Characterizing Water, Food, and Energy Interrelationships

By

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The more graduate students I interact with in an academic setting, the more proof I get that I have had a uniquely positive experience as a PhD student. Last spring I attended a pre-travel conference for my National Science Foundation East Asia and Pacific Summer Institute (NSF EAPSI) fellowship. A defining moment of my academic experience occurred when a NSF representative asked the group of 200 graduate students from across America and across disciplines two questions: is your advisor supportive of these type of opportunities (i.e., fellowships that require international travel and a commitment to live aboard for the summer) and do you have a mentor? It surprised me how easy these questions were for me to answer compared to my peers and how different my answers were compared to my peers.

My advisor, George Hornberger, has been a crucial part of the past six years, advising me, and more importantly, supporting me on everything from fellowship applications to chairing conference sessions. Working with George I have had the opportunity to gain skills that most students do not learn until their post-doctoral positions. He provides encouragement and advice, but never prescribes what I should do. Over the past few months, I have been faced with a number of tough decisions regarding my career path. I have found myself—more often than I would like to admit—running over to his office at 8am and 5pm alike, and I always find the door open and George willing to talk. A mentor can be difficult to come by—as a good majority of the NSF EAPSI fellows of 2013 can attest to—but I did not seem to have had trouble finding one. In fact, I find myself lucky in that I consider a number of Vanderbilt faculty, of few of who are on my dissertation committee, to have mentored me over the past six years. I appreciate the time and valuable input on my research that my advisor and committee members have given me, and more importantly, I thank them for their encouragement and advice.

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I am thankful for the support of my family and friends. My parents, Philip and Linda Perrone, have instilled in me a strong work ethic, which has come undoubtedly in handy these past few years. I am grateful for their willingness to listen to me talk about everything from environmental externalities to Sri Lankan paddy fields. My brother, Frank Perrone, has been a mentor of mine from as far back as I can remember. He is the reason I became interested in solving problems, and he is the reason for my habitual need to perform tradeoff analyses on everything from buying fish sustainably to professional decisions—often using EXCEL spreadsheets. I am grateful for my brother's wife, Elizabeth Perrone, who balances out the intensity of the Perrone family and always gives an optimistic perspective on the obstacles I encounter. My best friends—Lindsey Brough, Lianne Hansen, Erica Lynes, and Valerie Taryla—have earned their title. Best, traditionally defined, means the one superior to all others—I am lucky to have redefined that term so that it means the four better than all others.

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CHAPTER 1

THE WATER SECURITY, FOOD SECURITY, AND ENERGY SECURITY TRILEMMA

1.1 | INTRODUCTION

There has been much made in recent years about water security, food security, and energy security, but these terms do not carry precise definitions. In fact, these terms often mean different things to different people. The details of how to characterize water, food, and energy security are far from trivial,[a,1-5] yet water, food and energy rank as the top three problems humanity faces over the next 40 years.[6] What makes these three resources rise to the top of the list? Water and food are required to sustain human existence, and energy is required to develop economies and increase living comforts. The world in 2050 is expected to host 9.2 billion people living with a global economy that is more developed and affluent than the global economy today. Recent increases in competition for water, food, and energy are exposing the complex network threading these resources together. The interactions among the three resources are not defined well; considering the difficulty in defining water security, food security, and energy security, it is not surprising that the interactions among water, food, and energy resources are not defined well either.

Population growth and changes in lifestyle that follow development and growing affluence combined with a more diverse global energy portfolio will increase demand for water, food, and energy. Global crop demand is projected to increase 60[b]-110% between 2005 and 2050.[7,8] Historically, additional land has been exploited to meet increased agricultural demands; recently trends are quite the opposite,

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[a] Water security carries connotations of an adequate supply of clean fresh water to support humans.[1-3] Food security, in the context of global policy issues, is defined as “a situation that exists when all people at all times have physical, social, and economic access to sufficient, safe, and nutritious food to meet dietary needs and food preferences for an active and healthy life”.[4] Broadly speaking, energy security refers to the idea of providing adequate and affordable energy to human populations. Climate change adds an element of uncertainty to energy security; failure to account for the environment has the potential to result in large economic, social, and environmental costs.[5]

[b] The 2006 FAO report uses a different commodity composition and use pattern than the updated 2012 report, implying a 70% increase from 2005/2007 to 2050 as opposed to a 60% increase. The 2012 revised analysis does not change the terms of projected aggregate agricultural production, but decreases meat production and provides a smaller share of cereals to feed and more to biofuels.

taking formerly productive crop land and developing it for other uses or losing it to desertification, soil erosion, and salinization.[9] Sustainable intensification—increasing yields per unit area of land by optimizing inputs—has been suggested as the most sustainable path forward.[c,8] Expansion of irrigated agriculture will be part of this increased productivity. Irrigation reduces interannual variability of production and increases yields; under current climatic conditions, the variability of rainfed crops is double that of irrigated cropland[10] and the productivity is about half that of irrigated cropland.[11] Increased productivity of agriculture will likely require fertilizers and pesticides,[d,12,13] also increasing energy demands. Global electricity production to 2035 is expected to see an annual increase at a rate of 1-2%.[14] Although electricity production often stands out when linking water use to energy resources, almost all energy resources use and consume water.[15,16] Globally, water withdrawal and consumption by the energy sector is expected to increase by 20 and 85%, respectively.[14] Agriculture and energy are the largest water users already; increased production of food and energy will likely increase competition for water, a finite resource.

Water, food, and energy resources rise to the top of the list because these three resources are the fundamental building blocks of our society; each resource is required to maintain and enhance human existence. Furthermore, as pressures on each of the three resources grow, interactions among all three resources arise: a solution to address scarcity in one cannot be achieved without impact on the others. I call this the water security, food security, and energy security trilemma. In my dissertation I characterize water, food, and energy interrelationships, an important first step to understanding the water security, food security, and energy security trilemma. The objectives of my dissertation are threefold.

- Create frameworks to explore water-food-energy interrelationships.
- Use case studies to help untangle the complex feedbacks among water, food, and energy resources.
- Identify opportunities to meet the projected water, food, and energy demands of 2050.

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[c] The other physical constraint on food productivity is land resources; expanding agriculture land is not accepted, generally, as a sustainable path forward.

[d] Recent research has argued that organic farming practices could contribute to current global food demand, but these claims may not be applicable to the food demand projected in 2050.

1.2 | TWO-RESOURCE INTERACTIONS

It is challenging to integrate each resource into the management of the others because of the complex dynamics intertwining the resources. A good first step in exploring water-food-energy networks is capturing how each of the resources links to the others; that is, two-resource interactions (Figure 1.1). For instance, Water is withdrawn and consumed throughout the lifecycle of most primary and secondary energy sources.[16,17] Energy is consumed for acquisition, distribution, and end-use of water resources.[18,19] Water in streams and in groundwater aquifers (blue water) and rainfall that sustains crops and terrestrial ecosystems (green water) are vital in sustaining agricultural yields. Energy is a fundamental input for increasing crop yields and maintaining food security.[20,21]

Two-resource interactions are well established and intuitive (Figure 1.1). Nevertheless, it is difficult for communities to account for these interrelationships because data is not reliable and literature is not available readily. This is true especially for water-energy interrelationships (Figure 1.1A), where analysts are faced with gaps and inaccuracies in federal data on thermoelectric and nuclear power plant water use[22,23] and hard pressed to find statistics on the energy needs of water end-use (e.g., heating water).[19] Thermoelectric power plants are not the only energy sources that require water, but more often than not, thermoelectric power plants are the only energy sources incorporated into water-use studies; primary sources of energy (e.g., natural gas) and renewable sources of energy (e.g., solar thermal) all require water. Water's end-use stage requires significant energy resources, but this stage is not alone: local conditions, such as distribution distance and water quality, also impact the energy portfolio of a community's water system.

Water-energy decisions involve numerous tradeoffs and without adequate information, it is difficult to assess accurately the pros and cons of future courses of action. Chapter 2 of my dissertation introduces a framework that promotes communities to quantify water-energy interrelationships (Figure 1.1A), reveals how water and energy consumption by a community requires additional resources, and identifies values often overlooked in decision-making. Quantifying water-energy flows provides insight on the influence of geography on water and energy resources: as communities expand, water and energy use exceeds supplies from the proximate area, requiring an increasing reliance on hinterland resources. I conclude Chapter 2 by elaborating on this phenomenon and exploring how my framework can promote communities to think about their resource flows.

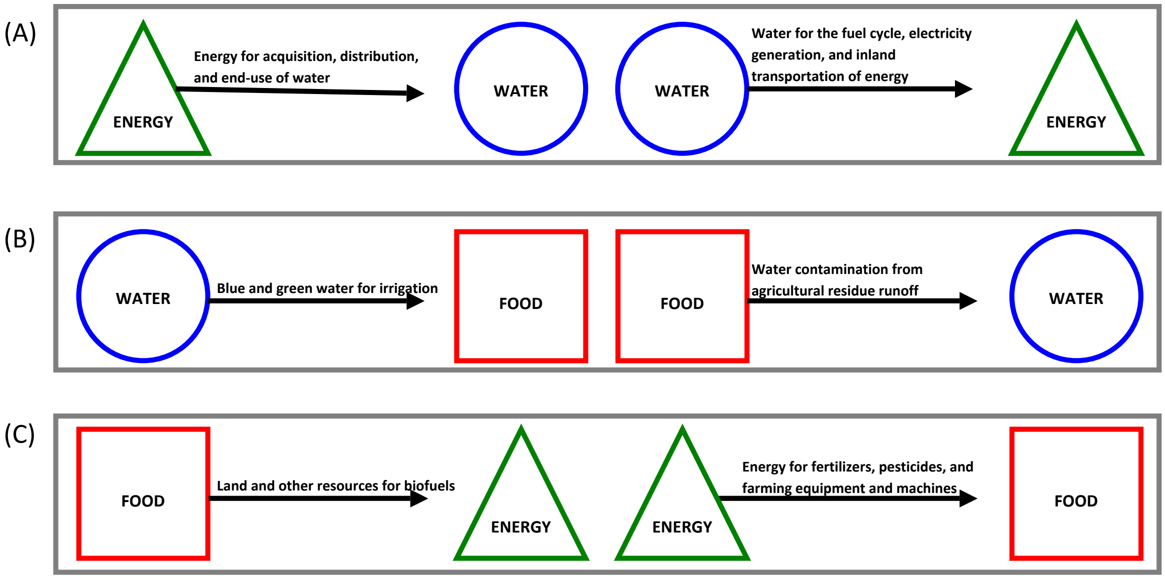

Figure 1.1 | Two-resource interactions.

Each gray box represents a two-way, two-resource interaction between water, food, and energy. Two-resource interactions are defined as a mutual dependence between two resources.

1.3 | THREE-RESOURCE INTERACTIONS

Two-resource interactions help with understanding the links between resources, but the interactions do not explain how the resources interact to affect the security of all three resources. For instance, water security is influenced both by its interactions with energy and its interactions with food. Chapter 3 builds upon my understanding of resource security by looking at the interactions among water, food, and energy resources. The water security, food security, and energy security trilemma creates a multi-dimensional web that is a structurally complex network with dynamic links among resources. In times when resources are abundant and reliable (i.e., secure), the interrelationships (i.e., links) among water, food, and energy are defined clearly. The three-resource interactions are often overlooked; two-resource interactions appear to be independent because the interactions do not directly influence the function of the network as a whole. As resources encounter stressors and limiters, the links between them become intertwined—affecting function—and it becomes obvious that all three resources are co-dependent (Figure 1.2).

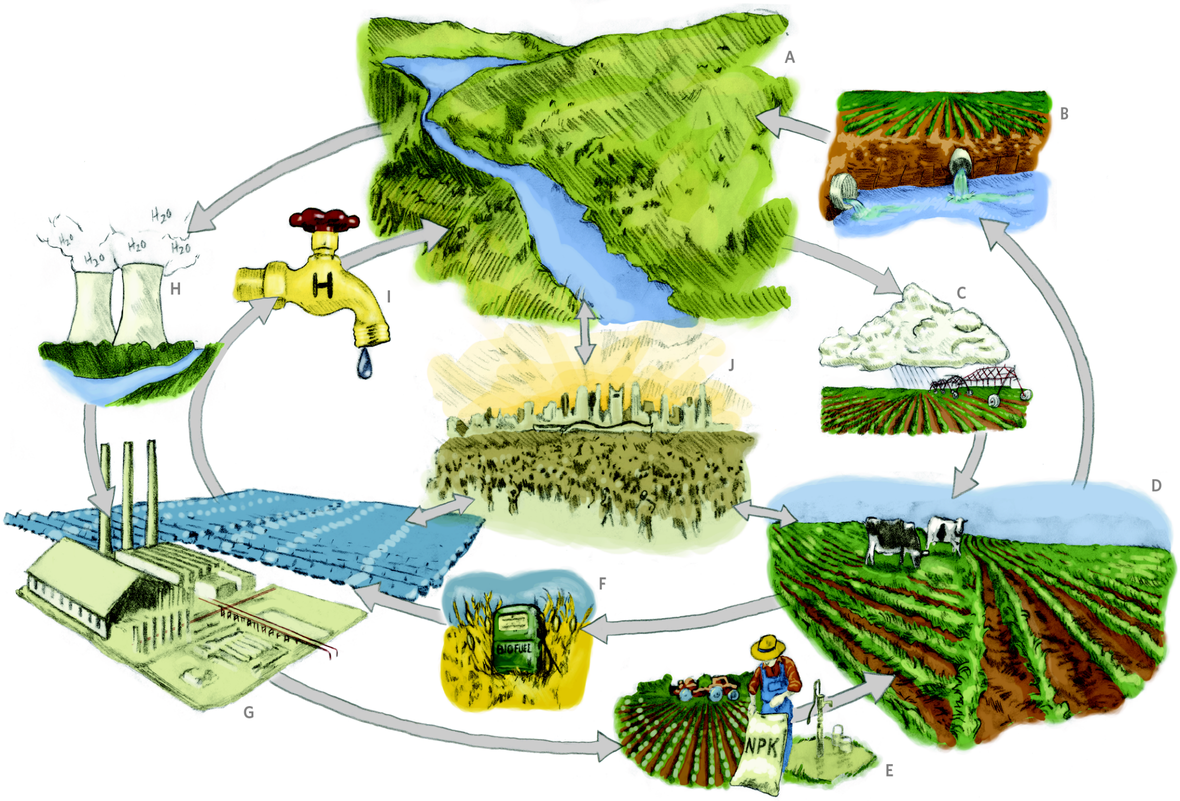

Figure 1.2 | Three-resource (water-food-energy) interactions.

(A) WATER RESOURCES, (B) water contamination from agricultural residue runoff, (C) blue and green water for irrigation, (D) FOOD RESOURCES, (E) energy for fertilizers, pesticides, and farming equipment and machines, (F) agricultural land and resources for biofuels, (G) ENERGY RESOURCES, (H) water for fuel cycle, electricity generation, and inland transportation of energy, (I) energy for acquisition, conveyance, treatment, and end-use of water, and water contamination from energy, (J) competition driven interrelationships, tradeoffs, and insecurities among (A) water, (D) food, and (G) energy. In times when resources are abundant and reliable (i.e., secure), the links among water, food, and energy are defined clearly. The three-resource interactions among resources are often overlooked; two-resource interactions (e.g., (H) water for energy) appear to be independent of the third resource because the third resource does not directly influence the function of the network. As resources encounter stressors (e.g., economic growth, population growth, weather and climate) and limiters (e.g., political opposition; social, behavioral, and cultural norms; spatial and temporal distribution), the links between them become intertwined and it becomes obvious that all three resources are co-dependent (J).

Because structure affects function,[24] characterizing the network anatomy that links water, food, and energy interactions is helpful when setting goals to meet resource security. I acknowledge that there are many other interactions that influence water, food, and energy security, but I am most interested in exploring water's role in the intersection among these three resources and understanding the trade-offs involved in meeting water, food, and energy security goals. Chapter 3 showcases three case study examples—Apalachicola-Chattahoochee-Flint River Basin in the United States, Mahaweli River Basin in Sri Lanka, and Brazil—that I use to explore water's role in the complex network and understand why it is that water is central to the water security, food security, and energy security trilemma.

1.4 | TRILEMMA TRADEOFFS: SRI LANKA AS A CASE STUDY

Increasing population, economic growth, and development suggest greater stress will be placed on water, food, and energy resources in the future. The impacts of a changing climate will exacerbate competition for these resources, especially given the strong interrelationships among water, food, and energy. Equally important, but often overlooked, political opposition and social, behavioral, and cultural norms can limit access to resources, playing an important role in securing resources.

Chapter 4 of my dissertation expands upon the Sri Lankan case study in Chapter 3; Sri Lanka is a microcosm for a localized, manageable, and discrete tradeoff analysis. The small island nation has a strong cultural attachment to paddy farming that stems from its history of ancient, sophisticated irrigation systems. Food self-sufficiency is high on the country's political agenda—but so is economic development, which requires reliable energy resources. Thus, Sri Lanka faces a tradeoff: water for energy and economic growth or water for agriculture, food security, and cultural preservation. During periods of high rainfall, there are enough water resources for agriculture and hydroelectricity, but current drought events have highlighted Sri Lanka's water vulnerabilities and the tradeoffs present in managing its water resources.

1.5 | OPPORTUNITIES

The problems that strew the path to global sustainability are massive and can be daunting. There is no single solution for our resource problems because each problem is unique, but we can use case studies, such as those presented in my dissertation, to help untangle the complex feedbacks among water, food, and energy resources. As you will see with the various case studies I use in my dissertation, it is overly simplistic to think that technological and non-technological solutions for water, food, and energy security can be pursued independently. The trick is to mix, and properly balance, technological and non-technological water-food-energy interrelated approaches.[25] In Chapter 5, I conclude my dissertation with both technological and nontechnological paths to meet our future water, food, and energy needs.

CHAPTER 2

GAINING PERSPECTIVE ON THE WATER-ENERGY NEXUS

2.1 | INTRODUCTION

More people now inhabit urban centers than rural areas. Shifts in population distribution are often coupled with a reorganization of resource distribution. As urban centers expand, water and energy consumption exceeds supplies from the proximate area requiring imports from increasingly distant sources.[26] Although urban areas allow more efficient use of resources, and the compact nature of urban areas protects undeveloped land,[27] the modern city results in relatively large quantities of point source consumption.[28] Consequently, urbanization is commonly coupled with desertification in the hinterland as advantage is taken of the resources available in rural regions.[29,30] This is especially true with water and energy.

Water and energy are used and lost through acquisition, processing, transportation, and end-use. These lost quantities of water and energy are rarely considered when accounting for resource consumption because they are virtually invisible.[31,32] The recognition that there is a nexus, or interrelationship, between water and energy further complicates these urban resource flows. Water is withdrawn and consumed throughout the lifecycle of an energy source and energy is consumed for extraction, distribution, and end-use of water resources.

Although urban communities cannot be sustainable in and of themselves, they can adapt to be responsible partners in achieving greater overall sustainability.[30,33] A first step in doing so is analyzing water and energy flows and identifying hotspots as candidates for active management. Unfortunately, this task is difficult for many reasons. Management of water and energy resources involves a wide range of stakeholders[23] and, consequently, data often are not available readily. Obtaining water-energy nexus (WEN) data for a specific region is difficult not only because the data are aggregated at the national scale, but also because they are outdated, unavailable for public use, or in raw form, requiring time and resources to make them useful. Organizational and jurisdictional boundaries do not align, further complicating data collection and compatibility of the analyses. Long supply chains, which play a role in accounting for resources in urban centers, are difficult to track, and the accurate allocation of demands along them is even more difficult, ultimately resulting in truncated analysis boundaries or major assumptions.

Material flow analyses used for lifecycle assessments (LCA) and calculating the urban metabolism of cities can be used to examine resource use systematically, and there has been some work done in this vein to reveal the trade-offs associated with water and energy use.[34,35] Such tools treat a comprehensive portfolio of resource inputs and emission outputs, but they can require a massive data assembly and analysis effort. Although LCA using economic data within an input-output approach reduces the effort required for such studies,[36] techniques that are based on national economic data do not capture the influence of a community's geographic location within the nation.[37,38] On the other hand, many tools that are created for a specific region[39,40] may be difficult to adapt to other areas. And, more often than not, analyses neglect consideration of both energy for water and water for energy.[41]

The WEN tool presented in this paper is designed to avoid some of these obstacles. The tool uses average and aggregate values as multipliers for different water and energy technologies, transportation methods, and end-user trends. It highlights the significance of geographic location by allowing users to select energy sources, transportation distances, and uses of water and energy specific to the urban area. The frameworks within the tool provide information on how delivered water and energy consumption by a community require additional resources and reveals values often overlooked in decision-making. To show the value of the WEN tool, I present results for Tucson, Arizona, United States. This case study exemplifies how a community's geographic location dictates the source of its water and energy, and thus, can affect resource portfolios and planning. A sensitivity analysis is used to evaluate the resource savings associated with reducing overall consumption and the impact of changing water and energy source allocations.

I conclude the chapter with a discussion on the applicability of the term "urban resource islands" for resource management and decision-making. In ecology, a resource island describes an enriched microenvironment; as nutrients are concentrated in the soil beneath desert shrubs, resources are slowly depleted from the hinterland.[42-44] Just as ecological resource islands acquire resources from their surroundings, urban centers rely on hinterland resources, and consequently, water and energy infrastructure to reduce their local resource stresses. Essentially all cities can be considered urban resource islands, with the degree to which they are limited by, and in turn limit, their surroundings, dependent on their geographic location.

2.2 | METHODS

2.2.1 | WEN Tool

The WEN tool was designed to take advantage of national reports and published data, yet still account for the nuances associated with a community's geographic location. There are two frameworks within the tool: Energy for Water and Water for Energy (Figure 2.1). By taking into account the specific sources, transportation distances, and use of a community's resources, these frameworks provide specificity for a hotspot analysis without the time and financial investment required for an in-depth, site-specific assessment. The tool's boundaries are based on the ability of users to acquire the information necessary for an analysis. Even with these boundary limitations, many of the resource implications of geographic features important to imports of water and energy are accounted for in the WEN tool. Thus, it provides a quantitative basis for the concept of the urban resource island.

2.2.2 | Urban Centers versus Community

Large cities can have more than one energy provider, especially because there are multiple energy sources available. The boundaries of different providers may not be aligned, and it is rare that they align with the boundaries of the urban center. Water has similar boundary issues, and to complicate matters, it is also rare for the water and energy boundaries to align with each other. Therefore, within the context of this chapter, I define a community as the area within or surrounding an urban center that aligns best with utility boundaries.

2.2.3 | Energy for Water Framework

This framework is divided into four stages: acquisition, treatment, local distribution, and end-use. I also divide water into two categories, delivered water and transport water. Delivered water is water consumed directly by the end-user. Water lost during the acquisition of water from a distant source (e.g., by evaporation) or local distribution (e.g., leaky pipes) is transport water; transport water can be considered an inefficiency value. Nexus energy is energy consumed for delivered and transport water. This includes the energy for acquisition, municipal treatment, local distribution, and end-use (e.g., energy to heat water) (Figure 2.1A).

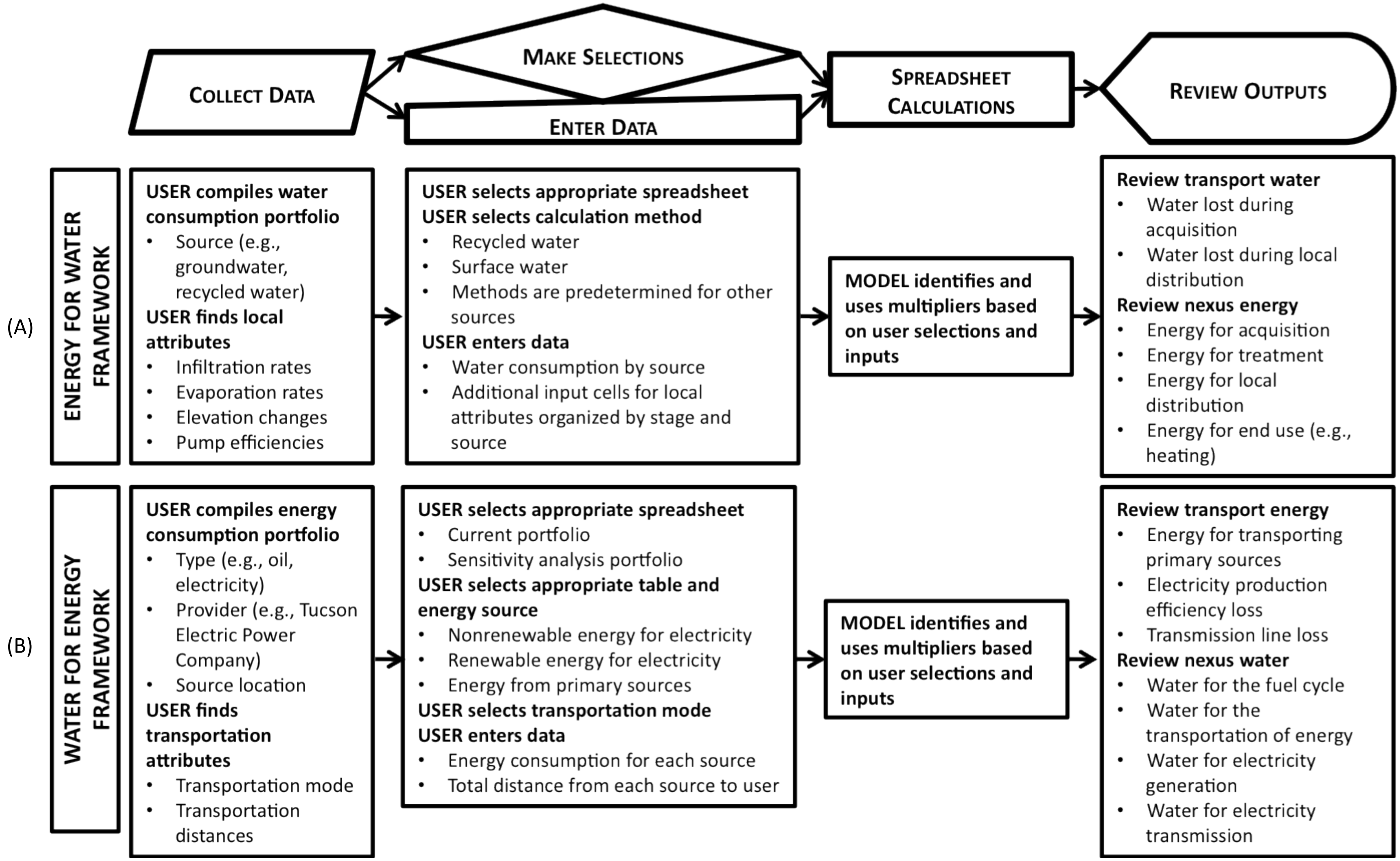

Figure 2.1 | Water-Energy Nexus Tool Concept Diagram

2.2.3.1 | Outputs and Inputs

This framework captures the energy consumed due to the water used by a community. It also calculates the water lost during the transportation of water sources. To obtain the outputs, the framework requires the community's water portfolio, or the total delivered water, which can be found in a public water utility report. Depending on the water sources, additional information, such as elevation changes from source to facility and pump efficiency, may be required. A detailed explanation of all inputs, instructions for this framework, and references for multipliers can be found within the tool.[e]

2.2.3.2 | Limitations

The data provided by the water utility may include transport water, so the data should be thoroughly reviewed. The transport water associated with the treatment process (i.e., water lost during treatment) and the water lost by the end-user (e.g., dripping faucet) are not considered. Energy for the end-use of water is difficult to calculate due to the varied users and uses of water, and therefore, has significant limitations. As the majority of work on this subject has been performed in California, the multiplier used within the WEN tool is calculated according to California's water and energy use, and thus the geographic and climatic variables specific to California are embedded in this calculation.[45] Online calculators for determining individual household water and energy use are available but are not used in this study (e.g., Pacific Institute's water-energy- climate calculator[46]). For more detailed methods on the creation of the Energy for Water framework and a comprehensive review of its limitations refer to Appendix A.

2.2.4 | Water for Energy Framework

This framework is divided into four stages: energy fuel cycle (e.g., mining, extraction, refining, etc.), energy transportation (e.g., fuel for trucks delivering coal), electricity generation (if applicable), and electricity transmission (if applicable). Within the framework, I also distinguish delivered and transport energy. Delivered energy is energy consumed by the end-user. Energy required for transporting each energy source (transportation stage), the loss of primary energy during conversion to electricity (electricity generation stage), and the energy lost during the transmission of electricity (electricity transmission stage) are considered transport energy. Nexus water, as calculated within the framework, is water consumed for delivered and transport energy. This includes water for the fuel cycle, transportation, electricity generation, and electricity transmission stages (Figure 2.1B).

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[e] The tool is an EXCEL spreadsheet available at http://pubs.acs.org/doi/abs/10.1021/es103230n.

2.2.4.1 | Outputs and Inputs

This framework captures water consumption for the energy consumed by a community. It also calculates the energy required to move energy resources, the energy lost during primary to secondary source conversion, and the energy lost during transmission of electricity as transport energy. To obtain the outputs, the framework requires the community's energy portfolio (delivered energy), mode of transportation, and distance traveled from source location to power plant or community if transported via truck, rail, or water. Energy portfolios can be found in a community's greenhouse gas report on their government or sustainability website. Transportation mode, geographic information system (GIS) data to calculate transportation distances, and additional supporting information can be found using government databases. A detailed explanation of all inputs, instructions for this framework, and references for multipliers can be found within the tool.

2.2.4.2 | Limitations

The indirect energy required for each source's fuel cycle (e.g., the energy required to build the equipment used in acquiring and processing the raw resource), the energy required to operate the power plant, and the energy consumed for transportation energy (e.g., transportation of the transportation fuels) are not incorporated into the model.

Data acquisition and compilation is the largest limitation for the user. Many urban areas have not produced a greenhouse gas report, so information may have to be compiled from raw government databases. There is also limited publicly available GIS data for energy infrastructure, so energy calculations for certain transportation modes (i.e., pipeline transport and electricity transmission) are based on efficiencies rather than distances. For more detailed methods on the creation of the Water for Energy framework and a comprehensive review of its limitations refer to Appendix B.

2.2.5 | Tucson Case Study

Tucson is located in southeast Arizona, about 100 kilometers (km) north of Mexico. Tucson's location in the Sonora desert, its arid to semiarid climate, and growing population make it an ideal city for exploring the water-energy nexus and applying the WEN tool. Water service to the city is provided by Tucson Water, a municipal water utility that serves people within the city of Tucson and the surrounding metropolitan area.[47,48] Energy information for residential, commercial, industrial, and transportation sectors was obtained from Tucson's greenhouse gas inventory; residential, commercial, and industrial energy primarily come from Tucson Electric Power Company and Southwest Gas.[49-51] Energy for urban transportation was included as oil imports, but because of the difficulty in tracking international primary energy sources, the boundary was set at the United States' port or city of entry.

2.2.5.1 | Limitations

The geographic and temporal distribution of water and energy data are slightly misaligned, a result of the available data and the lack of co-management between water and energy resources. Water data are from fiscal year 2005 (July 1-June 30) and include service to customers both inside and outside of the jurisdictional boundaries of Tucson (approximately 700,000 people).[47] Energy data are from 2005 and include data from within the jurisdictional boundary of the City of Tucson (approximate population of 530,000) and the city's government operations.[49]

2.2.5.2 | Assumptions

Both the water and energy portfolios required a close examination to ensure that nexus resources are not being considered in delivered resource categories. The water data includes users that purchase water from the municipal water utility and do not include independent wells. As a result, it is assumed that electricity companies within the city do not use municipal water, negating any concern about double counting.

The delivered energy portfolio, however, does include energy for residential end-use of water and for the operation of the public water utility, Tucson Water. Both end-use energy and water utility energy are nexus resources and calculated using the WEN tool. To ensure that these nexus resources are not double counted, Tucson's end-use energy and water utility energy are subtracted from the delivered energy when calculating Tucson's comprehensive energy portfolio (Section 3.3).

2.2.6 | Sensitivity Analysis

Two sensitivity analyses are also performed: demand reductions (decreases of 20% in water demand and 15% in energy demand) and portfolio alterations. After reviewing Tucson's Water Plan[52] and demand reductions achieved by other cities,[53,54] I use 20% for the water demand reduction analysis. The water portfolio alterations for Tucson—moving away from groundwater toward imported surface water—is an approach reflected in Tucson's Water Plan.[52] The reduction and portfolio changes for energy are based on the proposed regulation to require energy utilities to obtain 15% of their energy from renewable sources by 2025.[55] Because photovoltaic (PV) panels are currently being used by an energy facility that supplies Tucson's electricity,[56] PV was considered the most feasible renewable resource for the analysis.[57]

2.3 | RESULTS

2.3.1 | The Water Dimension

The energy needed to deliver and use water in an urban center depends on the source of the water. In 2005, Tucson's water portfolio was dependent on groundwater, on water delivered from the Colorado River by the Central Arizona Project (CAP), and on recycled water. In 2005, groundwater is the primary source of water (~50%). CAP water accounts for approximately 40%, and recycled water accounts for just under 10%; energy for water, however, follows different trends (Figure 2.2A).

CAP water is the most energy intensive (energy required per unit water) water source, averaging 23 MJ/m^3; the average energy intensities of groundwater and recycled water were 12 and 13 MJ/m^3, respectively. The large difference in energy intensities is due to the acquisition stage of CAP water. This stage requires 11 MJ/m^3, which is about 20 times more energy per unit of water than the acquisition of groundwater or recycled water. This results in the energy required for CAP tallying over 1300 TJ.

When looking at the overall contribution of all three sources by stage, end-use required significantly more energy than any other stage (Figure 2.2B). The energy consumed for water acquisition—750 TJ—is about half of the energy required for end-use. In comparison to end-use and acquisition, energy for local distribution and treatment is relatively small, but these stages combined require over 94 TJ.

2.3.2 | The Energy Dimension

Energy use can be divided into primary (e.g., gasoline use in the city) and secondary (e.g., electricity generation) sources. In 2005, Tucson's energy portfolio is composed primarily of coal, natural gas, and oil (Figure 2.2C). Minimal renewable resources are reported for electricity production, so renewable energy contribution is considered negligible. Primary uses of oil accounts for 52% of Tucson's energy, and electricity and primary uses of natural gas accounts for 26% and 22%, respectively. More than 99% of Tucson's electric power is from coal plants; less than 1% came from natural gas.

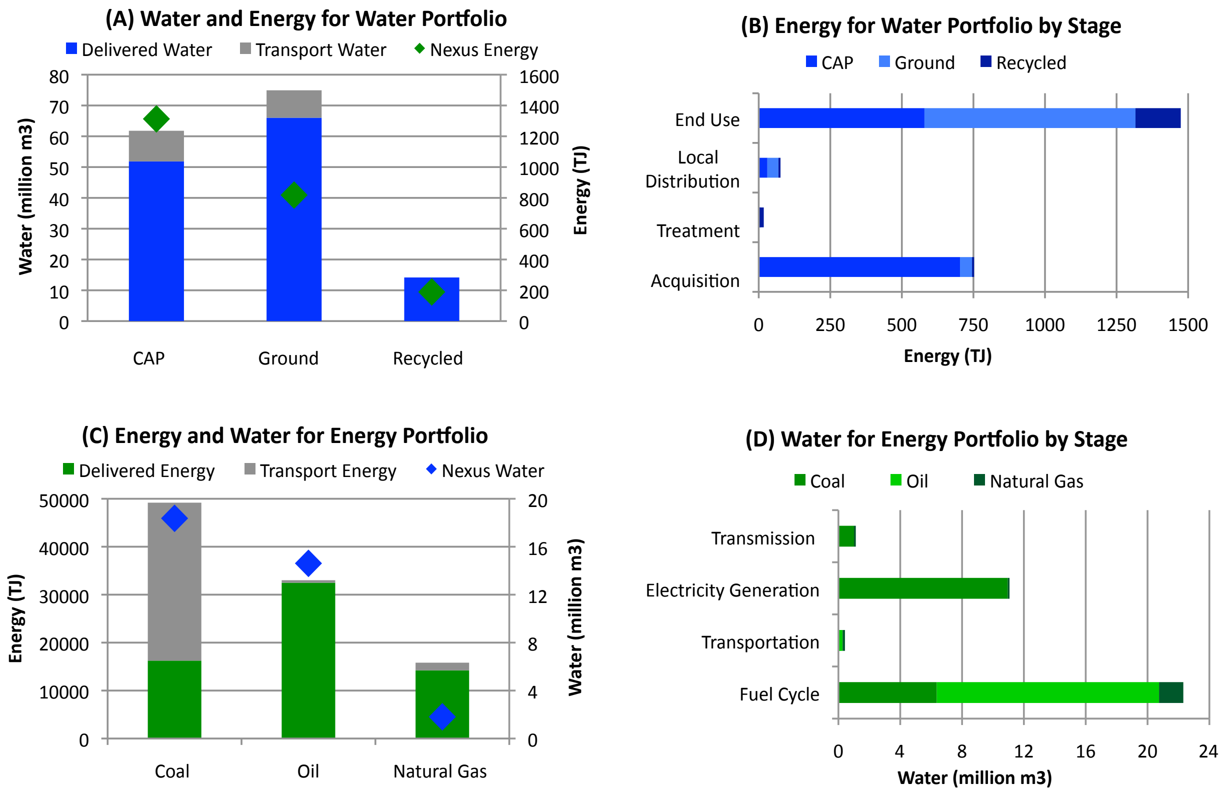

Figure 2.2 | Tucson's Water-Energy Nexus Portfolio.

(A) Tucson's water and energy for water portfolio. Tucson's delivered water is reported by Tucson Water. Water lost during the acquisition of water from a distant source (e.g., by evaporation) or local distribution (e.g., leaky pipes) is Tucson's transport water. Tucson's nexus energy includes the energy for acquisition, treatment, local distribution and end-use of water. (B) Energy for water portfolio by stage. Acquisition of water involves pumping and conveyance of water to the treatment facility. Treatment is dependent on the water source. Local distribution includes the transportation of the water from the treatment facility to the end-user. End-use energy includes uses from dishwashing to laundry, or any end-use that requires heating or cooling water. (C) Tucson's energy and water for energy portfolio. Tucson's delivered energy was obtained by a regional greenhouse gas report. Energy required for transporting each energy source, the loss of primary energy during conversion to electricity, and electricity lost in transmission is considered Tucson's transport energy. Nexus water is the aggregated water for each source's fuel cycle, transportation to user, and if applicable, electricity generation and transmission. (D) Water for energy portfolio by stage. The fuel cycle includes extraction, mining, refining, processing, and other plant operations. Transportation includes the movement of the primary resource to its user. Water for electricity generation and transmission is only applicable to those energy sources used for electricity.

Distinguishing between primary and secondary sources was a critical step; delivered electricity has primary to secondary conversion efficiency losses and transmission line losses associated with it. As a result, Tucson's coal-based electricity requires 33000 terajoules (TJ) of transport energy (Figure 2C). This is significantly more than oil and natural gas resource consumption, which only requires transport energy for the transportation of the primary source to the user. The high transport energy value in combination with the high water for electricity production values is the reason that secondary source consumption tends to be more water intensive per unit of energy delivered than primary sources. The water intensity (nexus water) of Tucson's coal based electricity, for example, was 1100 cubic meters per terajoule (m^3/TJ), whereas the water intensity of oil was 450 m3/TJ and water intensity of natural gas was 130 m^3/TJ.

Considering the overall contribution of coal, oil, and natural gas, the fuel cycle and electricity generation stages are much larger than the transportation and transmission stages (Figure 2D). In absolute terms, however, the transportation and transmission stages consume a substantial amount of water, approximately 1.4 million cubic meters (m^3).

2.3.3 | The Nexus Between Water and Energy

To address Tucson's WEN, the amount of water required for its energy is added to its delivered and transport water— a comprehensive water portfolio—and the amount of energy required for its water was added to its delivered and transport energy—a comprehensive energy portfolio (see section 2.2.5.2 for assumptions). In terms of total (i.e., delivered, transport, and nexus) water, Tucson consumes more than 180 million m^3 in 2005, and in terms of total energy, Tucson consumes about 98000 TJ. Tucson's total water portfolio includes 10% transport and 19% nexus water. Thirty-six percent of Tucson's total energy is transport energy and 2% is nexus energy. On a relative scale, nexus energy is small, but in absolute terms it accounts for 2300 TJ; with respect to Tucson's delivered electricity use, nexus energy is 14% of the community's total electricity consumption. This value is comparable to the California Energy Commission's calculation, which indicates that energy for water supply, treatment, and end-uses of residential, commercial, and industrial sectors is about 14% in 2001.[58] Water related energy use values, however, vary in the literature because of the difficulty in calculating the energy for end-uses of water.[41]

2.3.4 | Sensitivity Analysis

Two sensitivity analyses are also performed: demand reductions and portfolio alterations. A 20% decrease in water demand across all sources equates directly to a 20% decrease in energy for water and a 20% decrease in transport water. A 15% decrease in energy demand across all sources confers about an 18% decrease in water for energy and a 15% decrease in transport energy. For the second sensitivity analysis, the total water demand for Tucson remains the same while the water portfolio is altered to reflect the migration away from groundwater sources to heavier reliance on CAP water. Total energy for water increases from 2300 to 2900 TJ when increasing the percent of water supplied by CAP from approximately 40% to 75%, decreasing groundwater from 50% to 15%. Transport water increases by about 14%. For the energy portfolio, 15% of the total energy portfolio is switched to PV based electricity. This results in approximately a 17% water reduction and a 13% transport energy reduction.

2.4 | DISCUSSION

Planning and management for water and energy is not completed in an integrated manner. As a consequence, nexus resources are not considered in decision-making. Transport resources are also rarely considered, and even these transport resources require nexus resources. The WEN tool is designed to present delivered, transport, and nexus resource use with respect to the community of interest. The results from the Tucson case study exemplify how a community's geographic location dictates the source of its water and energy; the amount of treatment, processing, or refinement required for using its resources; the distance its water and energy must be conveyed or transported; and end demand. All of these factors play a role in the amount of delivered, transport, and nexus resources a community uses.

2.4.1 | Geographic Influence

During the mid 1990s, Tucson began to import billions of gallons of water from the Colorado River to reduce its groundwater overdraft.[52] Such shortages are not unique to water or this region. Tucson Electric Power anticipated natural gas and oil shortages for electricity generation during the mid 1900s, leading to the formation of coal utilities more than 320 km northeast of the city.[59] As Tucson continued to grow throughout the mid to late 1900s, there was an increase in demand for both water and energy. To fulfill these demands and reduce the localized stresses associated with consumption, the community expanded its infrastructure and, thus, its "extent" as a resource sink—a similar approach taken by many cities around the world.

The energy required to acquire, treat, and locally distribute Tucson's water is dependent on the source of water, distance from the source to community, and type of conveyance. Although groundwater and recycled water require energy for acquisition, both options are about 20 times less energy intensive than conveying water from northern to southern Arizona through the CAP project.

Recycled water requires about 130 times more energy per unit of water for treatment than CAP water or groundwater. Using CAP or recycled water increases energy demands.

Results of the sensitivity analysis indicate how impacts are changed depending on resource choices. Increasing Tucson's use of CAP water to reduce local groundwater stresses will increase both transport water and nexus energy. Tucson is not the only city dealing with such a conundrum; other cities are also considering untraditional methods to increase supplies and paying more for their growing needs.[60] The prediction that urban water use will reduce farm acreage in the West[60] is a direct recognition of the link between the increasingly growing urban center and the increasingly barren hinterland.

The location of Tucson also influences what type of energy sources it relies on and each type determines the amount of water necessary for processing, refining, and other stages of the source's fuel cycle. Transportation of primary energy sources and transmission of electricity are reliant on the type of source, distance from the source to community, and type of transportation.[61] Tucson's decision to rely on coal due to shortages in natural gas alters the amount of transport energy and nexus water consumed. Coal-based electricity generation outputs approximately 35% of the primary energy consumed; consequently, it requires a significant amount of transport energy. Coal used for electric power requires more water than primary uses of natural gas; water is not only demanded for coal's fuel cycle and transportation, but also for electricity generation and transmission. The location of the power plant determines both the distance and the mode of transportation to move a supply source from where it is mined and processed to the power plant. Some electricity plants have railroad infrastructure, while others rely on truck transportation, and trucks require more energy per tonne-kilometer than rail freight cars.[62]

It is important to note that the purpose of the WEN Tool and my case study is not to suggest that Tucson is unsustainable, but to highlight the importance of using water-energy interrelationships to support future resource management decisions and to promote community resilience to lower resource states.

2.4.2 | Resource Islands

Geography contributes to understanding flows within and between nature and society; changes in spatial flows reshape how place and space are defined.[63] An urban resource island, by my definition, is a densely populated area that controls the flow of resources through a region to increase its water and energy availability.

One example of a resource island in the field of ecology is a shrub mound of enriched soil, usually occurring in arid to semiarid desert ecosystems.[64] The shade and leaf litter provided by individual shrubs[42] lower surface temperatures, and increase nutrient deposition and soil moisture.[65] An individual plant can create a microecosystem that concentrates nutrients and fosters seedling survival and growth by continuing to move available resources (e.g., sediment, moisture, and nutrients) away from the intershrub area by wind and water; autogenic factors create positive feedbacks, further concentrating resources.[43,66,67] Such processes suggest increased desertification in the surrounding regions of a resource island.[43]

Just as the formation and growth of an ecological resource island determines the flow of resources through an ecosystem, a developing and expanding urban center controls the flow of water and energy resources through a region. With increase in growth, there is an increase in demand and external resources are tapped to alleviate local stress. With the development of water and energy infrastructure, the extent of a resource island can be expanded so long as engineering solutions are developed and implemented. The extent, however, also has roots in its geographic location; geography characterizes a community's climate, accessibility (i.e., size, culture, economic development, land features), and supply of water and energy resources, all of which dictate its water and energy demand. Ultimately, these factors all influence each other and create feedback loops.

The analogy between ecological and urban resource islands is clear at the level of a community's water and energy demand and feedback loops. But, can the parallel between these two concepts of resource islands be taken a step further? The development of ecological resource islands is an important step in transitioning from semiarid grassland to arid shrubland ecosystems and dictates water and resource movement within the ecosystem.[43] The stability of this transition may have limited resilience and be prone to shifts toward lower resource states, hinting that such a state may be highly irreversible.[68] I propose that there is also such a vulnerability argument for urban resource islands.

Because exploitation of local resources increases the difficultly with which urban areas can acquire resources in the future, urban communities are vulnerable to urban desertification. Acquisition of distant resources not only affects other communities, but it also has the potential to increase water and energy demands overall—water and energy are both lost and consumed as they are transported from outside to inside the urban center. The effect is to increase the vulnerability of the urban center. Resource shortages, caused by climate change and variability for example, can lead to significant changes in the vitality of an urban center through a series of complex feedback mechanisms, thereby decreasing its desirability and leading to decline.[69] Consequently, urban resource islands that extend their reach for water and energy resources may have a limited resilience[70] and be prone to lower water and energy states. The WEN tool presented in this chapter is designed with these ideas in mind, making it a useful tool for urban communities planning future resource portfolios.

CHAPTER 2 | SIGNIFICANCE STATEMENT

I develop a tool to quantify the extent to which water and energy are intertwined at the community level. Using the tool for my case study in Tucson, I show how impacts on water and energy change depending on the choices being made. Importing water helps secure water resources as Tucson's local supplies are threatened by groundwater overdraft. With regard to the water-energy nexus, the tradeoff is that conveying water from long distances is 20 times more energy intensive than pumping groundwater. Similar water-energy tradeoffs are being made on the energy front. To satisfy its energy requirements, Tucson imports coal-based electricity from more than 320 km away. Because thermoelectric power plants consume large quantities of water, it is not surprising that these sources are not in a more proximate location. Tucson's coal-based electricity has twice the water intensity of its oil resources and eight times the water intensity of its natural gas resources. Using the urban resource island concept to frame these resources flows promotes communities to think about hidden resource flows and how their resource use can impact surrounding areas.

CHAPTER 3

WATER-FOOD-ENERGY SECURITY: SCRAMBLING FOR RESOURCES OR SOLUTIONS

3.1 | INTRODUCTION

In this chapter I explore three-resource interactions that affect water security, food security, and energy security. Two-resource interactions are important, and I do not dismiss their place in resource management, but here I focus on three primary ways of water-food-energy interactions: water security for public supply and its competition with the agricultural and thermoelectric sectors; food security and its competition for water with the hydroelectric sector; and achieving energy security through the development of biofuels and its competition for water and land with food resources. I acknowledge that there are many other interactions that influence water, food, and energy security, but I am most interested in exploring water's role in the intersection among these three resources and understanding the trade-offs involved in meeting water, food, and energy security goals. Therefore, I begin this chapter by framing water, food, and energy security in the context of the complex network that links the resources together. I then explore water's role in the network; three case studies are used to help illustrate this theme.

3.2 | RESOURCE SECURITY AND NETWORK FUNCTION

3.2.1 | Water Security

Water security (Figure 1.2A) has two components—quantity and quality—both influencing its interactions with food (Figure 1.2B-C) and energy (Figure 1.2H-I). Water is needed for a variety of human and ecosystem purposes, including growing food crops and producing energy. Estimates of blue water withdrawals and consumption, although fraught with uncertainty because of a paucity of available measurements, indicate that large quantities of water are required for energy and for water (Table 3.1).[71-73] Globally, about 70% of freshwater withdrawals are used for agriculture[74,75] and almost 10% are used for energy;[75] water consumption from irrigation is one third of all blue water withdrawn globally.[76]

Demand for water from both sectors is expected to increase with population and economic growth. Urban environments are home to more than half of the world's population, and this fraction is likely to grow.[75] Industrialization and urbanization are likely to change resource demand patterns. In the United States (US), for instance, agricultural withdrawals (~35%) rank second to the thermoelectric sector (~50%), and the public sector accounts for just over 10% of withdrawals.[77] Urbanization can increase domestic water withdrawals and consumption, as well as wastewater, even with efficiency gains.

Food and energy resources affect the quality of water resources, and the quality of water resources affect food and energy production. Fertilizer and biocide residues in runoff from agricultural fields can cause hypoxia and contaminate surface water and groundwater, respectively;[78] feedlot runoff increases microbiological risks.[79] Poor crop-land management can result in high soil erosion rates, leading to sedimentation and high turbidity in surface waters.[80] Drilling for oil and gas wells produces contaminated groundwater if not treated properly, and coal mining can lead to acid drainage if not managed properly. Thermoelectric plants can, during low flows, pollute rivers thermally.[81] Water quality also affects the quality of food and the efficiency of energy production. Furthermore, water contaminated with organic and inorganic trace elements may require treatment prior to use, and this treatment requires energy.

Table 3.1 | Global blue water use (km^3/yr) for energy and for agriculture

Blue Water Use	Water for Energy		Water for Agriculture	
	Thermoelectric	Hydropower	Biofuels	Food Crops
Withdrawal	568[1]	--[2]	44[3]	2900[4]
Consumption	25[1]	50[1]	16[3]	1200[4]

[1] Median values reported.[71]

[2] Water use for energy sector activities not shown are smaller in magnitude than those included.

[3] Consumption is calculated assuming the same fractional value as that reported for all irrigated agriculture. Although direct use of biomass dwarfs biofuels and water consumption is correspondingly large, I assume that biomass for burning is not irrigated and therefore is not part of a blue water accounting.[72]

[4] Water for irrigation.[73]

3.2.2 | Food Security

Global food resources are highly dependent on water and energy inputs (Figure 1.2C-E). Irrigation, fertilizers and biocides, powered mechanical farm equipment, land-crop intensification, improved germplasm and genetically modified organisms, and landless livestock farming have all contributed to increased yields over the past three centuries.[82,83] Intensification of crop and livestock production has spared expansion of agricultural land, but ecosystems are affected from the concentrated outputs from food systems (i.e., non-point pollution).[83] Thus, there is a an additional feedback relating water, food and energy: blue and green water are needed to maintain crop and livestock production, and fertilizer, biocide, sediment, and coliform residues from crop and livestock production detrimentally impact water quality, thus necessitating additional energy to treat the water.

As a result of increased growth in population, income, and urbanization, food demand is projected to double in the next fifty years. In emerging markets, diets and the overall quality of life will change with affluence.[75] Food waste is a serious concern and, unfortunately, is most prevalent on a per capita basis in developed countries.[84] As wealth increases, diets will diversify and demand will increase for processed food, meat, and dairy. Over the past three decades, consumption patterns in Asia have moved away from cereals and towards animal protein.[85] Diversifying food portfolios to incorporate more livestock and less cereal is both water and energy intensive.[86] For example, between the 1960s and early 2000s, China’s per capita water requirement for food production increased by a factor of 3.4 as a result of increased meat consumption.[87] Globally, the agricultural sector accounts for 22% of greenhouse gas emissions, and nearly 80% of these emissions are attributed to livestock production.[82] Growth in food demand, combined with stress from anthropogenic climate change, will intensify competition for both water and energy resources.

3.2.3 | Energy Security

As developed countries work to maintain energy security, but shift towards a low-carbon energy future, demand for biofuels is growing.[88] Mandates in the US and European Union (EU) have driven production of biofuels.[89] The EU Biofuels Directive requires member countries to realize a 10% share of biofuels in the liquid fuels market by 2020, and the US Renewable Fuel Standard calls for production of 26 billion gallons of biofuels by 2022, with 21 billion gallons from second-generation (cellulosic) processes.[f] Despite the mandates and the increased production of biofuels over the past decade, the generally accepted view is that biofuels may have a limited place in the world, and that care needs to be taken to avoid impacts on water and food.[88,90] Thus, the use of biofuels to achieve energy security lends itself to a three-resource interaction among energy, food, and water (Figure 1.2F-H).

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[f] In January 2013 a federal appeals court vacated the US Environmental Protection Agency stipulation regarding cellulosic biofuels.

The importance of biofuels for energy security and for reducing emissions of greenhouse gasses has been debated.[88,91,92] In theory, biofuels can be produced with lower lifecycle greenhouse gas emissions than fossil fuels and with little competition to food production,[93] but the current generation of biofuels requires significant land, water, and energy resources[78,88] and can even result in large carbon debts.[92] In a global context, there is reason to question whether growth in the biofuels market can occur without resulting in food shortages over the next several decades.[94] Although land resources also may become scarce in the future,[95] the main way that stress manifests itself in the current energy security discussion is through water.[96]

The water footprint of transportation could increase by a factor of 10 by 2030.[97] Biofuel impacts on water resources include both quantity and quality of water.[78,98] Energy is needed to pump groundwater and power large-scale irrigation systems, and water is needed to produce the energy for these processes. Fertilizers increase the productivity of plants used for biofuels, but fertilizers are energy intensive and can contaminate ground- and surface waters.[99-101] Thus, the requirements of water for biofuels may add significantly to the already vexed issue of providing food for a growing global population while maintaining water of adequate quantity and quality to preserve ecosystem services.[102] The impacts of land conversion also must be weighed, in terms of greenhouse gas emissions as well as displacement of arable land away from food production.[103,104]

3.3 | WATER'S ROLE IN THREE-RESOURCE INTERACTIONS

I argue that water scarcity typically is the proximate cause of competition in the water-food-energy security arena. Increasing non-agricultural demands on water, growing food demands, changing food preferences, and demands for biofuels all place increasing pressure on water resources.[21]

Economic policy makers have acknowledged that water resources, and adequate management of these resources, play a vital role in national economies but are largely unaccounted for in planning.[105] Underpinning all aspects of development, water links together food and energy and is central to green growth, sustainable economies, and reliable resource supply. As noted by UNECSO,[106] "it is the only medium that links sectors and through which major global crises can be jointly addressed." I use three case studies to explore water security, food security, and energy security three-resource interactions and show how water drives the interrelationship among the three resources.

3.3.1 | Apalachicola-Chattahoochee-Flint River Basin (ACF)

The ACF river basin is located in southeastern US. The Chattahoochee River begins in northeastern Georgia and is impounded by dams operated by the US Army Corps of Engineers. One of the important upstream reservoirs, Lake Sidney Lanier, provides flood control and recreation, as well as residential and commercial water for Atlanta's metropolitan area. The upstream demands often limit downstream flow and, concomitantly, thermoelectric power[g] and hydropower generation (Figure 3.1). The Flint River Basin primarily supports the agricultural economy in Georgia. The Chattahoochee and Flint rivers meet and flow into Florida's Apalachicola River and Bay, where the preservation of reliable flow is critical for navigational purposes and ecological services. The Apalachicola Bay is home to one of the world's most biodiverse conservation sites and supports a multibillion-dollar oyster industry.[107]

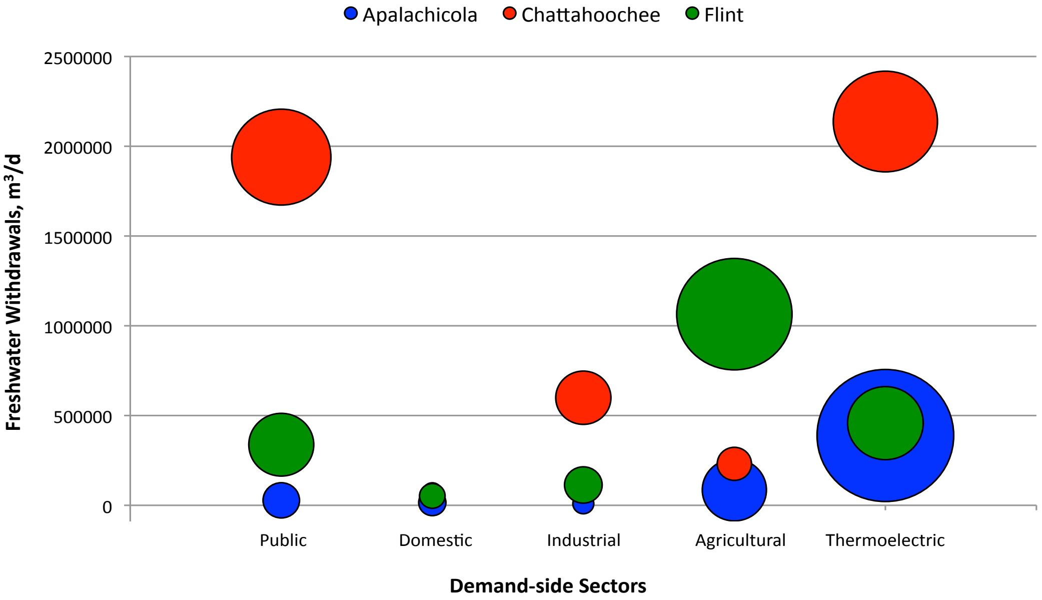

Figure 3.1 | Water withdrawals by sector for each of the rivers in the ACF River Basin

Colors correspond to the Rivers in the basin. Y-axis represents the amount of freshwater withdrawal in cubic meters per day (m^3/d). Circle sizes correspond to the percent demand each sector withdrawals within its corresponding river compared to the total demand of all sectors within the corresponding river. Public supply and thermoelectric withdrawals are the dominating sectors in the Chattahoochee River. The Apalachicola supports primarily thermoelectric power and the Flint River Basin supports primarily the agricultural economy in Georgia.[108]

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[g] The distinction between water that is consumed and water that is withdrawn is not trivial, especially with regard to thermoelectric plants. Recirculating systems consume twice as much water as once-through facilities, but once-through facilities often return water at an increased water temperature.

The ACF river basin experienced positive population growth from 2000-2010. The Atlanta-Sandy Springs-Marietta metropolitan area population increased by more than 90,000 from 2010 to 2011—the seventh largest increase in population in the US.[109] As a result of this urban growth, the portfolio of freshwater withdrawal has changed over the past three decades. In 2005, public supply withdrawals from the ACF river basin accounted for more than 30% of total withdrawals (Figure 3.2B); in 1970, public supply withdrawals were less than 10%, which is comparable to the national proportion of public supply freshwater withdrawals over the past 35 years (Figure 3.2A). Although public supply withdrawals are returned to the system and available for other uses, discharge is treated (requiring energy) before it is released back into surface water systems. Wastewater discharge increased by more than 80% between 1990 and 2005, primarily as a result of urban growth within the ACF and extensions of service outside the basin.

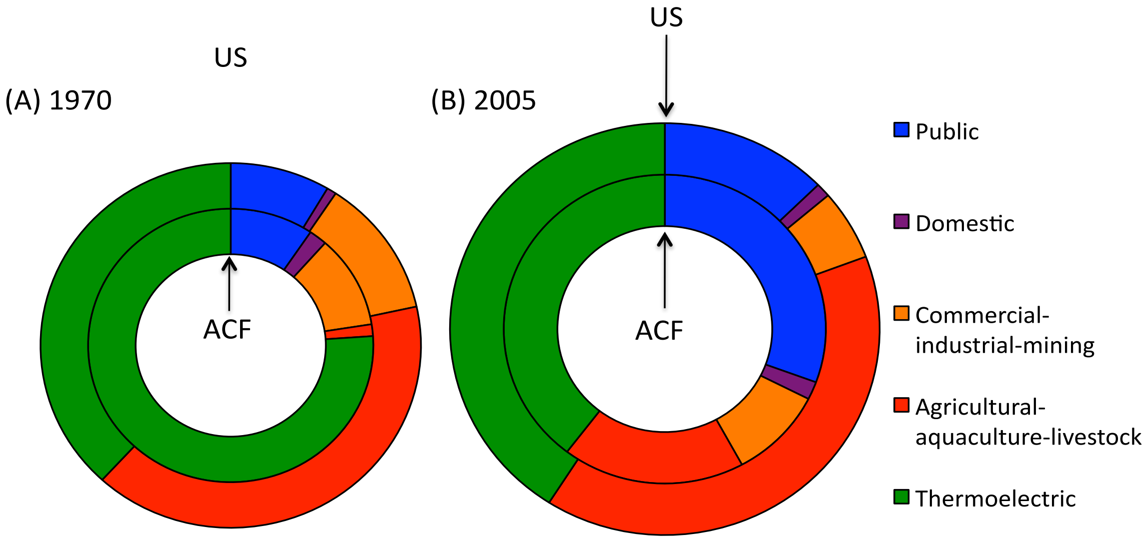

Figure 3.2 | Changing freshwater withdrawal demand patterns from (A) 1970 to (B) 2005

The outer circles show freshwater withdrawal (surface- and groundwater) percentages by sector for the United States.[110] The inner circles show freshwater withdrawal percentages by sector for the ACF basin.[108] In 2005, total withdrawals in the US increased by 10% 1970 values, and total withdrawals in the ACF river basin increased by 35% 1970 values.

In addition to significant urbanization in the past three decades, the river basin has experienced numerous multi-year droughts,[111] and drought related stresses are projected to grow more severe over the next century. The National Climate Assessment and Development Advisory Committee[112] identified the southeast as a region "exceptionally vulnerable" to climate variability and change. Drought events intensify water scarcity, and this stress increases the strength of the links among water resources and food and energy resources, transforming traditionally two-resource interactions into three-resource interactions. In years when rainfall is plentiful, there is likely to be enough water to satisfy demands placed by the urban population, the food and energy sectors, and ecosystem services.

In drought years, however, choices must be made. Downstream users need adequate water in-stream, but upstream users withdraw and consume water for their needs. When this spatial dimension of water is juxtaposed with the temporal component of supply and demand, management of water resources gets complicated. The agricultural sector is most likely to irrigate crops during the summer months, the same time that Apalachicola Bay oysters are in need of fresh water[113] and thermo- and hydro-electric plants are running at full production to satisfy the demand for air conditioning. Droughts in the ACF cause competition for water, but only a regional stress on water resources that also affects only regional food and energy production; there are no substantial implications for communities outside the basin. In fact, as a result of the global market that operates for a developed country, regional food security is not affected very much by drought in the ACF.

Conventional management of the ACF River Basin has focused on infrastructure solutions to increase supply of water resources. This approach often fails to gain widespread acceptance. Stakeholders most worried about the environment are not often involved in decision-making meetings[113] and involving them in the future may be politically infeasible if there is a pre-existing political conflict. This not only causes distrust among competitive water-users, but also overlooks the strong link between ecosystem services and economic vitality.[114-116] Feldman[113] suggests taking actions that are reversible and experimental in nature so that the parties involved can learn from mistakes and incrementally improve policy. Because tensions have escalated in the ACF during drought conditions, another challenge is to define specific plans to account for time-variable conditions, but at present, few water agreements include clauses for temporal changes in flow, intensifying conflicts during drought events.[117] One part of a path to determining the extent of stress on water during drought in the future will be choices about how electricity is supplied to the ACF.[118,119] Overall, an integrated water-energy management approach that involves a range of stakeholders is recognized as necessary to resolve water disputes in the ACF.[111,120]

3.3.2 | Sri Lanka

The current picture of Sri Lanka—a nation that is heavily reliant on agriculture to self-sufficiently maintain food security but which is rapidly developing and expanding its urban infrastructure—is not uncommon within the region or among developing nations throughout the world. Sri Lanka is a tropical island nation of some 66,000 km^2 with plentiful water availability on average; the mean annual rainfall of almost 2,000 millimeters (mm) is unevenly spatially distributed, with a large "dry zone" covering much of the arable land of the country. Sri Lanka's population has increased modestly and is expected to continue to increase at about a 1% growth rate per year for the next few decades.

Agricultural production is a heavily prioritized sector in Sri Lanka, with national self-sufficiency in rice production a food security goal and with a strong cultural connection to paddy farming. Agriculture accounts for only about 15% of total Gross Domestic Product, yet it covers about 40% of total land area and incorporates more than 25% of the labor force.[121] Rice production has increased dramatically over the past several decades, in large part due to a government resettlement program that opens land to paddy farmers in the dry zone through provision of irrigation water. This resettlement effort continues under a plan to develop urban centers in the Southern, Eastern, North Central and Northern provinces that will expand access to electricity and piped water to a population that is projected to reach 25 million by 2030.[122] Historically, more than 90% of Sri Lanka's electricity was produced through hydropower, but this percentage dropped to about 45% in 2010.[123] Total hydropower output has increased only gradually since 1990, because new sites for development are now limited.[124] In 1990, hydroelectric power plants supplied about 3100 giga-watt hours (GWh) to the national grid and there was a tiny amount of electricity generated by oil-fuelled thermal power plants; in 2007, hydropower supplied 3950 GWh and thermal plants supplied 5900 GWh.[124] The increased reliance on thermal power generation notwithstanding, hydropower still represents a very important source of electricity (Figure 3.3)

The process of making decisions about allocation of water between irrigation and hydropower[h,126] in Sri Lanka is complex; allocation of water takes into account seasonal precipitation projections and includes a wide-range of stakeholders. Traditionally, irrigation-hydroelectricity trade-offs are a matter of timing; that is, the conflict is more about setting the discharge schedule so that it

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[h] Although hydropower is considered often to be non-consumptive in terms of water, an analysis of large hydroelectric dams worldwide indicates that the blue water consumption from them amounts to about 10% of the blue water consumed by crops.[126]

either meets peak electricity demand or peak agricultural demand. In Sri Lanka, however, the decision has a strong spatiotemporal component because both systems are gravity dependent. The reservoirs and their releases are set at a high elevation. The potential energy of water can be either used to divert water into a canal for water intensive flood irrigation that produces twice as much output in the north than in the east or to maintain the natural flow of water, producing twice as much hydroelectricity in the east than in the north. Therefore, even in years when rainfall is plentiful, there is an uncertainty component that results from the spatial and temporal distribution of water. The correlation between rainfall and both paddy production and hydropower generation for the country suggests that trade-offs are currently being made (Figure 3.4).

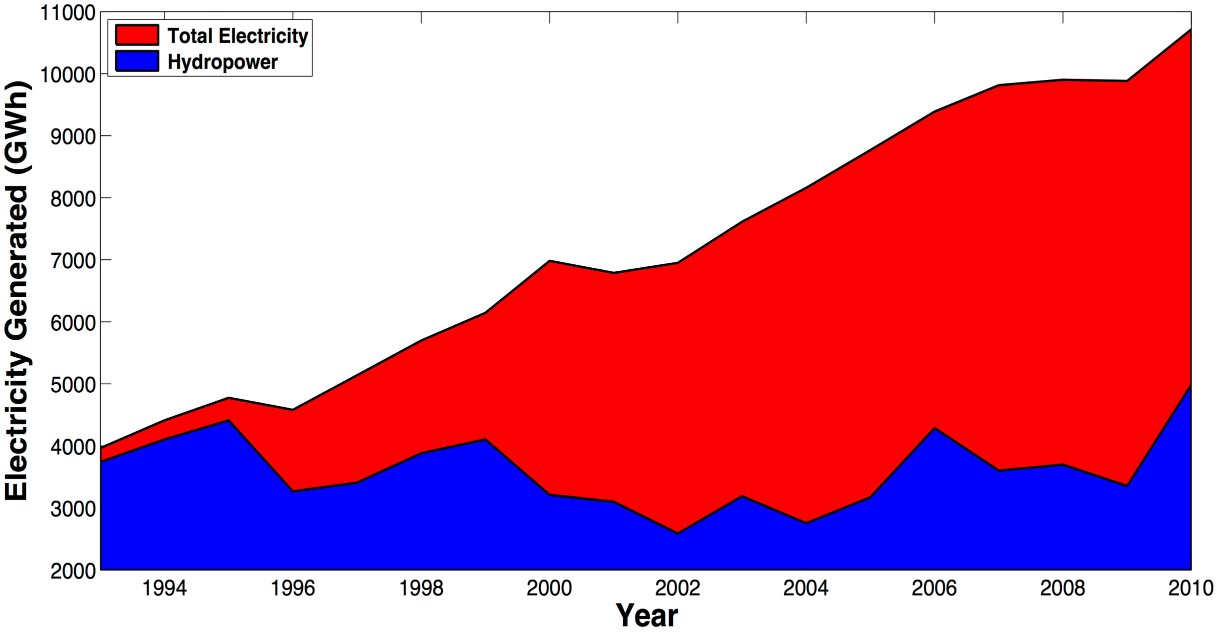

Figure 3.3 | Electricity generation in Sri Lanka

Hydropower supplied over 90% of the total in the early 1990's but supplies only about 40% currently.[123,125]

Current drought events have highlighted Sri Lanka's water vulnerabilities and the trade-offs present in managing its water resources. Countries suffering from water scarcity often import water intensive goods so that they can focus their limited resources on those that will result in a net benefit or a comparative advantage in production. This concept of water embedded in products, including its application to food and crops, is referred to as virtual water.[31,127,128] Sri Lanka endured back-to-back drier than normal monsoon seasons in the late 1990s. As a result, the country rose to the top of the global virtual water importers during those years,[129] allowing them to secure their people with food. Research looking at the role of virtual water to achieve food security and other national goals suggests that focusing on virtual water alone will not be sufficient in determining optimal policies.[130,131] In the short term, it is recognized that the globalization of virtual water prevents conflicts and increases food security.[129,132]

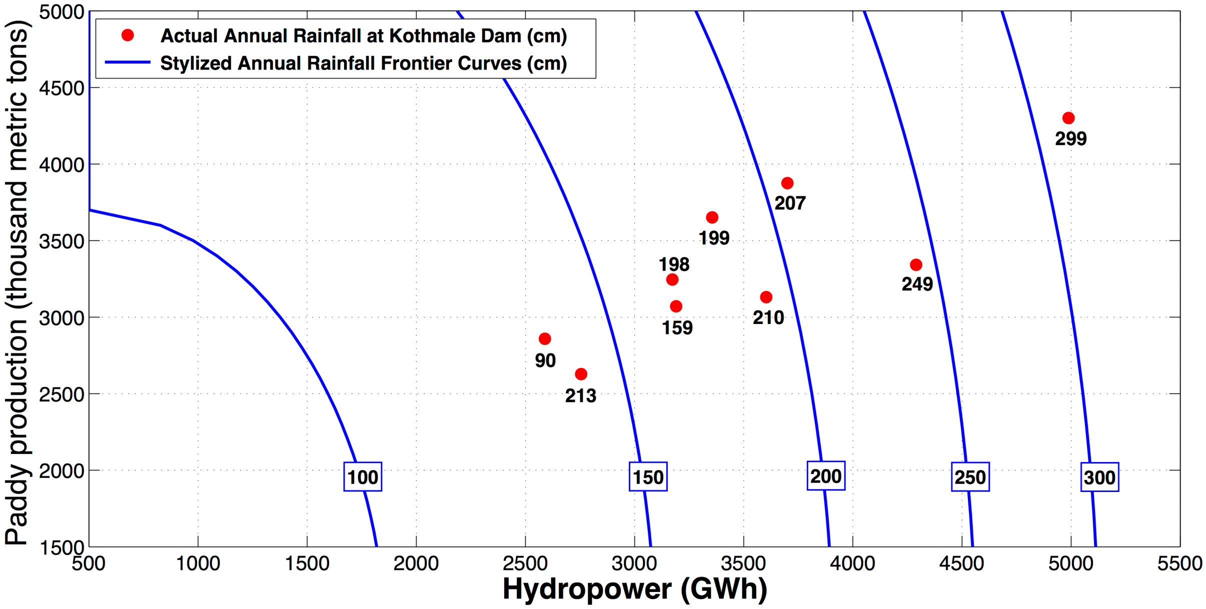

Figure 3.4 | Tradeoff frontiers between hydropower and irrigation

The annual rainfall at Kothmale Dam,[123] a large reservoir at the headwaters of the Mahaweli system, is used as a proxy for water availability in the system; annual rainfall is plotted as red circles and labeled in centimeters (cm). The blue curves are stylized tradeoff frontiers for annual rainfall of 100, 150, 200, 250, and 300 cm. For high rainfall (e.g., 300 cm), the hypothesis is that there is enough water that high levels of both paddy production and hydropower are possible—there is little tradeoff. For low rainfall (e.g., 150 cm) the hypothesis is that tradeoffs are significant; for example, a change in hydropower from about 2200 GWh to 3100 GWh results in a drop in paddy production from $5x10^6$ to $1.5x10^6$ metric tons (paddy production and hydropower generation data are at the national level). The data is not perfect (e.g., the actual annual rainfall outlier represented by 213 cm), but a general tradeoff trend is noticeable.

In the future, government policies supporting domestic rice production and a strong historic and cultural attachment to paddy irrigation suggest that the agricultural sector is likely to be preferred. Nevertheless, the government's current emphasis on economic growth hints that priorities may change. Addressing problems of agricultural water shortage already is a consideration in Sri Lanka as farmers have adapted to drought. A variety of measures have proved to be at least partially successful, including using drought tolerant crops, adopting new irrigation technologies, and engaging in collective activities to minimize extreme impacts to individuals.[133,134] Additional actions will be required in the future, however.

Urbanization and economic growth are rooted in increased energy production, also increasing water demands. Significantly more water might be used to generate hydropower if farmers were convinced to change their behavior with regard to irrigation, but achievement of this goal may be socially, politically, culturally, or economically infeasible.[135] As Manthrithilake and Liyanagama[136] state, "The water allocation process within this 'water–food–energy nexus' with its complex interconnections is a difficult task and has a significant impact on the social and economic life of the country." The use of the authors' simulation model in a participatory process suggest that informed decision-making may play an important role in achieving food and energy security for Sri Lanka.[136]

3.3.3 | Brazil

Despite some pessimism about the overall feasibility of having biofuels play a large role in a sustainable global water-food-energy framework, is it possible to have regional exceptions? Brazil is a country that has made very significant investments in development of a biofuel industry, beginning several decades ago.[137] In 1975, Brazil established a program, Proalcool, to convert sugar to ethanol. The move came two years after the 1973 oil crisis, but the program was really aimed more at shoring up the sugar cane industry than producing renewable energy. In 1979, following the Iran-Iraq war, however, the Brazilian government explicitly moved ahead with ambitious biofuel plans as the main goal of meeting energy security needs. Brazil is now a major exporter of ethanol. According to the US Energy Information Administration,[138] Brazil produced about 23% of the total biofuels globally in 2011, and it supplied about 20% of internal production of liquid fuels (Figure 3.5).

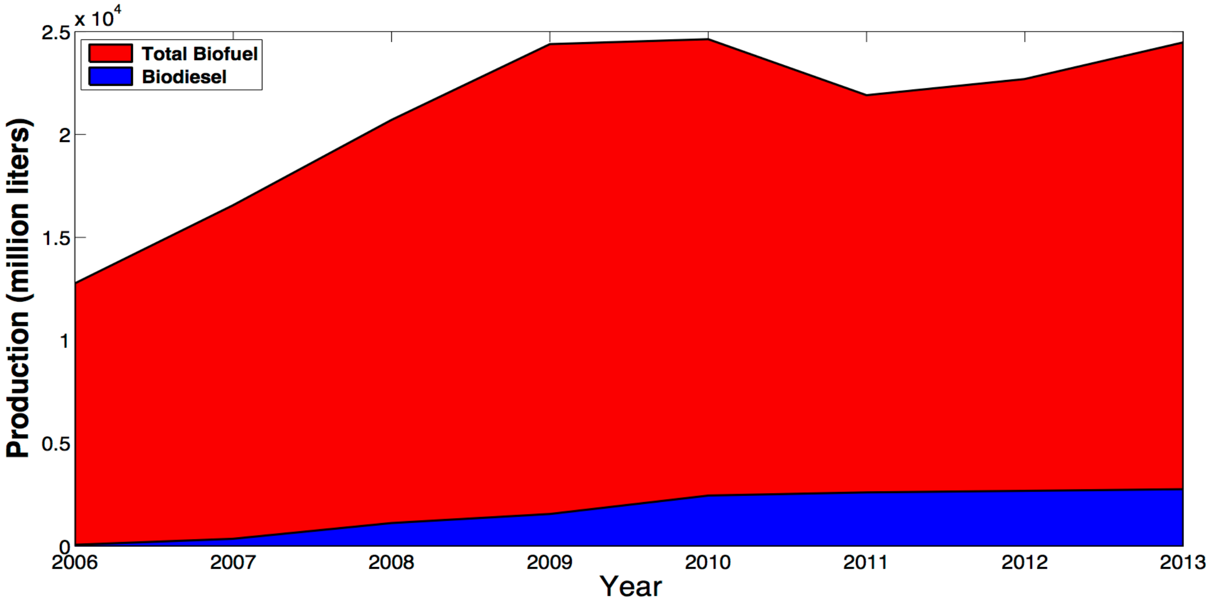

Figure 3.5 | Biofuel (biodiesel plus bioethanol) production in Brazil

Biodiesel feedstock is primarily soybeans (77%) with animal tallow second (16%).[138]

Brazil is a country with abundant water and land resources.[i,139] A direct effect of biofuel production on water resources within the country is not expected, but there are concerns, as with all intensive crop growth, that water quality could be adversely affected due to application of fertilizers and pesticides.[140] The expansion of land clearing, its potential impact on biodiversity,[141] and the potential of biofuels to take over cropland are of concern. Land use change for sugar cane production to produce ethanol, to date, has been mainly through displacement of pasture land and has not been at the cost of deforestation[142]. Nevertheless, a concern remains for the future. The proximity of the cane growing areas to the remnants of the Atlantic forest poses a potential threat to that fragile ecosystem.[143] Indirect land-use changes could threaten the Amazon rainforest, for example by expansion of soy farms.[144] The current ban on expansion of soy farming into the Amazon forest has been successful, and it is important

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[i] This case study does not include dams, hydroelectricity, or the Amazon River specifically. Three-resource interactions among water, food, and hydroelectricity do occur in Brazil, but because I cover similar three-resource interactions in the two previous case studies, I use Brazil to explore the water-food-biofuel nexus.

to maintain it.[140,145] Currently, water and land resources in Brazil appear adequate for expansion of both biofuel and food production,[146] so a three-resource competition among water, food, and energy within the country itself is unlikely to manifest in the next few decades. Concern that food prices affected by ethanol production in Brazil may impact food security in other countries also has not been evident to date.[147] This is not to say that there are no problems and that finding solutions to them is not critically important. The recommended actions to promote sustainability include adopting measures to control erosion, controlling nitrogen runoff, protecting riparian ecosystems, and promoting productivity growth on existing agricultural land to avoid expansion into natural ecosystems.[140,148]

3.4 | WATER AS THE DRIVING FORCE

The distribution of water, food, and energy resources is uneven; supplies and demands vary in both space and time. Water and energy reserves do not respect political boundaries,[149] but water has additional dimensions of complexity—it is a finite, mobile resource.[150] Water available as groundwater can be consumed faster than reserves are maintained and is often non renewable on human time scales. Water available as surface water has upstream and downstream users, is prone to variability in flow, and usually is considered renewable.

Because of the temporal and spatial dimensions of water supply (i.e., weather is chaotic), water disputes can occur even in areas where water is plentiful on average. The ACF is an illustrative example of how multiple, competing demand-side sectors, combined with population and urban growth, extreme drought events, and lack of collective action, can cause tensions over water resources in a traditionally water abundant area.

Upstream and downstream users often have conflicting needs; some users consume, withdraw, or divert water while others use the water in-situ. Sri Lanka's choices involving food and energy security are a descriptive example of trade-offs resulting from stressors and limiters.

The Brazil case study examining biofuel production highlights the importance of water in driving three-resource interactions. In the absence of water stress, there is less competition for water and fewer trade-offs to be made; consequently, water-food-energy interrelationships are limited to two-way, two-resource interactions.

As mentioned above, I think that water occupies a special niche in our discussion. Food and energy are private goods and sold in the global market as commodities. Water, on the other hand, is both a public and private good; there are human needs for water (e.g., drinking, bathing),[151] but there also are human demands for water as a commodity (e.g., landscaping, car washing).[150] Nevertheless, water is undervalued[152] and rarely priced as a commodity. Although water does not have substitutes, at least not in the traditional sense, food and energy resources are often transported over large distances, and both resources have substitutes. Because it is not economically feasible to move water over large distances because of its weight,[150] communities with water deficits or with a comparative disadvantage in water resources strategically import virtual water—that is, water embedded in commodities.[31,128,130]

Virtual water embedded in various products (e.g., grain) is often underpriced, so the importing economies get a subsidized bargain, while meeting their water needs without confronting the underlying issue of water scarcity.[31] Although virtual water trade can help achieve food security for communities that are faced with immediate food and energy trade-offs (e.g., Sri Lanka in the late 1990s), there are potential drawbacks of global reliance on strong networks. D'Odorico et al.[70] suggest that long-term reliance on the global trade of virtual water reduces societal resilience; in times of extreme water scarcity, there are fewer options available. Thus, "land grabbing," or the acquisition of arable land in developing countries, is a recent trend amongst water deficient regions hoping to gain some control of virtual water. Land grabbing allows governments to increase food security but also provides opportunities for biofuel production.[153] Therefore, it is no surprise that the "land grabbing" phenomenon is associated with the acquisition of freshwater resources associated with the purchased land, as much as it is associated with the acquisition of the land itself.[154]

The water requirements for biofuels often put biofuels at odds with food and energy security, but this is not the case for Brazil. It is not surprising, therefore, that almost 5% of the total global grabbed land is in Brazil, accounting for ~20 billion m^3 of grabbed green water.[155] If water stress did strike Brazil, it may be likely that countries dependent on Brazil's virtual water exports (i.e., crops and biofuels) will be affected, but the in-country impact likely will be small.

Water holds great cultural and spiritual significance and, therefore political trade-offs and trans-boundary trade-offs are laden with more than simple economic concerns. Water is a symbolic resource,[150,156] adding an additional layer of complexity, as illustrated by our Sri Lanka case study—agriculture is an important dimension not only in food security, but also rural livelihood. With growth and projected climate change, Sri Lanka will be faced with making trade-offs: water for energy and economic growth or water for agriculture, food security, and cultural preservation.[157] This trade-off between water for food and water for energy is not unique to Sri Lanka or countries in south Asia. "There is a broad agreement…that there will be significantly increasing water scarcity that will turn 'water' into a key, or the key, limiting factor in food production and livelihoods generation for poor people in…rural Asia and most of Africa, with particular severe water scarcity in the bread baskets of northwest India and northern China."[3]

3.5 | A LOOK TO THE FUTURE

Under current global pressures, solutions to overcome scarcity in a way that meets all demands are sought. I have argued that water resources drive water-food-energy interactions, but I recognize that solutions need to be all encompassing:

> *A number of international organizations highlight the water–food–energy nexus as illustrating the most difficult choices, risks and uncertainties facing policy-makers today. Examples abound of the various intended or unintended consequences of favoring one pillar over the other (e.g. food security versus energy security). A key challenge is to incorporate the complex interconnections of risks into response strategies that are integrated and take into account the many relevant stakeholders.*[105]

CHAPTER 3 | SIGNIFICANCE STATEMENT

I use the ACF Basin, the Mahaweli River Basin, and Brazil to deconstruct water's role in the intricate web that links water, food, and energy resources. Although each resource problem presents different challenges, and stakeholder preferences and perceptions vary across the problem sets, case studies are useful for understanding the tradeoffs faced by decision makers and the ramifications of increased stress on water, food, and energy resources.

CHAPTER 4

SRI LANKA'S WATER-ENERGY-FOOD NEXUS: WATER ALLOCATION TRADEOFFS

4.1 | INTRODUCTION

Looking at the water-energy-food trilemma from a global perspective illuminates society's move towards globalizing water through food trade. Importing resources can relieve the physical scarcity of water resources, as well as the political stresses caused by the lack of these resources. Nevertheless, many countries have a strong social and cultural attachment to maintaining a self-sufficient supply of food. In fact, recent research suggests that water scarcity may be less important in determining international trade patterns of food than other factors such as social, cultural, and economic valuing of water.[130,158] A Global perspective on water's impact on energy trade is not as obvious because a significant portion of energy's water portfolio, especially for secondary energy resources, is farther down the supply chain, making it more of a "local" problem. Most resource-society processes play out when local activities intertwine with larger structures so understanding what individual countries need and what they are limited by is central to understanding the tradeoffs they are making. That is, optimal rules in one environment may not translate into optimal rules in another.[159] A framework that allows for broader generalizations but incorporates local, specific information is valuable.[160] In this chapter, I expand upon my Sri Lankan case study in Chapter 3, using the Mahaweli Complex as a microcosm for a localized study of water-food and water-energy tradeoffs.

4.2 | SRI LANKA'S WATER-FOOD AND WATER-ENERGY TRADEOFFS

A number of unique traits complicate Sri Lanka's water resource management: its roots in ancient irrigation systems, its climate, and its eagerness develop its economy. Following Sri Lanka's independence from British rule in the mid twentieth century, irrigation projects were a major component of its economic and political platform. Reservoirs and dams were seen as a means for irrigation, food security, energy, and flood control; although projects span the entire island, the projects that are part of the Mahaweli Complex are most notable (Figure 4.1A). Dams, reservoirs, tunnels and channels were built to carry water from the Mahaweli River to multiple areas in the dry zone to meet the needs of people resettling the dry zone. The emphasis of the project was changed to hydropower in the late 1970's in response to high fuel prices. During periods of high rainfall, there are enough resources for agriculture and hydroelectricity, but current drought events have highlighted the tradeoffs present in managing Sri Lanka's water resources.

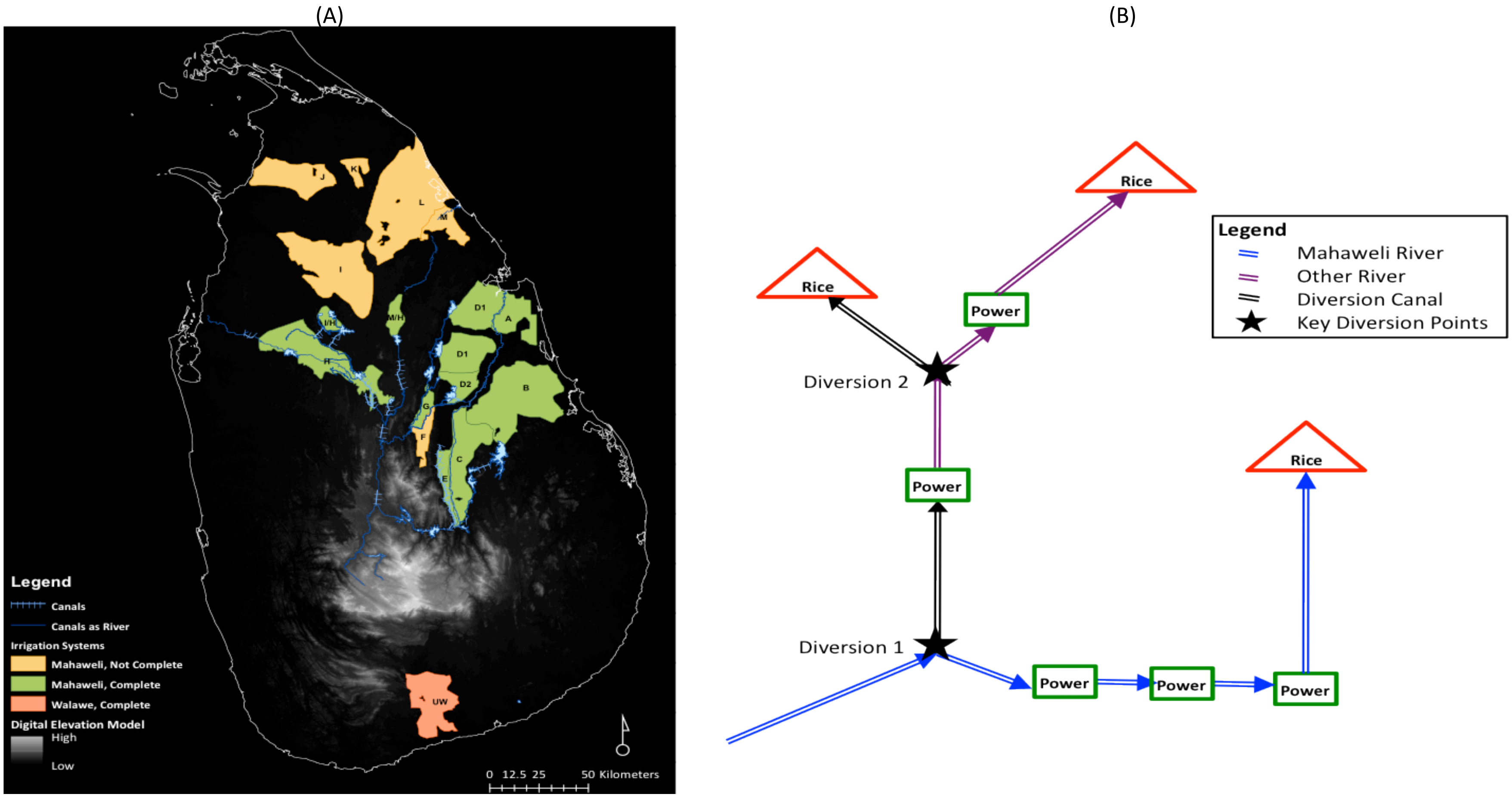

Figure 4.1 | Map and Schematic of Mahaweli Complex

(A) Digital Elevation Map of Sri Lanka with Mahaweli Complex rivers and canals (blue lines) and irrigation schemes (orange shapes). The Mahaweli Complex is gravity fed; water flows naturally from the center of the island (e.g., from highest elevation) to the east (e.g., lower elevation), then up to the northeast of the island (e.g., lowest elevation). (B) Simplified schematic indicating powerplants and irrigation systems, water flows, and diversion points. The first diversion point (e.g., Diversion 1) uses a canal to bring water to northern settlements. The second diversion point (e.g., Diversion 2) brings water to the flagship irrigation system.

Sri Lanka is divided into wet and intermediate zones in the Southwest and a dry zone encompassing the rest of the island; it is the dry zone that has the flat terrain and fertile soil ideal for growing rice, Sri Lanka's staple food.[161] To provide water to the country's flagship irrigation development, two diversion mechanisms were built. The first diversion takes water from the Mahaweli River, which flows naturally east and through three large-head hydroelectric facilities, and channels it to the north (Figure 4.1). This water meets with local inflow where it again hits a second diversion point. A diversion westward provides water to the flagship agricultural settlement, but bypasses a run-of-the-river hydroelectricity facility—foregoing power generation—and two other agricultural settlements.

Current government policies supporting domestic rice production and a strong historic and cultural attachment to paddy (i.e., rice plant) irrigation are consistent with the agricultural sector being preferred. Nevertheless, the government's current emphasis on economic growth and the development of new electricity plants hints that those priorities may change. Should Sri Lanka favor water for energy and economic growth, and thus import rice from the global market? Or, should Sri Lanka favor water for agriculture, food security, and cultural preservation, and import fuel from the global market? This study calculates the economic value associated with water diverted under wet, normal, and dry conditions to understand the economic tradeoffs associated with each unit of water diverted. Recognizing that the technical and economic solution to the problem may not be the social optimum, I engage in a discussion of the political and social constraints as they relate to paddy production.

4.3 | METHODS

Data on the Mahaweli Complex are acquired for 2003-2013 from various stakeholders in Sri Lanka.[162-165] A simplified model of the Mahaweli Complex is produced using current schematic diagrams, shapefiles, and information obtained from stakeholder meetings in Sri Lanka (Figure 4.1). [136,162] This schematic is used to identify the two key diversions in the Mahaweli Complex, as well as each powerplant and irrigation system.

A dynamic mass balance of the Mahaweli Complex is not practical because of data limitations. A model simulating ranges of diversions (0%-100% at both diversions) is created with the assumption that that every unit of water is accounted for downstream; that is, there are no losses or gains for the water diverted and the water left in the natural flowing rivers. This a an approach taken by studies that examine tradeoffs within other Sri Lankan complexes.[166,167] Refer to Appendix C for detailed methods.

4.3.1 | Wet, Normal, and Dry Scenarios

Wet, normal, and dry scenarios are used to examine paddy and electricity production and economic value under the range (i.e., 0-100%) of diversions for diversion one and two (Table 4.1). Each range within each scenario is referred to as a realization. The wet, normal, and dry cases are informed by historical data associated with inflows at Polgolla; that is, the highest inflows and lowest inflows are used to set the high and low case. The high and medium cases for the % of cultivated extent is found by comparing total extent values to historical paddy yield values. The low case for the % of cultivated extent is found by finding the range of extents that provides a tradeoff. A percent of 20 and higher leads to complete crop failure, so any value between one and 19% shows tradeoffs associated with the diversions. Fourteen percent is chosen for the base case scenario, but a sensitivity analysis is used to show how important this value is during the dry season (refer to section 4.3.5 for more details regarding the sensitivity analysis).

Table 4.1 | Attributes of base cases in tradeoff analysis

Item / Base Case	Wet Scenario	Normal Scenario	Dry Scenario
Polgolla diversion (million cubic meters (mcm))	Highest value historically	Midpoint between wet and dry cases	Lowest value historically
Rain amount (mm)	Highest value per system	Ave value per system	Lowest value per system
% cultivated extent	90%	50%	14%

4.3.2 | Paddy and Electricity Production

To calculate the production of paddy and electricity, production curves for each irrigation system and each hydroelectricity plant are used. Exploratory analyses of historical paddy yield data are used to identify a method for creating paddy yield production functions per unit of water depth (i.e., duty). These analyses reveal a maximum duty around four meters, where any additional water does not seem to increase yield, and a minimum duty around 0.5 meters, where any less water results in crop failure. Data with a duty between 0.5 meters and four meters are fit using least squares linear regression. The relationship between powerflows (i.e., volumetric amount of water used to turn turbines) and power production is fit for each hydroelectric facility using least squares linear regression of historical data.

4.3.3 | Economic Valuation

For paddy, farm gate selling prices from 2003-2011 are converted to 2011 Sri Lankan rupees (Rs); 2011 is the most recent data available. The highest and lowest prices in are identified to provide a range for the tradeoff analysis. For electricity, selling prices and costs to import fuel are identified using the same time periods as paddy. These values are converted to 2011 Sri Lankan rupees (Rs); the highest and lowest prices are identified to provide a range for the tradeoff analysis

- Nadu farm gate selling prices: 25 - 43 Rs/kilogram (kg)
- CEB Selling Prices: 13 – 17 Rs/Kilowatt hour (KWh)
- CEB Fuel Costs: 13 – 21.00 Rs/KWh

Because prices of imported rice are not available, a range is approximated using the information available. Sri Lanka has a 20 Rs tariff on imported rice.[168] It is assumed that the tariff is placed on the imported rice to make it at least as expensive as domestic rice. Any imported rice would also need to be adjusted to farm-gate prices so that it is comparable with domestic farm-gate prices; farm gate prices range from 70-80% of wholesale prices.

- Assumed farm gate import price: 7 – 32 Rs/kg

For the first set of runs, the lowest values of paddy and electricity are used because they represent present-day values best. The moderate and high prices of paddy and electricity are analyzed using a sensitivity analysis (see section 4.3.5).

Benefits are calculated by multiplying each unit of paddy produced by the farm-gate price of paddy and by multiplying each unit of power produced by the selling price of electricity. Costs are calculated for each scenario using the maximum outcome for energy and paddy in each scenario as the reference point for all realizations in the scenario. For each scenario, the actual amount of energy and paddy under each realization is subtracted from the reference point to calculate the amount of energy or paddy that is foregone. The amount of paddy and electricity foregone is multiplied by the cost of importing these resources. For each realization in the scenario, the costs are subtracted from the benefits and a direct search optimization is used. The direct search optimization allows for an understanding of how the costs and benefits change under each realization in the scenario.

4.3.4 | Constraints

Two types of constraints are identified: infrastructural and socio-political (Table 4.2). Infrastructural constraints are constraints that have a physical component. These are built into the model. Socio-political constraints are constraints limited by regulations or politically sensitive topics. These constraints are identified after the analysis is finished and “blacked-out”. (Refer to Appendix C for detailed constraints.)

Table 4.2 | Constraints on Water Allocation

Infrastructural Constraints	Socio-political Constraints
Diversion 1 tunnel capacity	Regulation on Diversion 1 reducing capacity by half Minimum water to maintain socio-political agenda (≠ 0% divergence)
Diversion 2 tunnel capacity	Minimum water to maintain socio-political agenda (≠ 0% divergence)
Hydropower plant capacities	Maximum hydropower production limited to “base load”

4.3.5 | Sensitivity Analysis

Two types of sensitivity analyses are run: price and cultivated extent. Low, moderate, and high prices of paddy and electricity are used to understand how price affects the total economic value of each realization within each scenario. The production of paddy is sensitive to the depth of water applied to the cultivated extent, where any depth less than 0.5 meters results in crop failure. As a result, during times of limited water supply, a farmer’s decision on the amount of cultivated land can have large impacts on total paddy yields. A sensitivity analysis is used to show how changes in percentages of cultivable land can affect total paddy production as the diversion volumes are changed.

4.4 | RESULTS

In years when rainfall is plentiful, water is available for hydroelectricity production and paddy irrigation. Under wet and normal conditions the amount of water diverted makes little difference in paddy production but does make a large difference in the amount of electricity produced (Figure 4.2A-B). Operating decisions are limited by infrastructural constrains, in addition to socio-political constraints (Figure 4.3A-B). It is in times of drought that the tradeoffs become most apparent for paddy production (Figure 4.2C). Dry conditions also have an impact on total electricity production, with zero diversions at diversion one providing the highest production, but again, socio-political constraints limit operating ranges (Figure 4.3C). Scenarios using combinations of high and low prices for paddy and electricity change total values (i.e., shift the surface up and down the z-axis), but do not change incremental values associated with each realization (i.e., the slopes between each realization). Paddy production, however, is sensitive to the cultivated extent of land as diversions change (Figure 4.4).

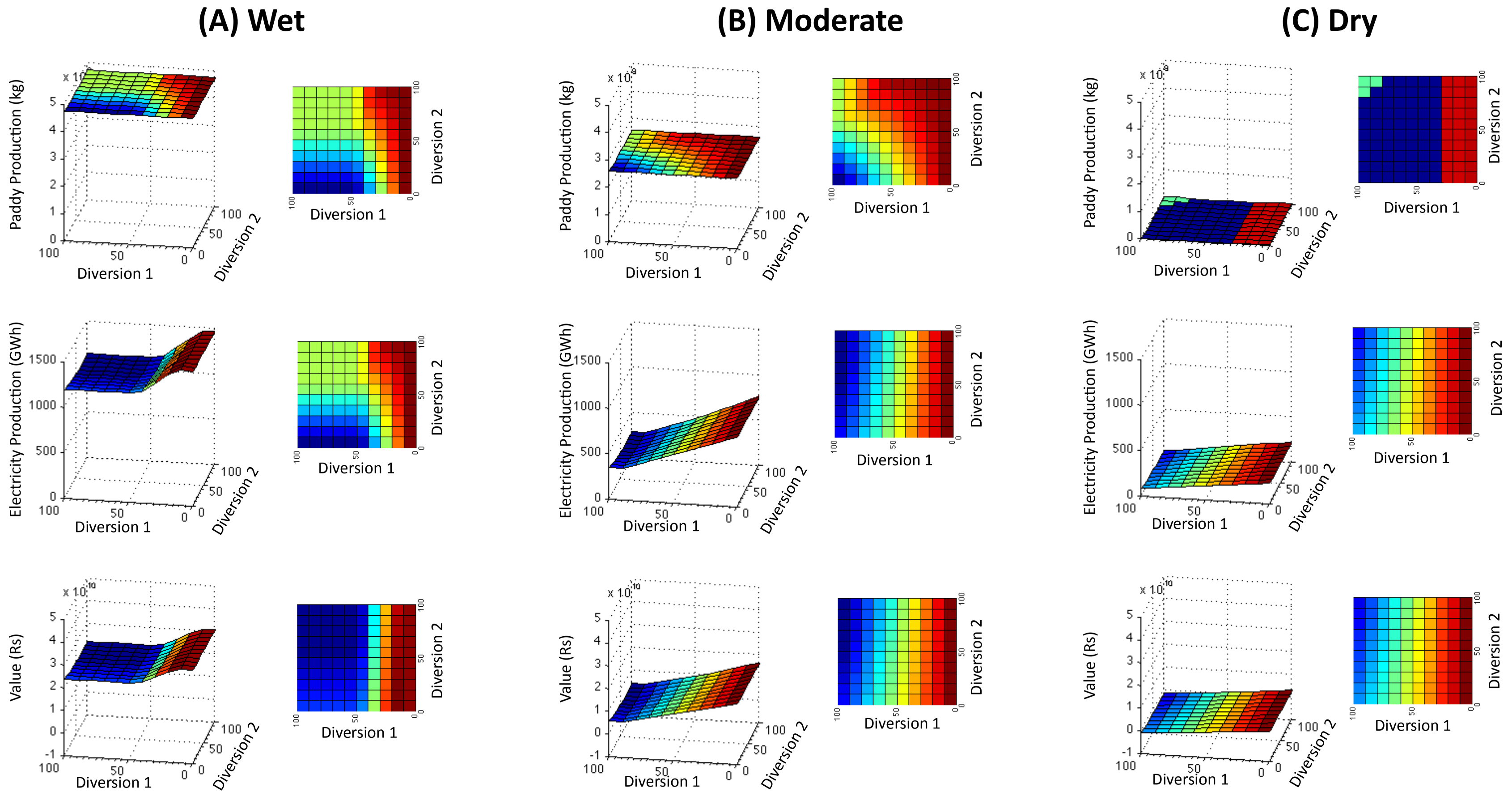

Figure 4.2 | Production and value of all realizations for each scenario

Economic value is in Sri Lankan rupees denoted as Rs. Each realization is denoted by a box on the surface. Colors show high (red) and low (blue) values for each subplot.

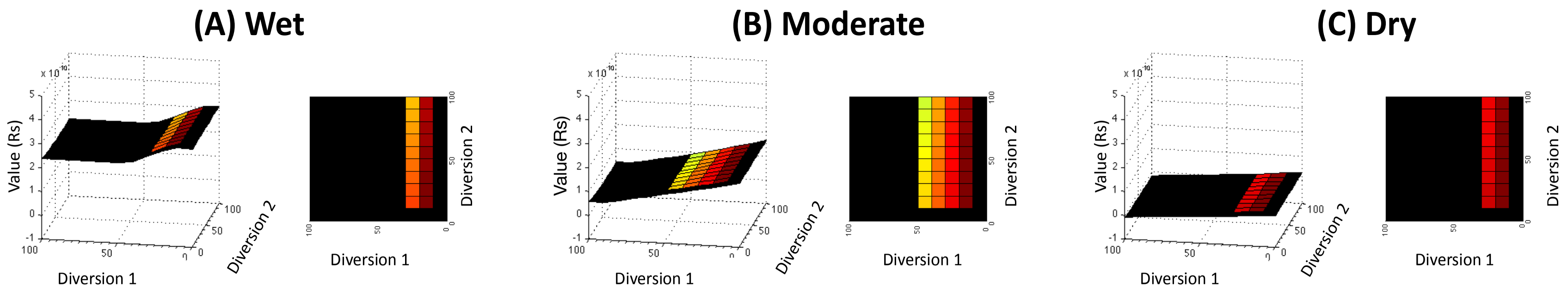

Figure 4.3 | Economic value of all realizations for each scenario with socio-political constraints blacked out

Economic value is in Sri Lankan rupees denoted as Rs. Each realization is denoted by a box on the surface. Colors show high (red) and low (blue) values for each subplot (same color scheme as Figure 4.2). Blacked out boxes indicate areas not feasible because of social or political constraints.

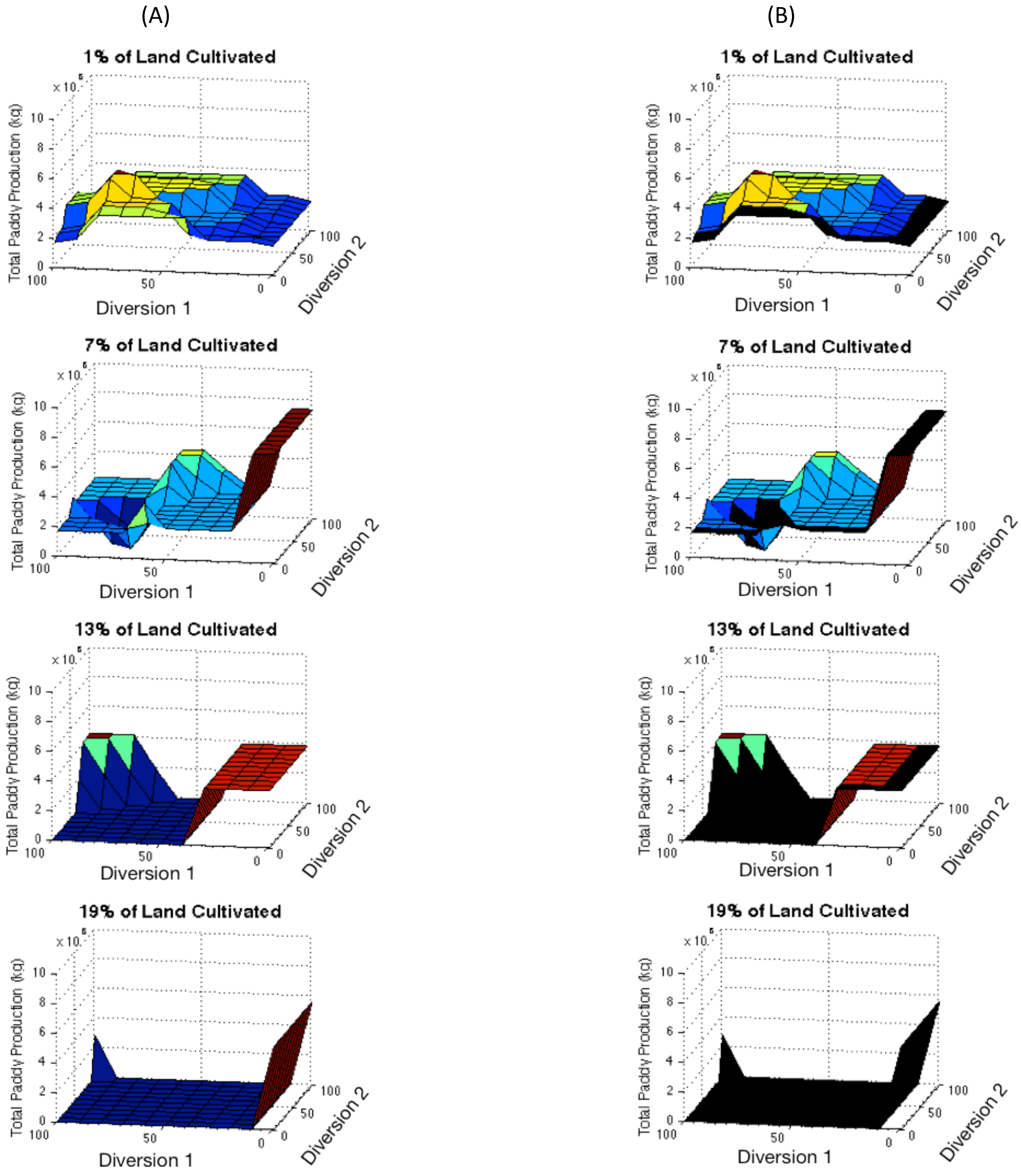

Figure 4.4 | Sensitivity of paddy production to percent cultivable land during a dry scenario

(A) Ranges of land cultivated and the associated paddy production without socio-political constraints. (B) Ranges of land cultivated and the associated paddy production with socio-political constraints in black.

4.5 | DISCUSSION

4.5.1 | Tradeoff Analysis

Under wet and moderate conditions, water requirements by both the irrigation systems and the hydroelectricity plants can be fulfilled. Decisions regarding diversion one result in larger incremental increases in total economic value as the percent diverted reaches zero; this indicates that the total economic value increases faster as diversions at diversion one get closer to zero. The trends in the economic value surface plots are significantly influenced by the production plots for electricity. The highest productions of paddy and electricity are under realizations using zero diversions at diversion one. Nevertheless, a closer look at paddy production indicates only a small difference in production across all realizations. This is because of the small incremental benefit in yield associated with each additional unit of water; changes in diversions under wet and normal scenarios have a small impact on production because rainfall provides the minimum amount of rain for systems to evade crop failure. The electricity production function, on the other hand, is highly sensitive to diversions at diversion one, with the realizations associated with no diversions at diversion one providing the highest value. Electricity production is not impacted significantly by decisions at diversion two because the hydroelectricity plant that depends on this diversion is a run-of-the-river facility with a smaller capacity compared to the large head dams on the main stretch of the Mahaweli River.

Dry conditions represent the most significant tradeoffs with regard to paddy production (Figure 4.2). Paddy production curves created with historical data indicate that there is a critical point in the amount of water duty required to produce paddy yields. After this point, each additional unit of water added provides only a small incremental increase in yields, and ultimately, there is a maximum realized yield. Paddy production is highest when the majority of water is kept in the Mahaweli River (i.e., low diversions percentages at diversion one), but quickly drops off around a 20% diversion indicating that water duties no longer meet the critical point on the paddy production curve. Under the dry scenario, diversions at diversion two become important, again indicating that critical point on the paddy production curve. For a dry scenario taking the socio-political constraints into account, small—but not zero—diversions at diversion one make the largest impact on both paddy and hydroelectricity, producing the highest economic value.

4.5.2 | Impact of socio-political constraints

It is overly simplistic to think that the results of this analysis—quantified in terms of economic costs and benefits—are enough to understand the true picture of allocating water in the Mahaweli Complex. This analysis takes a first cut look at how socio-political issues can constrain solutions. Sri Lanka's policies favoring rice self-sufficiency are deeply rooted in traditional norms and the country's agricultural history, which goes back 24 centuries.[169] The country's recent push indicates the high value it places on supporting its farmers and their culture; social costs are difficult to quantify, and analyses such as this one can offer insight on where to focus efforts and how to formulate hypotheses regarding social costs of these water-food-energy tradeoffs.

Because the flagship irrigation system is dependent on diversion one, the realizations associated with zero diversions at point one are not politically feasible (Figure 4.3). A regulation on the maximum diversion at diversion one is beneficial for electricity production because it constrains the solution by removing the least profitable realizations (Figure 4.3).

4.5.3 | Sensitivity Analysis

The sensitivity of paddy production to percent cultivable land is high during a dry scenario, indicating that informed water management can have a huge impact on the agricultural sector (Figure 4.4). Current research shows the effectiveness of seasonal forecasting and its benefits on farmers.[170,171] If farmers are informed of an upcoming dry season and reduced water allocations, they can plan to reduce their cultivated land so that the water they do receive meets the critical depth required to avoid crop failure.

For farmers in Sri Lanka, it is difficult to plan for their cultivation seasons because they only receive short-term forecasts (i.e., days). If seasonal forecast information is made available for farmers, farmers could use this information to gauge the amount of land they sow. Water managers can play an important role, too. If forecasts prove to be inaccurate, decision makers can adjust water diversions to meet the critical point in production that is necessary to avoid complete failure of the season's harvest. These results suggest that more effort should be put towards understanding the paddy production curve in Sri Lanka, as well as understanding the impact of forecasting on farmers' decisions and other stakeholder responses.

4.5.4 | More than a technical problem

The largest tradeoff between paddy production and electricity production is during dry cultivation seasons. The Mahaweli Complex could produce yields with less water resources, but it is important to recognize that doing so requires more than a technical solution. According to the current paddy production curve, there is a minimal depth required to maintain yields and avoid crop failure. Is there a way to push this critical point on the paddy production curve to the left (e.g., reduce the minimal depth) so that the production of paddy is not as vulnerable during a dry cultivation season?

Developing nations in Asia are experiencing a movement towards a planting method that decreases seed, water, and chemical fertilizer input, but increases yield; this method is called System of Rice Intensification (SRI). A recent survey of SRI in Sri Lanka reported a 44% yield increase, 104% income increase, 24% water savings, and 12% cost per hectare savings.[172] Adoption of SRI, however, requires that farmers change their behavior and adopt a method that is not only different than their traditional farming approach, but requires a significant amount of additional labor. The switch to SRI will require a better understanding of farmers' decisions and behavioral choices.

4.5.5 | Self Sufficiency and Resilience

Sri Lanka's tradeoffs between water for food and water for energy highlight the technical, economic, social, and political aspects of allocating water resources. Each decision has a tradeoff associated with it. A country's decision to focus its resources on food self-sufficiency offers an interesting topic in and of itself. Recent research suggests that relying on the global market for food resources can make a country more vulnerable to drought. Globalization of water through food resources has allowed arid regions to grow disproportionately by allowing communities to engage in the international market. Although this market has been helpful in short-term water deficits, it could reduce societal resilience to drought.[70] A community that is not self-sufficient in food is more prone to price shocks, which can have significant consequences on countries with developing economies. Countries seeking energy self-sufficiency and security so that they can enjoy affordable and uninterruptable access to energy, often make similar arguments, but the results are not as servere.[173] When a country is faced with making a decision between self-sufficiency in food and self-sufficiency in energy, how should it go about determining which to favor?

CHAPTER 4 | SIGNIFICANCE STATEMENT

I use Sri Lanka as a microcosm for a localized study of water-food and water-energy tradeoffs. Using a direct search optimization method promotes an understanding of how the costs and benefits change under each realization in each scenario; that is, the direct search optimization clearly depicts the tradeoffs associated with each diversion decision. The largest tradeoff between paddy production and electricity production is during dry cultivation seasons. Nevertheless, the irrigation systems in the Mahaweli Complex could produce yields with less water resources, but for this to be successful a better understanding of farmers' decisions and behavioral choices is needed.

CHAPTER 5

OPPORTUNITIES FOR ACHIEVING WATER, FOOD AND ENERGY SECURITY

5.1 | INTRODUCTION

As our world continues to globalize, communities will have trouble being sustainable in and of themselves. Local decisions will have greater impact on resources from exceedingly distant locations so that decisions in one location are not detached from the management of resources in another location. The recognition that there is a nexus among water, food, and energy resources exposes tradeoffs traditionally invisible in managing each resource individually, suggesting that the solution to address scarcity in one cannot be achieved without impact on the others. Social, behavioral, and cultural norms play an equally important role in securing resources. Thus, good tradeoff analyses require multi-dimensional information. Although there is no single solution for our local or global resource problems—each problem is unique and requires special attention to its specific social-ecological system—we can use case studies, such as those presented in my dissertation, to help untangle the complex feedbacks among water, food, and energy resources.

5.2 | DOOM AND GLOOM?

The issues that I have reviewed in this dissertation can seem to present overwhelming obstacles to reaching goals for water, food, and energy security for a global population expected to reach nine billion by the middle of this century. Concerns that the human population may face threat of collapse in the absence of efforts to conserve resources have been expressed for a long time and have been addressed even recently in the scientific literature.[174-178] The view is essentially Malthusian—populations tend to consume resources and catastrophically collapse at some point. Analyses of historical (local) population collapse and mathematical modeling of populations do not offer much comfort that a catastrophe can be avoided.[179] There *is* room for optimism—that human populations will be stabilized,[174] that technology will assist in the move toward global sustainability,[175] and that "green economies" will emerge.[180] Nevertheless, even the optimistic view that economic and technological advances will come to the rescue and avert a global crisis is suspect when considered carefully.[177,181]

Essentially all serious analysts indicate that finding solutions to our local to global water, food, and energy security problems will require significant action, either through institutional and behavioral paths (i.e., non-technological actions) or technological and infrastructural paths. As we have seen with the Sri Lanka case study, it is overly simplistic to think that technological and non-technological solutions for water, food, and energy security can be pursued independently. The trick is to mix, and properly balance, technological and non-technological water-food-energy interrelated approaches.[25]

To understand better the opportunities, it is important to understand first the context of resource scarcity. Problems of water, food, and energy scarcity can be framed in two ways—economic scarcity and physical scarcity. Economic scarcity occurs when there is a lack of investment in resources and the resources' infrastructure; communities with sufficient resources but limited infrastructure to access the resources face economic scarcity. Physical scarcity, on the other hand, relates to the absolute measure of the amount of the resource; it occurs when supply does not meet human and environmental demands, even after accounting for future adaptive capacity.[3, 85] Using these definitions, I note a divide between developed and developing worlds; developed countries often have sufficient infrastructure[j] and capital to investment in infrastructure to relieve their resource scarcity problems, whereas developing countries do not.

For example, malnutrition exists in Central Africa, a region with abundant water resources relative to water use; the lack of human, institutional, and financial capital limit access to the water and, thus, create an economic scarcity of water that translates to food insecurity.[85] This economic scarcity of water is reflected in recent land and water grabs. Africa accounts for 47% of the global grabbed area, and many countries within the continent exhibit high grabbed to cultivated area ratios, suggesting the area was not previously cultivated.[155] Land and water grabbing provides economic opportunities for rural farmers and can support technology transfers,[153] but inadequately managed foreign investments in agricultural land can lead to political instability and unsustainable practices.[153] The core argument in favor of land grabbing is that foreign investments can overcome economic scarcity and benefit the developing country and the resulting exports of virtual water can benefit the developed country.

In addition to placing water, food, and energy in the context of physical and economic scarcity, opportunities to meet water, food, and energy security can be framed according to two paths forward—a soft path and a hard path. An essential part of a path toward sustainability in the future is improvement in the efficiency with which water, food, and energy goods and services are produced and used. In an ideal case, society could match the needs of users without seeking sources of new supply.[182]

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[j] For the most part, it is true that developed countries are not plagued by economic resource scarcity. By definition, developed countries have more stable economies and governments than developing countries, as well as more advanced technologies and infrastructure. Nevertheless, even developed nations like the US, are subject to continual requirements to invest in infrastructure.

This is the foundation behind the concept of the soft path in water,[182,183] an ideal that originates from the energy sector,[184,185] and can also be applied to food; there is a finite amount of local resources and a soft-path approach focuses on reducing demand by providing water, food, and energy services more efficiently with a smaller physical quantity. Water, food, and energy policies that focus on the soft path concentrate less on increasing demand through large engineering feats and more on maintaining service at a modified consumption rate.[186] Thus, the soft path to water, food, and energy security is less about the quantity of the resource and more about the productivity and efficiency of the resource or ensuring that all demand-side sectors can effectively provide services and goods in a way that maintains or improves the lifestyle of society. Gleick[182,183] and Lovins[184,185] combine elements of technology and behavior, ultimately defining their soft path as flexible, polymorphous solutions focused on the quality of services and their hard path as inflexible, monolithic, solutions focused on the quantity of resources.

Both the context of scarcity and the paths forward complicate the analysis of opportunities. Although it may appear that a hard path, such as nuclear-powered desalination, would address physical scarcity by manufacturing large quantities of fresh water, this solution is limited by economic scarcity (i.e., the investment in desalinization infrastructure and maintenance). An intuitive soft-path solution, such as conservation, appears to address economic scarcity by reducing demand so the equilibrium point moves farther down the supply curve, but water is not a private good and typically is not adequately priced.[187] Conservation will play a vital part in maintaining resource security in developed countries, where economic scarcity is not a dominant problem and people are more disconnected from their resources.

5.3 | OPPORTUNITIES FOR WATER, FOOD, AND ENERGY SECURITY

Although there are opportunities specific to each of the resources, there also are opportunities with technological and non-technological options that would reduce the stressors and limiters on all three resources (Table 5.1A): reproductive education and services, increased equity and equality, and climate change actions. Paths forward must address both aspects of scarcity and take into account trade-offs and constraints.[188]

Table 5.1 | Technological and non-technological opportunities

There are opportunities that reduce the stressors and limiters on all three resources (A), in addition to opportunities that reduce the stressors and limiters on, specifically, (B) water, (C) food, and (D) energy. Many opportunities cut across the non-technical and technical spectrum, as well as the water, food, and energy categories.

Resource	Non-technological	Technological
(A) All Resources	Enhance reproductive education	Improve access to birth control and reproductive health services
	Improve equality through institutional transparency and promoting representation	Improve access (supply) and control (storage) of resources through financial (e.g., microfinance) and infrastructural (e.g., desalinization plants, carbon capture and storage) investments
(B) Water	Encourage behavioral changes to conserve energy and food	Use energy efficient or water efficient energy technologies (e.g., dry and hybrid cooling, reclaimed water); Build reliable transportation and energy infrastructure (e.g., roads)
	Encourage behavioral changes to consume less water Implement strict building standards for water-use	Encourage efficient and diverse water-use technologies (e.g., rainwater harvesting and storage)
(C) Food	Encourage best management practices in irrigation (e.g., no till, reduce excessive fertilizer use)	Use efficient irrigation technologies (e.g., drip irrigation, reclaimed water, capture nutrients and recycle)
	Encourage behavior changes for sustainable diet (e.g., vegetable based diets, lower calorie consumption)	Use genetically enhanced plants and animals
	Implement consumer awareness campaigns to reduce food waste	Build reliable transportation and energy infrastructure (e.g., roads, refrigeration)
(D) Energy	Encourage behavioral changes to conserve water and food	Use energy efficient or water efficient water technologies (e.g., rainwater harvesting, dual flush toilets); Build reliable transportation and energy infrastructure (e.g., roads, refrigeration)
	Encourage behavioral changes to consume less energy Implement strict building standards for energy	Use efficient and diverse energy portfolios with clean and renewable energy sources

Demand for resources is driven in part by the size of the population. The question posed by Ehrlich and Ehrlich,[176] "Can a collapse of global civilization be avoided?" is rhetorical, but emphasizes that the growth of the human population cannot go unabated if demands for resources are to be controlled. [k,189] Despite the fact that a reliable estimate of the Earth's carrying capacity for humans cannot be calculated,[190] it is clear that the population growth rate must continue to decline to stabilize total population. The issue is particularly serious in the poorest countries where water, food, and energy security concerns are greatest. Support for voluntary family planning programs are seen as the most promising policy approach,[191,192] an approach that includes reproductive education, as well as reducing gender inequality through institutional transparency and promoting representation. Access to birth control methods and access to reproductive health services is limited by economic capacity, so economic investments will be necessary.

Regardless of efforts undertaken now, effects will not be immediate. In the meantime, institutional and behavioral changes, such as reducing social-class and gender inequality and supporting adaptation to climate change, can be encouraged. On the technological side, efforts can be made to improve access and control of water, energy, and food through financial and infrastructural investments and to promote mitigation of climate change. Realistically, many of these opportunities are crosscutting and will involve both non-technical and technical elements.

5.3.1 | Opportunities for Meeting Water Security

I have argued in this dissertation that water plays a preeminent role in the water-food-energy nexus. It follows that water also will be a very important ingredient in solutions to problems. Projections of resource needs over the next several decades are a source of very significant concern for water managers.[102] The emerging globalization of water resources, however, argues that international cooperation and collaboration will be necessary in the future.[105] Analyses of previous efforts at international water management, orchestrated by developed countries, are not very encouraging[193] so there is much work to be done.

Solutions on the technology and infrastructure side focus on improving financial and infrastructural investments,[194] as well as installing energy or water efficient technologies[19,195] (Table

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[k] Mainstream economists debate the idea of physical limits to growth, emphasizing that more people increases human capital and innovation. This perspective is often founded on the assumption that markets will manage resources through substitutes and the perfect adjustment of supply and demand.

5.1B). In California, for instance, regulated energy utilities spent three billion dollars in 2010-2012 promoting energy efficiency; as part of this campaign, utilities focused on reducing hot-water use and encouraging water conservation through home appliances. The energy utilities were interested in the full lifecycle of water "because this information could allow them to claim credit for saving energy by saving water in addition to the energy required for direct heating that they already claim".[40] On the non-technological side, there are opportunities to encourage behavioral changes to conserve water, as well as food and energy.

5.3.2 | Opportunities for Meeting Food Security

Garnett[196] identifies three conceptualizations of the food security problem: a socioeconomic component, involving global institutions and the economy; a production component; and a consumption component, which involves diets and population. I add a fourth viewpoint to these—food wastage (Table 5.1C).

Technological solutions to increasing food production have been dominant to date. Crop production grew by 28% between 1985 and 2005, with 25% attributed to yield increases.[25] The yield increases occurred by virtue of a doubling of irrigated area and a 500% increase in fertilizer application.[25] Part of the increase in food production may be attributable to genetically modified plants and animals, allowing plants to overcome environmental pressures and animals to develop more quickly, but this has not been demonstrated clearly.[197,198] Nevertheless, within the next century, more radical genetic manipulations and enhancements may be feasible,[9] and future technological advances will be necessary to address global food security issues. Spiertz[199] notes that agronomists need to continue to improve crop properties to improve efficiency of water and nutrient use, including developing varieties to adapt to climate change.

Overall, food production has helped increase food security, but it is just one piece of the puzzle. Opportunities for agricultural intensification to close the yield gap (the difference between what is produced, especially in underdeveloped countries, and what could be produced with best practices) must be pursued.[200] Farmers could switch from traditional crop rotations and traditional crop varieties that are likely to suffer from climate change—corn, soybeans, cotton—to new patterns and crops better suited for the changing climate conditions.[112]

Much of the focus on future forecasts of food demand has been to extrapolate the increasing demand for meat protein, a trend that is acknowledged to exacerbate the stress on water and energy resources. For example, the water footprint for vegetables is about 300 liters per kilogram (L/kg) and for beef is about 15,000 L/kg.[201] Although growth in animal protein in the diets of people in the developing world is almost certain to occur, there is growing recognition that the dietary preferences of people need to be shifted.[178] Changes in eating habits will be an essential ingredient in achieving food security in the future. Behavioral changes, despite the problematic nature of determining how to develop them, will be necessary.[202] At a basic level, research indicates that absolute food availability, in terms of calories and protein available to humans, can be enhanced by shifting cereal production away from feedstock and energy crops.[25] It is also clear that human health outcomes can be improved if diets are shifted away from meat and toward more grains, fruits, and vegetables.[178,196]

Recognizing that roughly one-third of the world's food produced is wasted indicates that there are steps that can be taken to conserve these resources. Food is wasted along the entire supply chain, from agricultural production through consumption. In developed countries, much food is wasted by consumers, presumably because they can afford to do so. Raising public awareness through education is a necessary step to reduce such waste.[203] In developing countries, fresh produce is often lost pre-retail because of poor food-chain infrastructure, including processing and distribution, or the lack of investment in cold storage. Public investment in transportation infrastructure, combined with increased capital for things such as refrigeration are important for reducing waste and securing food resources.[9] Development of farmer organizations to promote resilience and avoid premature harvesting and development of market cooperatives to promote efficient distribution of food are other ways to minimize waste in developing countries.[203] Part of the solution also involves eliminating waste at the retail and post-retail stages (i.e., discarding food because of cosmetic reasons).[9,178,196] Changing the perspective of people and improving international institutions is far from an easy task, but arguably one that must be engaged. Ehrlich and Ehrlich[176] suggest that, to avoid a collapse of global civilization "international negotiations will be needed, existing international agencies that deal with them will need strengthening, and new institutions will need to be formed."

5.3.3 | Opportunities for Meeting Energy Security

Despite continued warning signs that climate change impacts may become severe over the next several decades, society has yet to see much in the way of a real commitment to a more environmentally benign energy path. Again the issues are complex, and it is apparent that economic, social, and political levers are needed to move the world in the right direction, and that a substantial change in how nation states view security may also be a prerequisite.[204] Considering the following statistics, it is patently obvious that advances will be needed along both technological and non-technological sides (Table 5.1D) in the energy security sphere to avoid water and food conflicts.

- Between 2000 and 2010, total world generation of electricity went from about 14,600 thousand GWh to about 20,200 thousand GWh, an average annual growth rate of about 3.3%.[205]
- Between 2000 and 2010, world generation of electricity from hydropower went from about 2,600 thousand GWh to about 3,400 thousand GWh, an average annual growth rate of about 2.9%.[205]
- The growth in demand for electricity to 2035 is forecast to increase at a rate of about 1-2% per year.[206]
- Between 2000 and 2011, world production of biofuels rose from a little over 300 thousand barrels per day to almost 1,900 thousand barrels per day, an average annual growth rate of almost 18%.[206]

The technological advances to manage water in the context of thermoelectric power generation have complex interactions among cost, energy efficiency, and water savings.[207] Once-through cooling systems withdraw large amounts of water but return most of it to rivers or lakes, albeit at a higher temperature, whereas closed loop cooling systems withdraw less water but consume more of it.[22] Dry cooling systems reduce water withdrawal and consumption significantly, but there is an energy penalty—that is, less electricity is generated per unit of fuel consumed with dry cooling than with wet cooling.[207] The option of construction of large hydroelectric dams has well-documented environmental downsides, but the potential for generating electricity is large and the benefits, especially in developing countries, can be large as well. Technological advances that have been put forward are the development of small-scale hydroelectric installations, which are distributed and may have significant advantages in countries that do not have a modern electrical grid. These small-scale installations have been touted as avoiding the majority of the adverse environmental impacts associated with large dams, but analyses indicate that this may not be the case.[208]

The technology related advances for biofuels revolve around further development of second-generation methods, that is, those that do not use food crops as feedstock. Provided that production of biofuels from cellulosic materials can be made economically feasible, the use of marginal lands in the United States (and elsewhere) may prove to be beneficial.[209] Nevertheless, the challenge of managing land for energy production, as well as food production and biodiversity conservation, is a huge challenge. Policies will have to resolve trade-offs involving food, renewable energy, biodiversity conservation, and environmental pressures from intensive agriculture.[210] There have been many research efforts directed at use of cellulosic material as feedstock[211] and at using algae to produce biofuels.[212] Not everyone agrees that development of biofuels represents a high priority goal, but regardless of viewpoint, it is clear that the social and environmental impacts of biofuel production must be evaluated.[213] There is considerable debate about whether first-generation biofuels improve energy security,[88] and certainly, there is much that remains unknown about how and if second-generation fuels will in fact prove to be a panacea.

5.4 | THE TRANSITION TO A NEW PRACTICE

There are clear, concrete steps that can be taken to mitigate the water-food-energy collision, a few of which I present above (Table 5.1). These and other measures[214] can form a comprehensive approach that incorporates soft and hard paths to managing the risks that face humanity with respect to physical and economic water, food, and energy security. Nevertheless, the challenge to make a transition to sustainability in the world is daunting.

Engineering is traditionally defined as the application of mathematics and science to solving technical problems,[215] such as those surrounding water security, food security, and energy security. Civil and environmental engineers plan, design, create, and renew infrastructure to use water, food, and energy resources efficiently.[216] In the abstract, resolving the conflicts surrounding resource scarcity can be viewed as an optimization problem of allocating scarce resources to maximize utility. It has become apparent, however, that solving technical problems successfully requires a social utility component in addition to the economic utility component. For engineering to remain relevant in the future, it will have to transition to an approach that merges technical issues and efficient, economical design with the needs of specific social-ecological systems.[216]

Many of the opportunities outlined above require the diffusion of innovation or adoption of behaviors focused on reducing water, food, and energy use and waste. It is helpful to describe systems from the bottom up so that the complex dynamics describing social phenomena can be understood and used to inform engineering design and policy.[217] An Agent Based Model (ABM) is a technique that is helpful in modeling the interactions among multiple agents (e.g., people) to understand better how adoption of technology and behaviors occurs; ABM's are useful as a learning tool to understand how people are influenced by their surroundings.[217] For example, an ABM might be developed with Sri Lankan farmers as the agents to explore (1) the influence of better forecasting information on each farmer's decision regarding the amount of land to cultivate or (2) the social contexts behind adoption of system of rice intensification. Both of these behaviors have the potential to decrease the tradeoffs between water for energy and water for food in a dry season, but the success of these behavioral changes is dependent on social and behavioral characteristics of the farmers and how each of the farmers interact with one another in the community. ABM's have been successful in understanding the social dynamics that govern the adoption of technology or policies[218,219] and could prove useful in addressing the water security, food security, and energy security trilemma.

APPENDIX A

ENERGY FOR WATER

A.1 | Description of the Energy for Water framework

The *Energy for Water* framework calculates the energy consumed due to the municipal water demand of an urban center. It also calculates the water lost during transportation of the water from source to end-user (e.g., water lost to infiltration or evaporation). Although the model does not perform a full lifecycle analysis, it does highlight the key stages in providing an urban center with municipal water resources.

This component of the WEN model is divided into the following stages: acquisition, treatment, local distribution, and end-use (Figure A1). The acquisition stage is defined as the energy used to extract or collect water from a source area and move it to a treatment facility. The treatment stage is defined as the energy used to treat water to usable standards (potable and nonpotable uses). The local distribution stage is defined as the energy to distribute water to end-users (potable and non-potable end-users). The end-use stage is defined as the energy consumed during the use of water by the end-user (e.g., heating water, pumping water in house, etc). The WEN model is further divided by water source to allow for the comparison of the energy requirements of different water sources. The water sources built into the model include: imported surface water, local surface water, groundwater, recycled water and desalinated water.

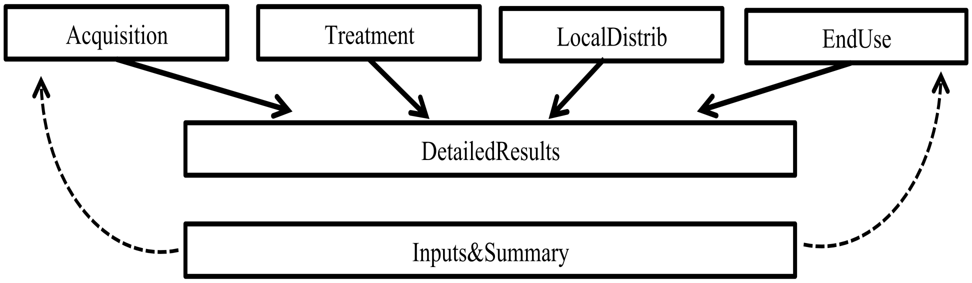

Figure A1 | Energy for Water Framework by Stage

A.2 | Energy for Water Definitions & Model Calculations

The WEN model calculates the energy used to provide an urban center with its municipal water supply. The water lost as it is moves through each stage is also calculated. Total water in this study is the sum of delivered and transport water as defined below. When using this model particular attention must be given to determining when water quantities include or exclude transport water. For the Tucson case study, total water is back-calculated by first determining the transport water involved in the acquisition and local distribution stages and then adding that quantity to delivered water.

A.2.1 | Delivered Water

Delivered water is defined as the amount of water consumed by the end-user (i.e., total demand). The quantity is drawn from records of the public water utility (e.g., water plans or annual fiscal reports). It is assumed that this type of data accounts for the water used by all residents and commercial businesses within the city limits. These data can be limiting because it may include some transport water (i.e., lost or unaccounted for water typically due to leaking water mains or metering errors). If transport water is determined to be included, this quantity needs to be subtracted to achieve delivered water (i.e., the amount of water used by the end-user).

Limitations. Only municipal water is used in the calculations of the WEN model—water withdrawn directly from the water's source by an end-user is not included (e.g., irrigation and industrial water withdrawn from a local river).

A.2.2 Transport Water

Transport water is defined as the amount of water lost during the transportation of water to the end-user. This typically includes water lost to evaporation and infiltration during conveyance, in addition to leaky public water mains during local distribution. These data can typically be acquired from the public water utility or conveyance provider (e.g., Central Arizona Project).

Limitations. The energy used to treat wastewater is not included in the WEN model because this stage is assumed to require a similar amount of energy regardless of the water source. Due to the lack of available data concerning efficiency of water treatment methods, the water lost during treatment is not considered in this model. Additionally, water lost by the end-user (e.g., dripping faucet) is not considered.

A.2.3 | Nexus Energy

Nexus energy is defined as the amount of energy consumed to provide municipal water to an urban center. This includes the energy required to provide delivered water (e.g., electricity to power local distribution water pumps) and transport water (i.e., the energy required to move or treat the water eventually lost during transport). The calculation of nexus energy is the main goal of the WEN model. Nexus energy is calculated for each water source. Methodology, calculation equations and assumptions (organized by stage in the WEN model) are described below.

Acquisition. Acquisition is defined as the energy used to extract or collect water from a source area and move it to a treatment facility. Inputs for this stage are source dependent and typically include: (1) total water (delivered + transport water), (2) change in elevation from source to treatment facility, (3) pump efficiency, and (4) if recycled water is a source, energy used for local distribution (typically available in greenhouse gas reports). For surface water (imported and local), the general horsepower equation is used to calculate the energy required to pump water over increasing elevation.

$$hp=(y*Q*H)/(550*e) \qquad (\textit{equation A1})$$

Where hp = horsepower, y = specific weight of water, Q = flow, H = change in elevation from source to treatment facility, and e = pump efficiency. Horsepower is converted to kWh (1 hp = 0.7457 kWh). For groundwater, *equation A1* is also used but H = change in elevation from water level to surface. Additionally, desalination uses *equation A1*, but H = change in elevation from source to treatment facility. For recycled water, the proportion of energy used for local distribution that is attributable to recycled water is

$$RWe=TLDe*(\%RW) \qquad (\textit{equation A2})$$

Where RWe = energy for recycled water collection, TLDe = energy for local distribution (or wastewater collection), %RW = proportion of recycled water to potable water. Although local gains and losses occur during this stage, only the water lost due to evaporation and infiltration for conveyed water is determined.

Municipal Treatment. Municipal Treatment is defined as the energy used to treat water to usable standards (potable and non-potable uses). Inputs are specified by source and the quantity of water to be treated. The amount of water used to calculate these values excludes transport water from the acquisition stage (i.e., the water lost to infiltration, evaporation or leaking pipes during acquisition).

For surface water treatment a multiplier is used to calculate the energy required to treat surface water to useable standards. The multiplier (the energy required to treat a unit of water) is scaled according to the size of the water treatment plant.[220] This multiplier includes the energy used for pumping water within the treatment facility. The multipliers in this section are not specific to particular treatment methods and do not account for advancements or deficiencies in various treatment technologies.

For groundwater treatment a multiplier is used to calculate the energy required to treat groundwater.[221] The multiplier (the energy required to treat a unit of groundwater) is a constant and assumes the water is disinfected through chlorination.

For recycled water treatment a multiplier is used to calculate the energy required to treat wastewater. Specific treatment levels[220] use a particular multiplier. Each multiplier for recycled water treatment is a single national average that is based on many assumptions pertaining to each treatment process.

For desalination treatment a multiplier is used to calculate the energy required to treat saltwater or brackish water according to specified treatment methods.[222,223] These multipliers are based on total dissolved solid concentration and reverse osmosis technology. Other desalination technologies are not incorporated into the model.

Local Distribution. Local distribution is defined as the energy used to distribute water to the end-user (potable and non-potable). The water input for this stage is the total water that excludes transport water (water lost to infiltration, evaporation, or leaking pipes) from the previous two stages. There are two methods for determining the nexus energy required for local distribution.

The first method can be used when energy data related to public water utilities are available. The energy used during distribution can typically be pulled directly from greenhouse gas reports. Proportions are then used to determine the amount of energy required for the potable and recycled systems as needed. Due to the varied elevations between the treatment facility and end-users, extracting this value directly from the greenhouse gas report provides reasonable accuracy. The greenhouse gas report, however, may not provide enough information to infer what the local distribution energy data includes. The second method should be used if no energy data are available.

For the second method, the energy required to pump water for local distribution is calculated via the amount of money spent by the water utility on local distribution. The cost of water pumping for local distribution is divided by the average electricity rate paid by the water utility. The result is the amount of energy spent on water pumping for a given year. Often the electricity rate paid by the water utility may vary over the course of a year, thus using the average rate provides a reasonable estimate.

End-use. End-use is defined as the energy consumed by the end-user in processes that consume water or use and return water to the municipal provider. This includes pumping and cooling, however, heating water accounts for most of this stage. The water input for this stage is the delivered water only (the amount of water reaching the end-user). An end-use multiplier is used to calculate the average amount of energy consumed during the end-use of water. This multiplier is determined by dividing the total amount of energy consumed during the end-use of water in California for 2001[45] by the total amount of water consumed by the public supply, domestic and industrial sectors in California for 2000.[224]

Limitations. The energy consumed during water end-use is notoriously difficult to estimate due to the lack of available data; obstacles in data collection; and the shear enormity of end-users, water uses, and various water using technologies. Thus, the end-use calculation in the WEN model is based on a host of assumptions and the method outlined below is a rough approximation of end-use and must only be knowingly and cautiously applied to other locations. Since the multiplier is calculated according to California's water and energy use, geographic and climatic variables specific to California are embedded in this calculation.

APPENDIX B

WATER FOR ENERGY

B.1 | Description of the Water for Energy framework

The *Water for Energy* framework calculates the water consumed due to the energy demand of an urban center. It calculates the energy required to transport energy resources (e.g., coal, natural gas) and to transmit electricity, as well as the energy lost from converting primary sources into secondary sources. Although the model does not perform a full lifecycle analysis, it does highlight the key stages in providing an urban center with its energy resources.

This component of the WEN model is divided into four stages: fuel cycle, transportation, electricity generation, and electricity transmission (Figure B1). The fuel cycle includes exploration, extraction, mining, enrichment and other processing operations used for each energy source.[16] The transportation stage is the movement of resources from their source location (e.g., mine) to either the end-user (e.g., urban center) or the electricity power plant. Electricity generation and transmission stages are only applicable for secondary[l] energy sources.

The WEN model allows the user to choose from a range of energy sources so that the user can capture its community's energy portfolio, as well as compare the water and transport energy requirements of different energy sources. The nonrenewable energy sources built into the model include: coal, oil, natural gas, and nuclear. Renewable electricity sources include: solar photovoltaic, solar thermal, hydropower, and wind power.

B.2 | Water for Energy Definitions & Model Calculations

B.2.1 | Delivered Energy

Delivered energy is defined as the amount of energy delivered to the community (i.e., total demand). This quantity is a community's energy portfolio as presented by its energy providers and can be found in a community's greenhouse gas report on their government or sustainability website. Supplemental material may be required; the EIA (Form EIA-860) and EPA (eGRID) have large energy databases with information on national power plants.[50,51]

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[l] Primary energy is energy that is used directly as a supply source. Secondary energy uses primary energy (e.g. electricity production from coal).

Limitations. Many urban centers have still not compiled a greenhouse gas report, making the acquisition of these data difficult. Furthermore, extracting information from EIA and EPA databases can be tedious and time consuming.

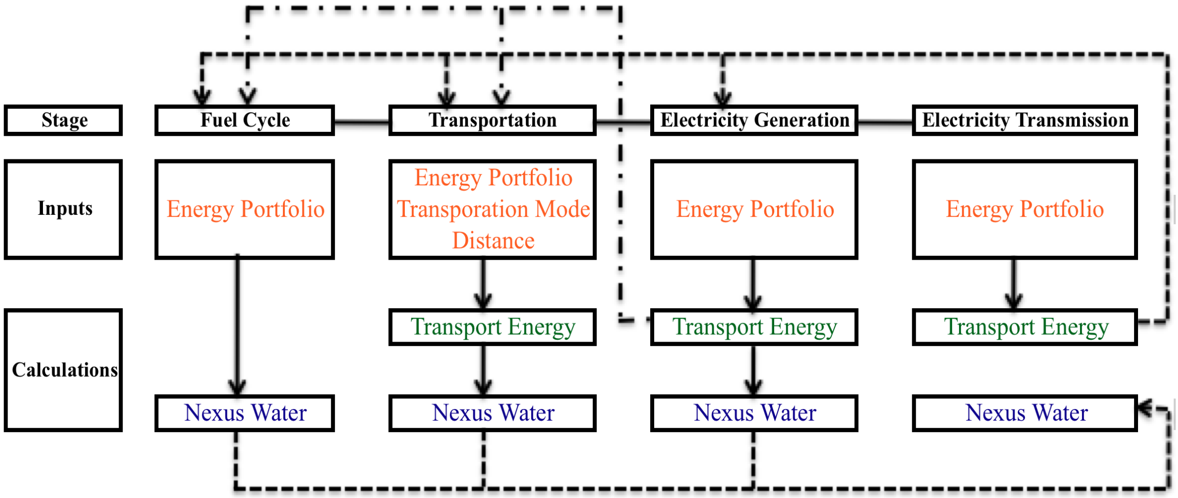

Figure B1 | Water for Energy Framework by Stage.

Transport energy has three dimensions. The first includes the energy required to move primary sources of energy to their users (e.g., the community or a power plant). This transport energy is included as part of the transportation stage. The second dimension of transport energy includes the energy lost when primary energy sources are converted into electricity. This transport energy (dash dot lines) is fed-back into the transportation and fuel cycle stages. The last dimension of transport energy is transmission line loss. This component of transport energy is also fed-back through previous stages (electricity generation, transportation, and fuel cycle), but is still counted under the electricity transmission stage (dash lines).

B.2.2 | Transport Energy

Transport energy has three dimensions. The first includes the energy required to move primary sources of energy to their users (e.g., the community or a power plant). The second dimension of transport energy includes the energy lost when primary energy sources are converted into electricity. The last dimension of transport energy is transmission line loss. Transport energy can be thought of in terms of efficiency: a certain amount of energy is lost or used during the movement of energy between two locations (dimension one and three) and the conversion of thermal energy to electrical energy (dimension two).

The computation of this energy typically requires data pertaining to a community's energy portfolio (delivered energy) and mode of transportation (rail, truck, waterborne freight, or pipeline). Distance from source location to power plant or community is needed if the transportation mode is truck, rail, or water.

Although a community's greenhouse gas report may have its delivered energy consumption, it may not have the mode of transportation. EIA-860 forms can provide this information.[51] The easiest way to find transport distances is to obtain shape-files and use a GIS software package to plot and measure an "average" route.

Dimension 1: Transportation Energy. There are two categories of energy transportation. The first is rail, truck, or waterborne freight. The second is pipeline delivery.

Rail, Truck, or Waterborne Freight. Because GIS shapefiles for roads, rail tracks, and waterways are easily attainable for the US, these transportation modes are calculated using distances. Calculating transport energy using transportation distances more adequately accounts for geographic location than using average percent efficiencies. Transport energy for the transportation of energy resources via rail, truck or waterborne freight is calculated using the following equation.

$$\frac{\text{Energy * Energy Intensity * Distance}}{\text{Heat Content}} = \text{Transport Energy} \qquad \text{(equation B1)}$$

Where Energy (BTU) = Delivered Energy, Heat Content (BTU/ton) = Heat Content of source, Energy Intensity (BTU/ton-mile) = Energy intensity of freight mode (truck, rail, waterborne), Distance (miles) = Distance from source location to power plant or community, and Transport Energy (BTU) = Energy required to transport the delivered energy. The model has heat content multipliers[71,225] and energy intensity multipliers[225,226] imbedded into the spreadsheets, so the user only needs to enter in transportation distance and delivered energy values.

Pipeline. Pipeline GIS data are not publically available, and therefore, this transport energy calculation is based on percent efficiencies of pipeline transportation. Within this framework, pipeline transportation is only available for oil and natural gas resources. Transport energy for the transportation of energy via pipeline is calculated according the equation below.

$$\frac{\mathit{Energy}}{(1 - \mathit{Pipeline\ Losses})} - \mathit{Energy} = \mathit{Transport\ Energy} \qquad (\mathit{equation\ B2})$$

Where Energy *(BTU)* = Delivered Energy, Pipeline Losses *(%/100)*= Energy lost in the transportation of the fuel, and Transport Energy *(BTU) =* Energy required to transport the delivered energy. The model has pipeline efficiencies for natural gas and oil imbedded into the spreadsheets.[227]

Dimension 2: Primary Energy to Secondary Energy Losses. Transport energy for the energy lost when thermal energy is converted to electrical energy is calculated according to the equation below.

$$\mathit{Energy} - \frac{\mathit{Energy}}{(\mathit{System\ Efficiency})} = \mathit{Transport\ Energy} \qquad (\mathit{equation\ B3})$$

Where Energy *(BTU)* = Delivered Energy, System Efficiency *(%/100)=* efficiency term for the conversion from thermal to electrical energy, and Transport Energy *(BTU)=* Energy lost in the conversion from thermal to electrical energy. The model has conversion efficiencies imbedded into the spreadsheets.[16]

Important Note. The model takes this transport energy and runs it through each stage prior to electricity generation (Figure A2, dash dot lines). We use this feedback because we assume the energy consumption reported by the community is the energy consumed by the end-user. Therefore, for electricity, this value does not reflect the amount of primary energy that needed to go through the fuel cycle or get transported from the source to the power plant.

Dimension 3: Transmission Line Losses. Transmission line GIS data is not publicly available, and therefore, this transport energy calculation is based on percent efficiencies of power lines. Transport energy for transmitting electricity is calculated according to the equation below.

$$\frac{\text{Energy}}{(1 - \text{Transmission Losses})} - \text{Energy} = \text{Transport Energy} \qquad (\textit{equation B4})$$

Where Energy *(BTU)* = Delivered Energy, Transmission Losses *(%/100)=* efficiency term for the energy lost in transmission of electricity, and Transport Energy *(BTU)=* Energy lost in electricity transmission. The model has transmission efficiencies imbedded into the spreadsheets.[227,228]

Important Note. The model takes this transport energy and runs it through each stage prior to transmission line loss (Figure A2, dash lines). We use this feedback because we assume the energy consumption reported by the community is the energy consumed by the end-user. Therefore, for electricity, this value does not reflect the amount of primary energy that needed to go through the fuel cycle, get transported from the source to the power plant, and be converted from primary to secondary energy. The outcomes of this feedback (transport energy and nexus water values) are counted under electricity transmission. This is different than dimension two (Figure A2, dash dot lines), which does not loop back to the electricity generation stage.

Limitations. In the *Water for Energy* portion of the WEN model, transport energy is calculated only for the transportation, electricity generation, and electricity transmission stages. The boundary of this framework is based on the ability of users to acquire the information necessary for an analysis. As a result, the indirect energy required for each source's fuel cycle (e.g., the energy required to build the equipment used in acquiring and processing the raw resource) is not considered in this model. In addition, the energy required to run the power plant is not considered.

Obtaining the shape-files can be expensive; government agencies cannot give out transmission line data because they are in a copyright contract with private firms.[229] Platts and Rextag, energy information companies, have GIS data or can produce custom maps plotting the information specific to the WEN tool user's needs (i.e., providing distances). Nevertheless, this inconvenience led us to the decision to use efficiencies for these calculations rather than distances. Other than pipeline and transmission line shape-files, GIS data are usually available to the public.

Transmission line losses vary with voltage level and loading on each line so an average efficiency was used. The efficiencies used for transmission line losses also include transformer losses that are part of the model.

B.2.3 | Nexus Water

Nexus water is the amount of water consumed to provide energy to an urban center. This includes the water to provide delivered and transport energy. Nexus water is usually not accounted for within a community's water portfolio because mines, processing plants, power plants, etc. are typically not located within the community. Double counting these resources is a concern, however, so WEN tool users should review both the water and energy portfolios to confirm that nexus resources are not being counted twice.

Fuel cycle. The fuel cycle includes the total water consumed for exploration, extraction, mining, enrichment, and other processing operations. Data is aggregated by source (i.e., coal, oil, natural gas, nuclear). A multiplier that relates water consumed per energy unit is used to calculate the water consumed during the fuel cycle stage. Water consumption varies by source, so there are different multipliers for each source.[16]

Important Note: The input for this stage of the WEN model is delivered energy. Dimensions two and three of transport energy are also fed-back into this stage, but this is done automatically within the dataset.

Transportation. Water for transportation is the water required for the energy associated with the transportation of the delivered energy (e.g., coal) from its source location (e.g., coal mine) to its secondary location (power plant or community). A multiplier is used to calculate the water for transportation;[16] the multiplier is based on the transportation mode selected.

Important Note: The input for this stage is the energy consumed for the transportation of a community's energy sources (Dimension 1 of Transport Energy); this is done automatically within the framework. It should also be noted that dimensions two and three of transport energy are also fed back into this the transportation stage.

Electricity Generation. Water for electricity generation is the water consumed at a power plant. A multiplier is used to calculate the amount of water required to generate electricity; the multiplier is based on the type of power plant, so different power plants have different multipliers.[16,71] Efficiency of the conversion from thermal to electrical energy is already incorporated into the multipliers.[16]

Power plant type can be specified within the WEN model. Built in options include: conventional coal combustion (once-through or cooling tower, anthracite or non-anthracite coal), oil and natural gas combustion (once-through or cooling tower), or nuclear generation (light water reactor or high temperature gas-cooled reactor). More specific power plant options are not distinguished, however, there is an "average" option for when the specific power plant type is unknown. There are also four renewable electricity options, including solar photovoltaic, solar thermal, hydroelectric, and wind.

Important Note: The input for this stage of the WEN model is delivered energy. It should also be noted that dimension three of transport energy is also fed-back into this stage.

Electricity Transmission. Water is consumed for the fuel cycle, transportation, and electricity production of the energy lost in transmission. When electricity is transmitted through power lines a percentage of energy is lost in the process. This energy is calculated as transport energy (Dimension 3). This energy also consumes water along the way, and therefore, water for this transport energy needs to be calculated for all the previous stages: fuel cycle, transportation, and electricity generation (Figure A2). The model does this by feeding the transport energy value back through the other stages (as noted above).

Limitations. The electricity transmission stage assumes that all electricity values inserted into the model (as delivered energy) are the values obtained from end-use meters. Therefore, it is assumed that these values do not include transmission line losses.

APPENDIX C

SRI LANKA CASE STUDY

C.1 | Important Definitions

- **Mahaweli River Basin:** Largest river basin in Sri Lanka; includes the Mahaweli River which is the longest river in the county carrying a predevelopment flow of 7,300 mcm/y to the Bay of Bengal.
- **Mahaweli Development Scheme:** development and management of water and land resources within the Mahaweli River Basin for irrigation, hydropower generation, and land settlement; main objectives include developing, operating, and maintaining irrigation systems and hydroelectric facilities to increase agriculture and electricity production while generating employment and development and conserving watershed health.
- **Mahaweli Complex:** hydroelectric plants, and their reservoirs, and agricultural land within the Mahaweli River Basin managed under the Mahaweli Authority of Sri Lanka
- **Diversion points:** There are two key diversion in the Mahaweli Complex. The first is Polgolla and the second is Bowatenna.
- **System:** Land set aside by the Mahaweli Development project for paddy production.
- **Scheme:** A sub-system. Some systems are made up of multiple schemes (Table C1).
- **Powerflow:** Volume of water that is used in a hydroelectricity plant to spin its turbines.
- **Water Duties:** Depth of water associated with extents of agricultural land.
- **Water Issues:** Volume of water associated with extents of agricultural land.

Table C1 | Mahaweli Complex systems, schemes, and diversions.

System	Schemes within System	Key Diversion
H	Dambulu Oya, KHFC Scheme, Kandalama, Kalawewa RB, Kalawewa YE, Kalawewa LB, Rajangana, Neela Bemma	Polgolla (Diversion 1), Bowatenna (Diversion 2)
MH	Hurulu Wewa	
IH	Nachchaduwa, Nuwara Wewa, Tissawewa	
G	Elahera	Polgolla (Diversion 1)
D	Gritale, Minneriya, Kaudulla, Kantale, Parakrama Samudra	
E	Minipe LC	None; offshoots of Mahaweli River
C	Sobora Wewa, Mapakada Wewa, Dambarwa Wewa, Ulhitiya	
B	Vakeneri/Rathkinda, Maduru Oya LB	
A	Allai	

C.2 | Data Acquisition

Data are obtained from a variety of stakeholders in Sri Lanka (Table C2)

Table C2 | Data acquired and reference information.

Data	Detailed Information	Reference Cited
Hydropower plants	Powerflows (MCM) Power generation (GWh) Maximum capacity (MW)	2003-2013 Mahaweli Authority of Sri Lanka's Maha and Yala Seasonal Summary Reports (MASL SSR)[162]
Irrigation Systems	Water duties (m) Paddy Extent (ha)	MASL SSR[162]
Diversion Points	Polgolla inflow and diversions (MCM) Bowatenna inflow and diversions (MCM)	MASL SSR[162]
Paddy Yield	Yield (kg/ha)	Sri Lanka's Department of Census and Statistics[163]
Paddy Price	Seasonal farm-gate costs of paddy	Hector Kobbekaduwa Agrarian Research and Training Institute[165]
Electricity Price	Costs of electricity (Rs/GWh) Incurred costs of importing fuel (Rs/GWh) Energy generation per year (GWh)	Ceylon Electricity Board[165, 230]
System Information	History of system Regulated flows Data limitations	Dam Safety Report[231]

Yield data are not available for all systems at the system level, but yield data are available for all districts. Some systems fall within multiple districts. The percent contribution of each system's area within each district is calculated in ArcGIS. These percent contributions are multiplied by each district's yield to obtain a weighted area average of yield for each system based on district yield information.

C.3 | MATLAB Function Files

C.3.1 | Organize data

The *reservoir* function reshapes and organizes reservoir storage, downstream discharge, and powerflows in a structure for use in analysis. It outputs a .mat file that can be loaded into MATLAB as a structure when needed.

The *crop* function reshapes and organizes water issues, paddy and other field crops (OFC) extent, and rainfall data. It outputs a .mat file that can be loaded into MATLAB when needed.

C.3.2 | Calculate System Duties

The *duties* function calculates water rainfall and irrigation duties for each system. It outputs a .mat file that can be loaded into MATLAB as a structure when needed.

Within the function, water issues are imported for each scheme. Entries of water issues with N/A and zero are removed. A weighted average of system duties is calculated using each scheme's paddy extent and water issues; duties are calculated by dividing water issues (million cubic meters) by paddy extent (hectares) to obtain a depth (meters).

Seasonal Summary Reports (SSR) appear to have calculated duties by dividing issues by area extent of **both** paddy and OFC. Field visits suggest that irrigation water is primarily used for paddy, and farmers tend to have a strong preference for paddy farming and only plant OFC if irrigation water is not available. Furthermore, the original Mahaweli development plan notes that irrigation water should be used for paddy. Using this information, I make the following assumptions.

- Only paddy is irrigated.
- Each scheme contributes a different amount of paddy to the system because the extent of paddy varies from scheme to scheme.

As a result of these assumptions, the water duty is calculated by dividing each scheme's water issue by each scheme's paddy extent. A weighted average is calculated for each system's duty based on the paddy extents of each scheme.

C.3.3 | Perform Mass Balance

A mass balance was run to identify gains and loses between key points in the Mahaweli Complex (*mass_balance* function). Storage volume, powerflow, and spill data are available for all hydroelectric units, so the mass balance calculates the unknown inflow or outflow water volume between all units. This information is plotted along with volume, powerflow and spill data to gain insight into the system; these data are used to understand better the system and are not used in the tradeoff analysis.

C.3.4 | Calculate Production Functions

The *production_FUN* function creates production models for hydroelectricity and paddy yields.

Hydroelectricity. Each hydroelectricity plant in the Mahaweli Complex has a model relating electricity production (dependent variable) to a volume of water that is run through the hydroelectricity plant's turbine (powerflow, dependent variable). This relationship is fit using lest squares linear regression (Figure C1).

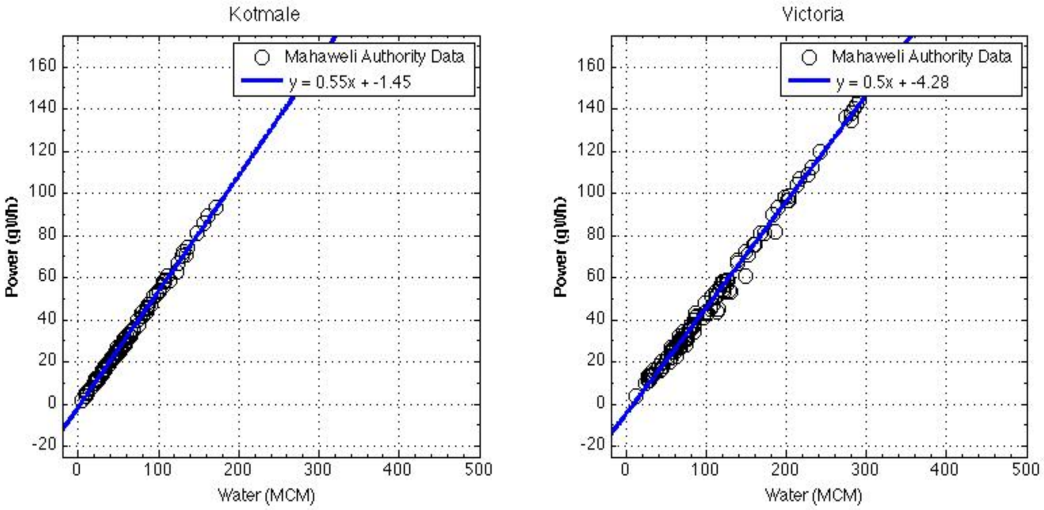

Figure C1 | Hydroelectricity Production Functions for Kotmale and Victoria Dams

Paddy Yields. Exploratory analyses of yield data are used to identify a method for creating paddy yield production curves. The first approach fit a nonlinear model for each system in the Mahaweli Complex relating its paddy yields (dependent variable) to water depths (duties, independent variable). Iterative solutions are needed to minimize the square residuals with nonlinear estimation. The computation implements the Nedler-Mead simplex algorithm for minimizing a nonlinear function of several variables. The function

$$\hat{y} = Y_{max}*K*x/(1+K*x) \qquad \textit{(equation C1)}$$

is fit to the data where $\hat{y}$ is the estimated yield, Y_{max} is the maximum realized yield, K is a yield coefficient, and x is the water duty. To fit this function to the data, the Marquardt-Levenberg process is used to find K and Y_{max} (Press et al., 1986). In any case where the Y_{max} is greater than the maximum realized yield for Sri Lanka—8000 tonnes/hector (t/ha) (Weerakoon)—the Marquardt-Levenberg process is reinstated with a set Y_{max}. In systems where there are water duties but zero yields, the curve is shifted to the right; this shift is based on the largest duty that results in a zero yield.

The results of the nonlinear model (Figure C2) suggest that the data are not represented well. To explore the data further, a Bayesian multilevel and an ordinary linear regression approach are used. Both methods produce similar results (Figure C3): Few systems have yield slopes significantly different from zero. Consequently, all systems' data are plotted to explore the relationship between water duties and paddy yields with a larger sample size. This plot suggests that there is a minimum duty required, and any duty under this amount lends itself to crop failure. Once past this threshold, the data are poorly correlated, suggesting only small yield benefits are added per unit of duty added. Weerakoon reports a ceiling on paddy yield in Sri Lanka; the maximum realized yield in Sri Lanka is 8000 tonnes per hectare (t/ha) in the maha cultivation season and 7000 t/ha in the yala cultivation season. Nevertheless, yield data from Sri Lanka indicates that maximum yields are much smaller.

These results are used to inform the method used in the function *production_FUN*. Limits are set for minimum duties resulting in a yield and maximum yield. Crop failure occurs with a duty smaller than 0.5 meters. Plotting the data reveals a maximum duty around four meters. All data points with a duty between .5 meters and four meters is fit using lest squares linear regression. The maximum yield is set to 4,150 kg/ha, the linear regression model's yield using a duty of four meters (Figure C4).

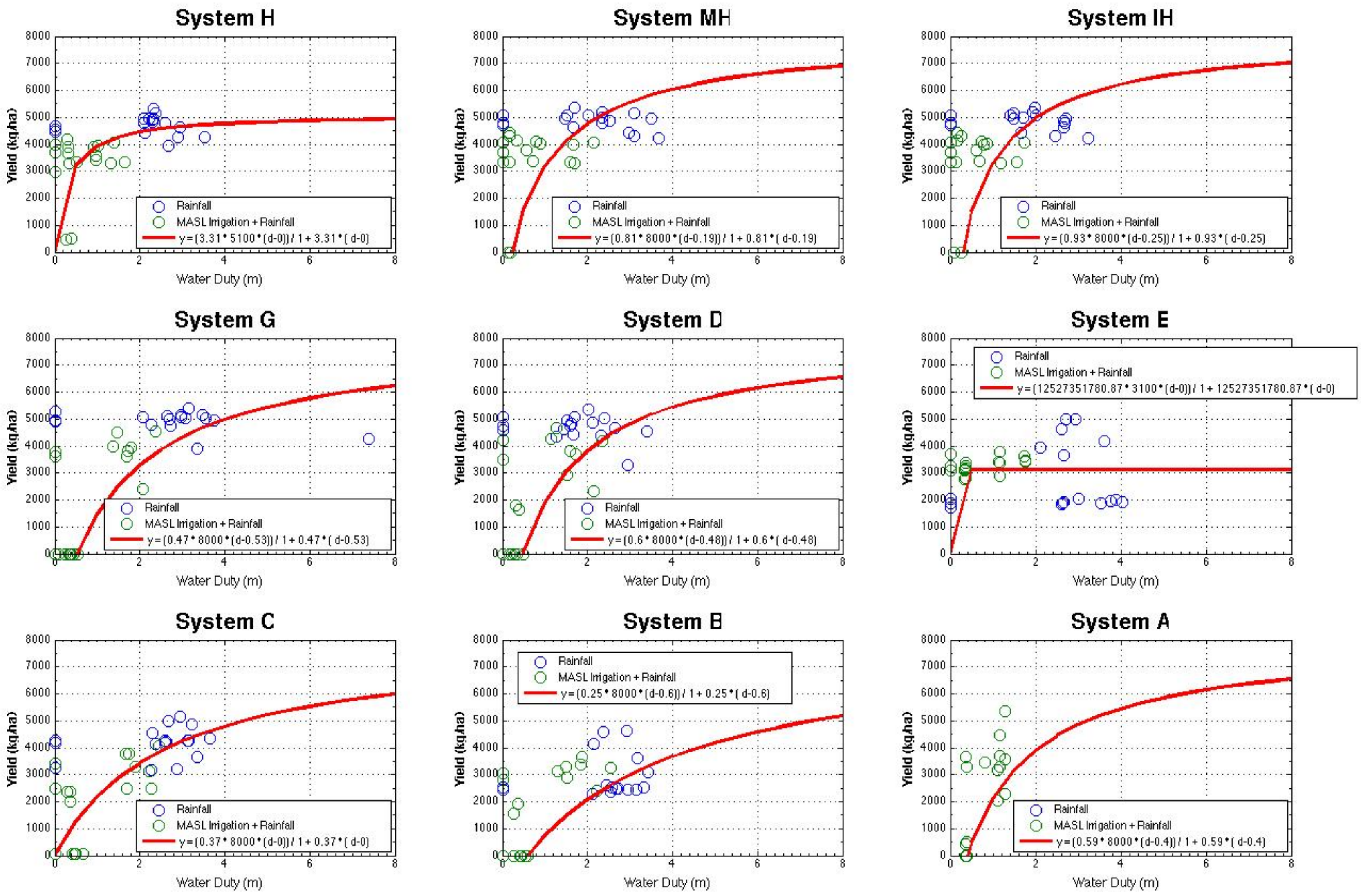

Figure C2 | Nonlinear production curves for paddy yields.

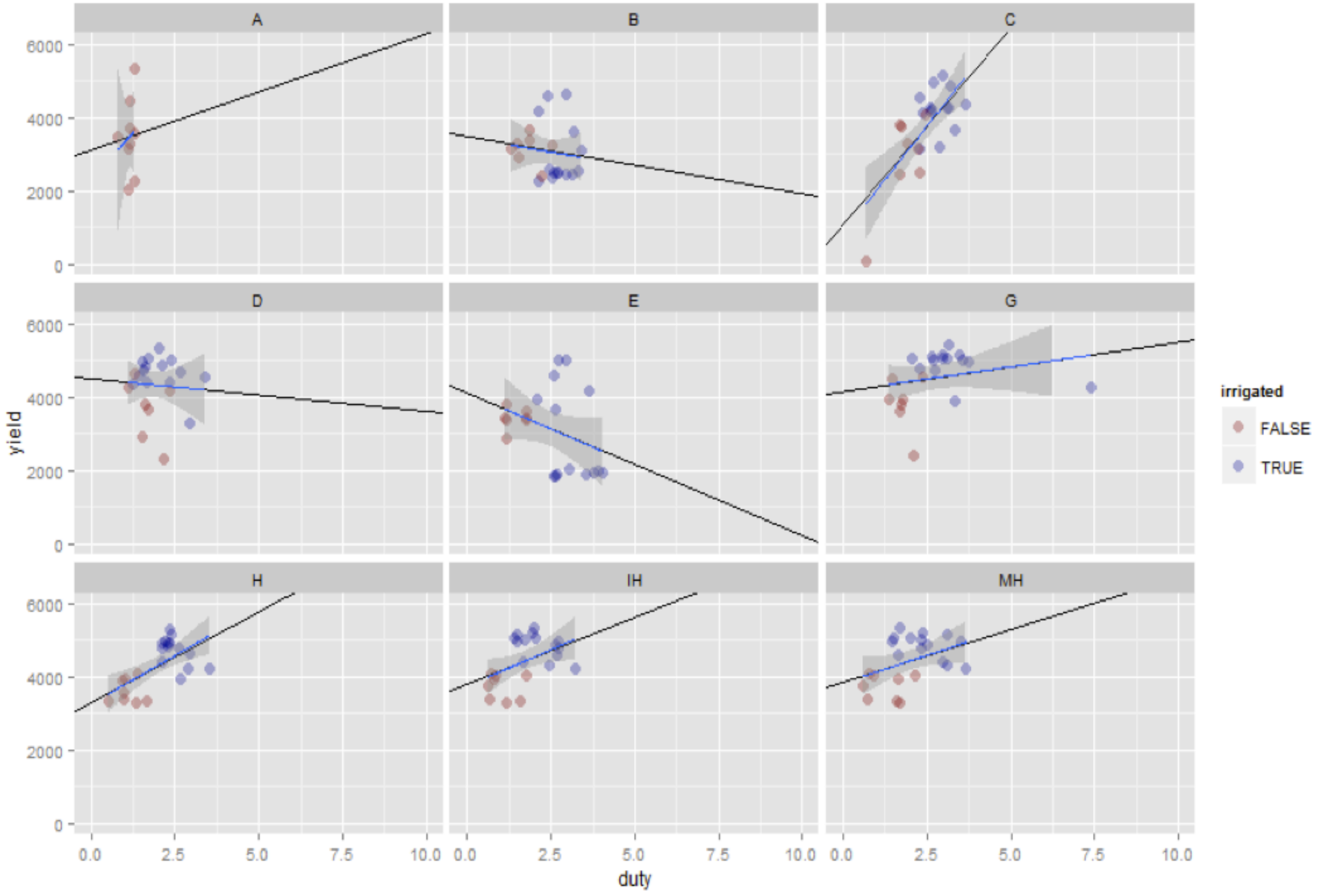

Figure C3 | Bayesian multilevel (black line) and an ordinary linear regression (blue line) results for each system.

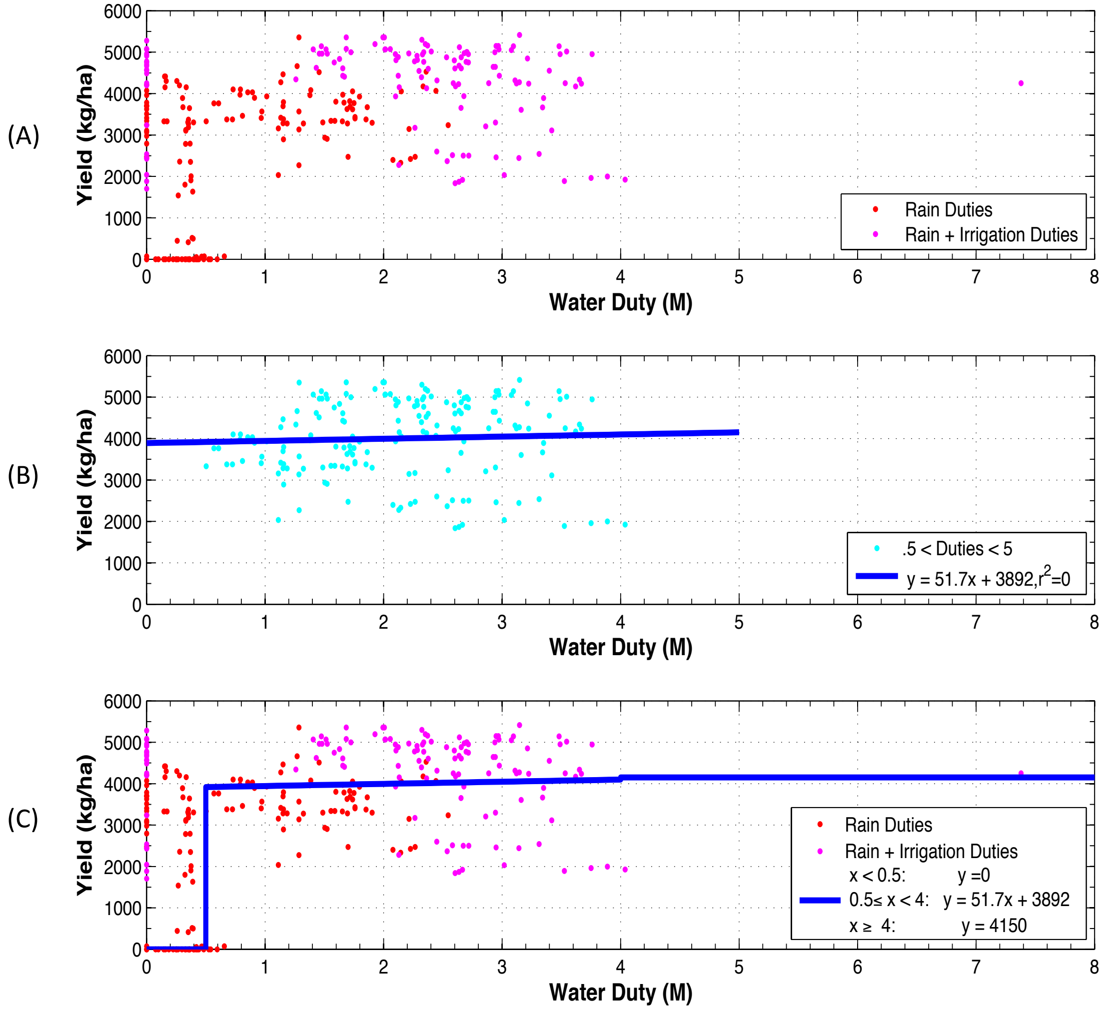

Figure C4 | Yield Plots for All Irrigation Systems in the Mahaweli Complex.

(A) All systems' paddy yield plotted as a function of water duty. Left of 0.5 meters of water duty, the data do not have any relationship. Around 0.5 meters of water duty, there seems to be a spike in paddy yields, but each additional unit of water duty does not lend itself to a large increase in yield. (B) Linear regression results for yields between 0.5 meters and five meters. (C) Production function used in analysis with constraints on minimum water duty and maximum yield.

C4 | Identify Constraints

Two types of constraints are identified: infrastructural and socio-political (Table C3). Infrastructural constraints are constraints that have a physical component. These are built into the model. Socio-political constraints are constraints limited by regulations or politically sensitive topics. These constraints are identified after the analysis is finished and "blacked out."

Table C3 | Constraints on Analyses

Infrastructural Constraints	Socio-political Constraints
Polgolla tunnel capacity	Regulation on Polgolla diversion, reducing capacity Minimum water to maintain socio-political agenda (≠ 0% divergence)
Bowatenna tunnel Capacity	
Polgolla Inflow	Failure of paddy systems is not socially or politically favored
Bowatena Inflow	Failure of paddy systems is not socially or politically favored
Hydropower plant capacities	Maximum hydropower production limited to "base load"

Because hydropower cannot be stored, it is used often to meet base loads. Although a dynamic program is not used to account for this, a constraint can be placed on the maximum production of hydroelectricity so that it is a realistic number. Historical values from Ceylon Electric Board (CEB) suggest that hydropower should only be 1/3 to 1/2 of the total energy portfolio. The maximum amount of hydroelectricity produced was about 5,630 GWh (Table C4), but this includes plants outside the Mahaweli Complex. Therefore, the max base load was set to 5000 GWh.

Table C4 | Hydropower production and gross generation of electricity by CEB.

Item	2004	2005	2006	2007	2008	2009	2010	2011
Hydropower (GWh)	3451	4634	3947	4130	3881	**5634**	4618	3291
Gross Generation (GWh)	8769	9389	9814	9901	9882	10714	11528	11801

C5 | Benefits and Costs

Pricing Paddy and Hydroelectricity. According to a presentation by a research officer at Hector Kobbekaduwa Agrarian Research & Training Institute, of three main types of rice—Kekulu, Samba, and Nadu (white)—Kekulu and Nadu are consumed the most. Within central Sri Lanka (i.e., where the Mahaweli Rover Basin is located), Nadu rice has the highest average monthly household consumption quantities. Farm gate prices are used to align with electricity selling prices. As a result, yearly average farm-gate Nadu selling prices are used in the analysis. CEB provides average selling prices per unit electricity, as well as average fuel costs (i.e., costs per unit of diesel or coal imported to generate thermoelectricity).

The 2002 Consumer Price Index (CPI) for Sri Lanka is used to convert prices nominal prices to real prices (2002 Rs).[232] Prices were also converted to 2011 prices using the same CPI information (Table C5). Price data for Paddy is available up to 2011; other sources report more recent price statistics, but to maintain consistency, data sources are not mixed. (I ran into trouble comparing data across sources when I collected other paddy statistics.) Price data for electricity is available from 2004-2012, but because 2011 is the most recent year for paddy, 2011 is used in the analysis. For both paddy and electricity, the highest and lowest prices in 2011 Rs are identified to provide a range for the tradeoff analysis.

- Nadu farm gate selling prices: 25 - 43 Rs/kg
- CEB Selling Prices: 13– 17 Rs/KWh
- CEB Fuel Costs: 13 – 21.00 Rs/KWh

Because prices of imported rice are not available, a range is approximated using the information available. Sri Lanka has a 20 Rs tariff on imported rice.[168] it is assumed that the tariff is placed on the imported rice to make it at least as expensive as domestic rice. Any imported rice would also need to be adjusted to farm-gate prices so that it is comparable with domestic farm-gate prices; farm gate prices range from 70-80% of wholesale prices.

- Assumed farm gate import price: 7 - 32 Rs/kg

Table C5 | Price statistics for rice and electricity.

Bolded values indicate highest and lowest costs in 2011 Rs.

Item	2003	2004	2005	2006	2007	2008	2009	2010	2011
CPI Sri Lanka	105.80	110.90	124.40	133.50	151.80	183.50	203.10	216.40	231.20
Nadu Selling Price (Rs/Kg)	13.61	18.11	16.15	14.30	19.20	34.26	35.510	31.29	30.39
2002Rs	12.97	16.33	12.98	10.71	12.65	18.67	17.49	14.46	13.14
2011Rs	29.75	37.76	30.02	**24.76**	29.25	**43.16**	40.43	33.43	30.39
CEB Selling Price (Rs/KWh)	N/A	7.66	7.71	8.99	10.56	13.17	13.10	13.03	13.21
2002Rs	N/A	6.91	6.20	6.73	6.96	7.18	6.45	6.02	5.71
2011Rs	N/A	15.97	14.33	15.57	16.08	**16.59**	14.91	13.92	**13.21**
CEB Fuel Cost (Rs/KWh)	N/A	7.09	8.25	9.77	11.07	16.64	12.02	11.72	13.07
2002Rs	N/A	6.39	6.63	7.32	7.29	9.07	5.92	5.42	5.65
2011Rs	N/A	14.78	15.33	16.92	16.86	**20.97**	13.68	**12.52**	13.07

C.5 | Run tradeoff analysis

A mass balance of the Mahaweli complex using dynamic programming is not an option because of data limitations. Because a dynamic program is not used, storage is not taken into account. In an attempt to account for local inflows and outflows, I try to link the relationship between inflows at each diversion to downstream powerflows and water duties using lest squares linear regression. The fits are poor and the error terms are large; the error terms are large enough that running the program over 1,000 times does not stabilize results.

Similar tradeoff studies in Sri Lanka assume that every unit of water is accounted for downstream (i.e., no losses or gains), and thus, do not link inflows at the diversion points to downstream users.[135,157,166] This work takes the same approach, simplifying the analysis so that the uncertainty is focused on the sensitivities with each scenario (Table C6).

The high, medium, and low cases are informed by historical data associated with inflows at Polgolla; that is, the highest inflows and lowest inflows are used to set the high and low case. The high and medium cases for the % of cultivated extent is found by comparing total extent values to historical data yield values. I conduct a sensitivity analysis to see how of the items in Table C6 impact the scenario runs. Changes in percentages of cultivable land alter the total production, but do not alter the incremental changes corresponding to diversion amounts (i.e., there is not significant change in the value slopes when the percent of cultivable land is changed). The low case for the % of cultivated extent is found by finding the range of extents that provides a tradeoff. A percent of 20 and higher leads to complete crop failure, so any value between one and 19% shows tradeoffs associated with the diversions. Fourteen percent is chosen for the base case scenario, but a sensitivity analysis is used to show how important this value is during the dry season.

Table C6 | Sensitivities for scenario runs

Item	High Case	Medium Case	Low Case
Polgolla Diversion (mcm)	Wet: 2100	Normal: 1000	Dry: 300
Rain amount (mm)	Wet: Highest Maha value per system	Normal: Ave Max Maha & Min Yala value per system	Dry: Lowest Yala value per system
% of cultivated Extent	Best: 90%	Moderate: 50%	Poor: 14%
Paddy Pricing (Rs/kg)	Benefit: 25 Cost: 7	None	Benefit: 43 Cost: 32
Electricity Pricing (Rs/GWh)	Benefit: $13*10^6$ Cost: $13*10^6$	None	Benefit: $17*10^6$ Cost: $21*10^6$

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