under cooperative or non cooperative assumptions. The net savings are calculated as the difference between non-cooperative and cooperative scenario of the system cost  $\pm$  costs/earnings of food products and energy trade. The ratio between the total savings and the total costs in the non-cooperative scenarios gives an idea of the relative economic benefit. Scenario *SDG-WaterReq* (- and +) are sensitivity cases with respectively 10% decrease and increase in crop water requirement. *SDG-CropYield* (- and +) explore the cases of 10% variation of crop yields

Sector/area	BAU-coop	SDG-GM	SDG-GM-coop	SDG-NL-coop	SDG-NE-coop
Energy & GHG emissions (SDG 7.2 and 13a)	Determined National tributions (NDCs) to Paris agreement	Con- NDC; 90% carbon-free elec- tricity generation in 2050; coal phase out	Con- NDC; 90% carbon-free elec- tricity generation in 2050; coal phase out	Con- NDC; 90% carbon-free elec- tricity generation in 2050; coal phase out	Con- NDC; 90% carbon-free elec- tricity generation in 2050; coal phase out
Water treatment and access to sanitation (SDG 6.3)	Projection of current rates with GDP growth	95% water treatment access to sanitation	95% water treatment access to sanitation	95% water treatment access to sanitation	95% water treatment access to sanitation
Water efficiency (SDG 6.6)	BAU constrained by physical boundaries	Constraint future agriculture water withdrawals to historical levels	Constraint future agriculture water withdrawals to historical levels	Constraint future agriculture water withdrawals to historical levels	Constraint future agriculture water withdrawals to historical levels
Environmental flows	BAU constrained by physical boundaries	Minimum Indus river level in Delta area of 46 MCM/day (Kharif) and 12 MCM/day (Rabi)	Minimum Indus river level in Delta area of 46 MCM/day (Kharif) and 12 MCM/day (Rabi)	Minimum Indus river level in Delta area of 46 MCM/day (Kharif) and 12 MCM/day (Rabi)	Minimum Indus river level in Delta area of 46 MCM/day (Kharif) and 12 MCM/day (Rabi)
Agriculture (SDG 2.4)	Continuity of flood being the main irrigation technique	95% of agriculture water use from efficient irrigation	95% of agriculture water use from efficient irrigation	95% of agriculture water use from efficient irrigation	95% of agriculture water use from efficient irrigation
Electricity trade	Electricity trade among riparian countries	National electricity transmission within and outside the basin border	Electricity trade among riparian countries	Electricity trade among riparian countries	National electricity transmission within and outside the basin border
River flow allocation	In line with the Indus Water Treaty	In line with the Indus Water Treaty	Improved allocation to optimize other sustainable objectives	Improved allocation to optimize other sustainable objectives	Improved allocation to optimize other sustainable objectives
Agriculture production/trade	Basin-wise production, crop shift to maximize yields and minimize water withdrawals	National production; crop shift to maximize yields and minimize water withdrawals	Basin-wise production, crop shift to maximize yields and minimize water withdrawals	National production; crop shift to maximize yields and minimize water withdrawals	Basin-wise production, crop shift to maximize yields and minimize water withdrawals
Water availability	Default	Reduced	Reduced	Default	Default

Table C.4: Extra scenario assumptions, where *SDG-NL* stand for SDG 'No Land', *SDG-GM* refers to 'Glacier Melt' and *SDG-NE* to SDG 'No Energy'

Country	Organization participating to the meetings
Pakistan	Lahore University of Management Sciences (LUMS) Ministry of Planning, Development and Reforms Planning and Development, Gov. Punjab Planning and Development, Gov. Baluchistan Planning and Development, Gov. Khyber Pakhtunkhwa LEADS Pakistan Pakistan Meteorological Department (PMD) Pakistan Council on Research of Water Resources (PCRWR) Pakistan Agricultural Research Council (PARC) US Pakistan Center for Advanced Studies in Water, MUET Climate Change, Alternate Energy and Water Resources Institute (CAEWRI) Pakistan Business Council Water and Power Development Authority (WAPDA) Ministry of Planning, Development and Reforms Upper Indus Basin Network Ministry of Science & Technology
India	The Energy and Resources Institute-TERI Council on Energy, Environment and Water (CEEW) Department of soil and water conservation-Government of Punjab Indian Council for Research on International Economic Relations/IWMI Indian Institute of Technology (IIT) - Kharagpur Institute of Defense studies and Analysis (IDSA) Integrated Research and Action for Development (IRADe) International Development Research Center (IDRC) National Institute of Hydrology (NIH) National Institution for transforming India (NITI) Technology Information, Forecasting and Assessment Council (TIFAC) TERI School of Advanced Studies The Celestial Earth United Nations Development Program (UNDP) University of Kashmir TERI School of Advanced Studies Ministry of Environment Forests and Climate Change
Afghanistan	Environmental Conservation Specialist Organization of Afghanistan (ECSOA) Ministry of Energy and Water Ministry of Agriculture, Irrigation and Livestock (MAIL), Kabul
China	National Climate Centre and Chinese Academy of Sciences Xingjiang Institute of Ecology and Geography National Climate Centre
Nepal	The International Centre for Integrated Mountain Development (ICIMOD)
United Kingdom	Oxford University
USA	The Massachusetts Institute of Technology Institute (MIT) The Global Environment Facility (GEF)

Table C.5: List of stakeholders' organizations

### C.3 Supplementary Discussion

In addition to the scenario described in the main text, Supplementary Tables C.2 and C.3 includes cases of parametric sensitivity and impacts on saving related to cooperation. Crop water requirements and crop yield (in *SDG-WaterReq* (- and + ) the *SDG-CropYield* (- and + ) respectively ) are varied by a factor of  $\pm 10\%$ , to account for the uncertainty in the data and the data processing technique (i.e. aggregation of spatial data). The lowest total costs, both for cooperative and non-cooperative solution, seem to occur in the case of high crop yield assumptions (*SDG-CropYield+*, see Supplementary Table C.2). High crop yields not only imply lower water requirements with given overall production, but also allow optimization of land use. Interestingly, the highest saving due to cooperation are *SDG-CropYield-* and *SDG-WaterReq+*, both scenarios that imply higher water stress, especially in lower Pakistan, Supplementary Table C.3.

Fig. 3.14 illustrates different output changes under the BAU scenario in response to an arbitrary variation in input parameters (-25%,+25%). Intuitively, some outputs as groundwater extraction and energy production are strongly affected by the variation of sector-related parameters, irrigation and power plants' efficiency respectively. The plot also shows some significant cross-sectoral feedbacks. For instance, changes in energy efficiency and investment cost impact groundwater and surface water withdrawals by up to 5% and irrigation efficiency strongly impact fossil-fueled energy production. Land use seems not to be sensitive to the input parameters here considered. Looking at total cost alterations, multiple parameters induce variations comparable with the scenario following scenario uncertainty.

Fig. 3.13 (a) shows different level of monthly total runoff from the CWaTM using different climate models and under two different climate scenarios (RCP 2.6 and 6.0). We notice major diversity in trend given by different climate models, while climate scenario implies changes mostly in the eighth and ninth months of year 2020. When running the optimization model in NEST, outcomes carry the uncertainty from the hydrological model and cumulate it with other types of uncertainty. Fig. 3.13 (b) shows total cost for the Indus region where the uncertainty of different SSP assumptions is added the previous set of climate scenarios. We notice how SSP assumptions more greatly affect total cost compared to either climate model or RCP (each bundle of same-color lines includes runs with all climate scenario and RCP assumptions). However, looking at SSP 2 and 1, with reduced stress caused by population growth, climate uncertainty is more significant than for SSP 5.

## C.4 Supplementary Methods

The project team has organized several meetings in between 2017 and 2018, engaging stakeholders from different Indus countries and background (Supplementary TableC.5): two national consultation meetings (Delhi and Lahore, March 2018), and one basin meeting (Vienna, May 2018) co-organized with the International Centre for Integrated Mountain Development (ICIMOD), the International Water Management Institute (IWMI) and the World Bank, and a final stakeholder meeting (Kathmandu, August 2019). A comprehensive description of the whole engagement process is described in Magnuszewski et al. (in preparation, [3]), while a summary of the meetings, participants and outcomes is provided below.

### **Meeting 1: Identifying challenges and priorities needs regarding water, energy, and land**

This first Indus meeting turned into two separate country meetings: Delhi (23 March 2018) and Lahore (26-28 March 2018).

The purpose of the two consultations was to:

- strengthen and build partnerships with national organizations from the two countries
- identify in a neutral environment what are the country perspectives on the sectoral and transboundary challenges
- establish new partnerships with local research organizations well connected within their respective countries and at the same interested in stayed engaged in the project

The outcomes of the two meetings translated into:

- identification of main sectoral challenges regarding WEL
- identification of stakeholders that later joined the scenario workshop.

### **Meeting 2: Developing water, energy, and land nexus scenarios for the Indus Basin**

With the aim of supporting knowledge generation and sharing for the sustainable management and future of the Indus, IIASA in partnership with International Centre for Integrated Mountain Development (ICIMOD), the International Water Management Institute (IWMI) and the World Bank convened two interlinked events from May 29th through

June 2nd 2018 in Vienna and Laxenburg: a Scenario Workshop on "Developing Visions and Future Pathways for the Indus Basin" and the Third Indus Basin Knowledge Forum, whose theme for this year was "Managing Systems Under Stress: Science for Solutions in the Indus Basin".

The overall aim was to go one step beyond the first consultations held earlier in the year and bring together experts and stakeholders from the four riparian countries, to jointly discuss this time desirable futures and pathways in the Indus basin and its riparian countries for the management of water, energy, and land. The workshop was based on a scientific approach but it also aimed to produce policy relevant results.

The outcomes of the Indus Scenario Workshop consisted of:

- Three visions for the Indus basin, differentiated by the value preferences of the stakeholders, composed of spatial representation of development as well as sectoral challenges, and a range of potential solutions (technological but also behavioral, and policy related).
- Enhanced and shared understanding on the implications of different investments in the basin and their consequences cascading through the WEL sectors.

### **Meeting 3: Preliminary results discussion, definition of research questions and scenarios**

The research and modelling team, following some inputs from the previous meeting, adapted the scenario narrative from previously defined socio-environmental-economic pathways toward SDG oriented narratives, mostly by reshuffling elements collected during the first two meetings. In the third and last meeting, those scenarios assumptions were presented and discussed.

Purpose:

- Present the updated version of the modeling tool and the preliminary results of the new scenarios
- Continue enhancing capacities around nexus by running a participatory exercise using a newly develop simulation scenario exercise
- Receive feedback from the stakeholders both in terms of the tools and the scenarios and way forward (communication and tool/knowledge transference)

Main outcomes:

- Modeling tools. Overall there is a great interest in the model and the potential for scaling it out within the countries. The basin approach is seen as interesting but the largest demand is for country applications. In India ENE has already signed a project with Ministry of Forest and Climate Change, and in Pakistan there is a big interest. In its present format the model has some limitations that need to be carefully addressed, especially if it wants to be presented to national policy makers.

### **Bi-lateral collaborations, model and scenario co-production**

In addition to stakeholder engagements in the above-mentioned workshops, bi-lateral interactions with specific stakeholders has led to external contribution to model development and application. Implementation of specific model component (i.e. environmental flows, smart irrigation technologies) was outcome of such collaboration. On the same line, some values of the SDG targets (reported in Table 4.1 in the main text) were discussed in bi-lateral conversations or are outcome of analyses that will be published separately from this work. It should be noted the large majority of stakeholders have an academic and research background. To guarantee a comprehensive processing of all steps from policy thinking to intervention assessment and planning, the stakeholder engagement process would benefit with more participation of regional policy makers and government administrators. Due to political reasons, such sessions are arduous to organize within Indus countries and represents a major limitation in achieving international agreements such as for countries aligned with the Water Convention [5].

## Appendix C Bibliography

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5. *Water - Home*