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METHODS OF THE WATER-ENERGY-FOOD NEXUS

BY

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Article

Methods of the Water-Energy-Food Nexus

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Abstract: This paper focuses on a collection of methods that can be used to analyze the water-energy-food (WEF) nexus. We classify these methods as qualitative or quantitative for interdisciplinary and transdisciplinary research approaches. The methods for interdisciplinary research approaches can be used to unify a collection of related variables, visualize the research problem, evaluate the issue, and simulate the system of interest. Qualitative methods are generally used to describe the nexus in the region of interest, and include primary research methods such as Questionnaire Surveys, as well as secondary research methods such as Ontology Engineering and Integrated Maps. Quantitative methods for examining the nexus include Physical Models, Benefit-Cost Analysis (BCA), Integrated Indices, and Optimization Management Models. The authors discuss each of these methods in the following sections, along with accompanying case studies from research sites in Japan and the Philippines. Although the case studies are specific to two regions, these methods could be applicable to other areas, with appropriate calibration.

Keywords: water-energy-food nexus (WEF); integrated tools; integrated indices; benefit-cost analysis (BCA); optimization management models; integrated maps; ontology engineering; physical models; interdisciplinary; transdisciplinary

1. Introduction

1.1. Background

The concept of the water-energy-food (WEF) nexus emerged in the international community in response to climate change and social changes including population growth, globalization, economic growth, urbanization [1], growing inequalities, and social discontent. These issues are putting more pressure on water, energy, and food resources, presenting communities with an increasing number of trade-offs and potential conflicts among these resources that have complex interactions. It is estimated that the global population will grow to 8 billion by 2025, 10 billion by 2050, and 11 billion by 2100 [2]. In terms of globalization, the traded percentage of food produced has grown globally from 10% in 1970 to 15% in 2000 [3]. The World Population Prospects estimates that 54% of the global population lives in urban areas, and that this proportion is likely to rise to 66% by 2050 [4]. Currently, some 1.1 billion people in the developing world do not have access to a minimal amount of clean water [5], and 1.2 billion still live in extreme poverty [6].

At the same time, the global water cycle is changing in response to warming caused by climate change, though the effects are expected to vary across areas and seasons, with some exceptions [7]. The demands for water, energy, and food are estimated to increase by 40%, 50% and 35%, respectively, by 2030 [8]. The interlinkages between these areas further complicate the matter of addressing their growing demands. Addressing the WEF nexus in a sustainable manner has therefore become one of the most critical global environmental challenges of our time.

1.2. The Study Context

This article presents the key methodological results from the Water-Energy-Food Nexus (WEFN) project by the Research Institute for Humanity and Nature (RIHN) [10]. The objective of the project is to maximize human-environmental security (*i.e.*, minimize risk) in the Asia-Pacific region by choosing policies and management structures that optimize WEF links, including water-energy (water for energy and energy for water) and water-food (water for food) connections. We base our approach on the view that it is important for transformative, sustainable solutions to maximize human-environmental security and decrease vulnerability by optimizing the linkages within the WEF clusters. We will take a regional perspective to tackle these global environmental problems around the Pacific Ocean, where the Asian monsoon dominates hydro-meteorological conditions. The populations that live under these natural circumstances face an elevated risk of negative impacts due to natural disasters, while also benefiting from abundant ecological goods and services. Thus, there are trade-offs and conflicts within WEF resources, as well as among the region’s various resource users.

Figure 1 shows the dynamics of the WEF nexus under RIHN's WEFN project, which focuses on groundwater, spring water, and surface water for the water cluster; geothermal, micro-hydropower and shale gas for the energy cluster; and fishery, aquaculture, and agricultural production for the food cluster. A primary challenge of this undertaking is to examine the interlinkages between groundwater and fishery production, in terms of the hypothesis that the flow of nutrients from the land to the ocean affects the coastal ecosystem. This suggests that water use for producing and consuming food and energy on land might affect fishery production in coastal zones. To examine this theory, the authors present the four case study areas of RIHN's WEFN project: Obama City, Otsuchi Town, Beppu Bay, and Laguna de Bay (Table 1).

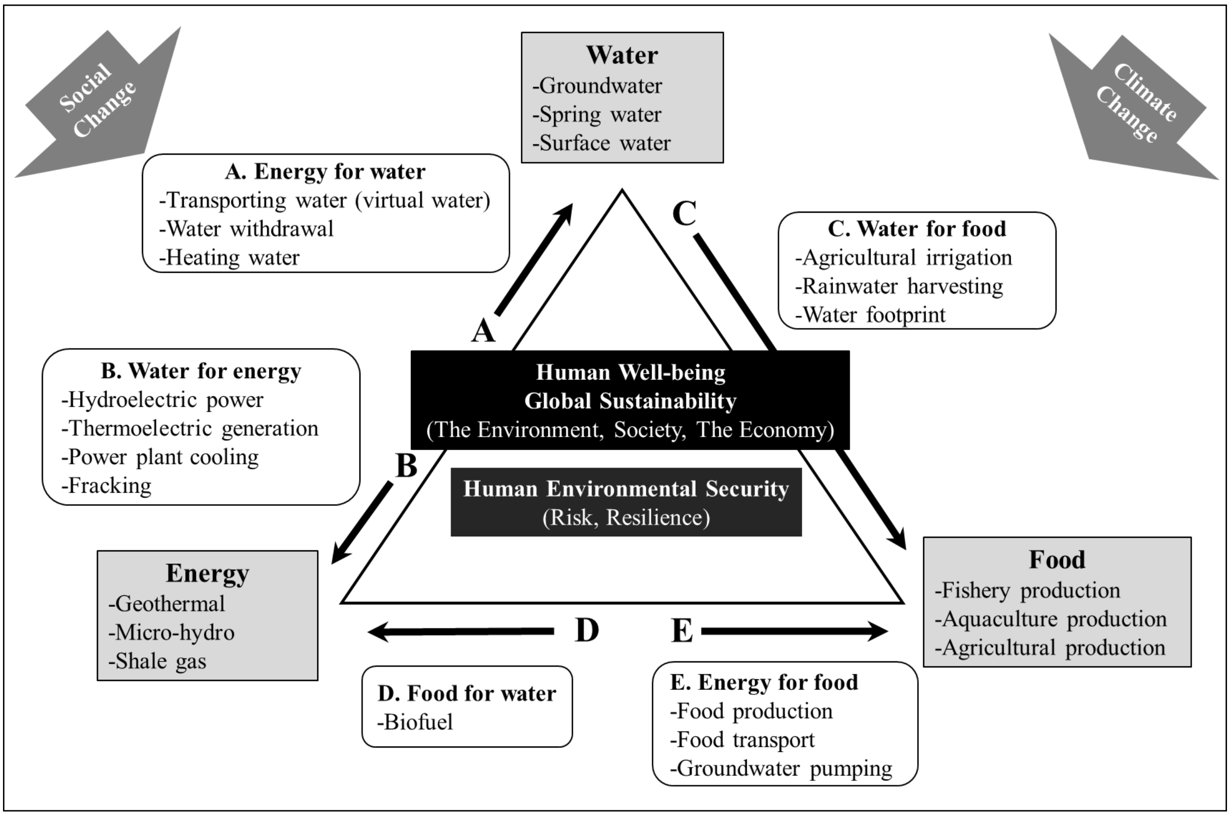

Figure 1. Dynamics of the WEF nexus under Research Institute for Humanity and Nature Water-Energy-Food Nexus (RIHN WEFN) project. Source: Authors modified from [9].

Table 1. Case study areas of RIHN WEFN project.

	Otsuchi			Obama			Beppu			Laguna de Bay		
	W	**E**	**F**	**W**	**E**	**F**	**W**	**E**	**F**	**W**	**E**	**F**
for W		—	—		P	—		—	—		—	—
for E	H		—	Gr		—	H/G/Gr		—	H		—
for F	F	—		F	P		F	—		F/A	—	

Notes: H: micro-hydropower; F: fishery production; P: pumping; G: geothermal energy; Gr: ground heat exchanger system; A: agriculture production.

1.2.1. Obama City

Obama City is a coastal city of about 33,000 in central Wakasa District, at the mouth of the Kita River on the Sea of Japan in southwest Fukui Prefecture, Japan. The coastline around Obama City and Wakasa Bay is steep, irregular, and very scenic. The mixture of cold and warm currents in Wakasa Bay provides fertile fishing grounds. While fishing used to be the main industry, now the city is mostly supported by tourism. Groundwater has always been an important resource for the Obama area for domestic, municipal, industrial, and limited agricultural uses; in addition, groundwater has a cultural and historical significance. For example, it is used to melt snow in winter since it maintains a constant temperature throughout the year. It also provides a steady supply of nutrients to the nearshore region via submarine groundwater discharge (SGD) into the sea. Several commercially important fish species appear to thrive in the low-salinity, high-nutrient environment that SGD provides such as sea bass, oysters, and crabs.

1.2.2. Otsuchi Town

Otsuchi Town is located in Iwate Prefecture in northeast Japan, and was one of the most adversely affected towns following the March 11, 2011 Tohoku earthquake and tsunami that devastated the northeast part of the island of Honshu. The catastrophe obliterated the town harbor and all low-lying areas, inundating about half the city. The two important river basins include the Otsuchi and Kotsuchi Rivers. With an economy based on commercial fishing and to a lesser extent small-scale agriculture, Otsuchi lost nearly all its fishing boat, and the tsunami completely destroyed the town’s sea farm industry. Through death and displacement, the local population fell from about 16,000 in 2011 to an estimated 12,000 in 2014. The flowing spring water wells played important roles before and after the tsunami as resources for drinking and other human security purposes. However, most of these springs have been covered in order to raise the ground level, thus cutting off local people’s access. In addition, the national and local governments are planning to build 14-meter dikes along the coast to protect the town from future tsunamis.

1.2.3. Beppu Bay

In 2014, Beppu City’s population was 120,000 and has been falling since its peak in 1981. The population of people 65 or older account for 35% of all inhabitants, and the number of children has decreased. Regarding topography, an alluvial fan is gently spreading from west to east. Hot springs originating at Mt. Tsurumi in western Beppu flow to the urban sectors. The hot spring water has a higher temperature in the mountainous areas than in the lowlands. Oita Prefecture ranked first in terms of the total amount of hot spring discharge points and spring water sources, and Beppu City has ranked first in the overall quantity of discharged hot spring water in the prefecture. The Hiya, Shin, Hirata, Haruki, Sakai, and Asami Rivers flow into Beppu Bay, and household and hot spring wastewater run into these rivers.

1.2.4. Laguna de Bay

Laguna de Bay is the largest freshwater lake in the Philippines and supports more than 35,000 fishermen. The lake consists of four bays in the west, center, south, and east. Calamba City and the urban municipality of Los Baños are the project's target sites, located in the south bay in Laguna Province in the southern part of Manila. The country's Department of Environment and Natural Resources classified the lake as class C freshwater, which means that it is generally designated for fish culture and propagation. In addition, the lake can be used for Class II recreation (no water-contact tourism activities) and Class I industrial water supply (for manufacturing purposes). Laguna de Bay has been extremely stressed by rapid urbanization and industrialization, which contributed to an increase in water demands for other uses such as agriculture, household consumption, tourism, and operating hydroelectric plants. Competition and unregulated use by multiple actors has been causing the quantity of water to decline, and its quality to degrade.

2. Methods for Analyzing the WEF Nexus

In this paper, we follow a framework for the interdisciplinary and transdisciplinary co-creation of new knowledge based on the concepts of co-design and co-production [11], the goal being to link the ideas and actions of numerous stakeholders from various sectors. We consider different temporal and spatial scales, including vertical and horizontal dimensions, to achieve sustainable development based on the international research platform Future Earth 2025 Vision, which prioritizes eight key focal challenges. The WEF nexus is one of them, and Future Earth's mission states "*Deliver water, energy, and food for all, and manage the synergies and trade-offs among them, by understanding how these interactions are shaped by environmental, economic, social and political changes.*"

Following this concept, the project was designed consisting of five teams that carried out the following (see the project's structure in Figure 2):

(1) Biophysical measurements and analyses using space satellites, geothermic, and hydrogeological techniques (the water-energy nexus team);
(2) Biophysical measurements and analyses using geochemical, coastal oceanographic, geophysical, hydrologic, and ecological methods including isotopic tracers (the water-food nexus team);
(3) Social measurements and examinations of WEF relationships using stakeholder analyses, social network analyses, and community surveys, based on sociology, economics, anthropology, psychology, and behavioral science approaches (the stakeholder analysis team);
(4) Environmental governance, science in/for society, and co-design/co-production strategies emphasizing the integration of local-national scale stakeholders, and regional scale stakeholders (the science in/for society team); and
(5) The interdisciplinary team.

The interdisciplinary team conducted the research presented in this article with a mission to: (1) identify research problems; and (2) determine the methods and/or create new discipline-free methods [12] based on synthesizing and harmonizing team-based production, collected from individual scientists in different disciplines from each team in order to assess human environmental security. In addition, the team further developed these approaches to incorporate non-scientific/-disciplinary views on the analysis.

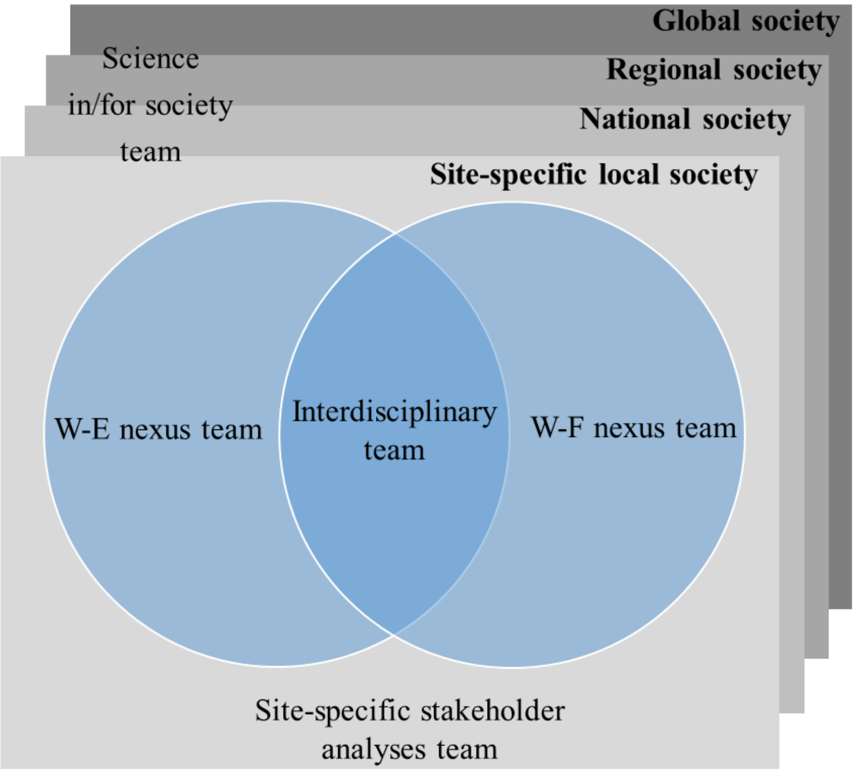

Figure 2. The structure of RIHN WEFN project.

We classified these methods as qualitative or quantitative (see the taxonomy in Table 2) for interdisciplinary and transdisciplinary research approaches, emphasizing the interaction between different scientific disciplines. The methods for interdisciplinary research can be used to unify a collection of related variables, visualize the research problem, evaluate the issue, and simulate the system of interest. Qualitative methods are generally used to describe the nexus in the region of interest, and include primary research methods such as Questionnaire Surveys, as well as secondary research methods such as Ontology Engineering and Integrated Maps. Quantitative methods for studying the nexus include Physical Models, Benefit-Cost Analysis (BCA), Integrated Indices, and Optimization Management Models.

The authors discuss each of these methods in the following sections, along with accompanying case studies from research sites in Japan and the Philippines. Although the case studies are specific to two regions, we see that these methods can apply to other areas with appropriate calibration. All methods discussed here are transdisciplinary in that they begin by engaging stakeholders in order to identify the appropriate research question. Then, they are used to design the scientific approach to collect appropriate data in order to parameterize and develop models. In turn, this allows researchers to answer the policy or management question of interest.

Table 2. Water-energy-food (WEF) methodology and taxonomy.

Type of Data		**Functions**	**Interdisciplinary Research Approaches**				**Trans-Disciplinary Research Approaches**
Primary	**Secondary**	**Methods**	**Unification**	**Visualization**	**Evaluation**	**Simulation**	
Qualitative Methods							
√	√	Questionnaire Surveys	√	√	√	--	√
--	--	Ontology Engineering	√	√	√	√	√
√	√	Integrated Maps	√	√	√	√	√
Quantitative Methods							
√	--	Physical Models	√	√	√	√	√
√	√	Benefit-Cost Analysis	√	√	√	--	√
√	√	Integrated Indices	√	√	√	√	√
√	√	Optimization Management Models	√	√	√	√	√

Source: Endo, A.; Orencio, P.; Kumazawa, T. and Burnett, K.

3. Qualitative Methods to Describe the Nexus

Although the fundamental relationships between water, energy and food have been used to operationalize concepts such as security, no single approach has been deemed suitable for every situation. A variety of factors including but not limited to scales, populations, institutions, and socio-economic conditions are central to deciding which approach should be used for an integrative and interdisciplinary analysis [13]. In developing countries, security can be defined simply as access to basic needs [14] or entitlements [15]. Following this concept, one way to evaluate security is by looking at the convergence of the core properties of water, energy and food systems; such attributes include access, availability, utility, and stability at the individual and household levels [16].

An analysis of how the core characteristics of water, energy, and food systems interact, whereby individual or household needs are compromised, usually requires specific measurements. However, most global frameworks developed to jointly analyze the three systems are not intended to be used at the local or regional levels because they do not incorporate the proper temporal and spatial scales [16]. Hence, studying the place-based interactions of each system at various spatial scales is valuable for decision-making. In the sub-sections below, we share our experiences using three qualitative methods to analyze water, energy and food systems: Questionnaire Surveys, Ontology Engineering, and Integrated Maps.

3.1. Questionnaire Surveys

We used Questionnaire Surveys in the case of Laguna de Bay (see above) to assess the WEF nexus. We based our methodology on the approach suggested by Strasser *et al*. [17], who stressed that basin-level information would be ideal for an accurate appraisal and can be gathered through a questionnaire that screens the nexus resources.

Questionnaire Surveys contributed to a nexus assessment that aimed to address the question of how the population's security is affected when various natural and social hazards disrupt the linkages among the three systems. Energy plays an important role in understanding human security within these connections. However, in this study, we paid particular attention to the relationship between water and food because the degradation of the water-food system has affected the socio-economic conditions of people in the study area in a multitude of ways; for example through pollution [18], competition for access to limited resources [19] and fish operations [20,21].

We designed the Questionnaire Survey based on a set of concepts that underlie water, energy, and food systems e.g., [22–24], namely availability, access, utilization, and management. The collected information will be used to develop the integrated index, which will support decision-making related to the inter-relationships of water and food. The Questionnaire Survey consists of four sections. The first section deals with demographic characteristics, while the second section looks at household access to and utilization of food and water resources. It also aims to determine each household's choice of food and water sources, and what types of activities are employed to manage major sources. The third section focuses on socio-economic activities, including an in-depth assessment of each household's main sources of income. The fourth section examines risk management, identifying available mitigation systems at the household level.

Prior to distributing the survey questionnaires, we gathered feedback on the survey's content and duration through field-testing. We then created a final web-based questionnaire using Google Forms to facilitate a paperless survey (http://goo.gl/forms/WceqPbHspM).

We carried out the field activities in March 2015 in targeted households of the two towns. In Calamba (*N* = 258), the households came from three agricultural barangays (*n* = 85), three barangays in sub-basins (*n* = 87) and three barangays in lakeshore areas (*n* = 86), respectively. In Los Baños (*N* = 202), the total number of samples came from households in two agricultural (*n* = 73) and two lakeshore (*n* = 129) barangays.

An assessment of household heads' sources of livelihood show that the income of the studied households in Calamba and Los Baños comes from various water-related activities. Farming and forestry contributes to 15% and fishery-related work around 20% of their livelihood sources. There is a strong dependence on water for food production, yet only around 15% recognize the government policies on water management systems currently in place. One can attribute this problem to a lack of management and access to information or financial systems.

We found the use of Questionnaire Surveys to screen and gather pertinent information on the inter-relationships of different nexus resources at the local level to be promising. The Questionnaire Survey was especially useful in incorporating the local people's general outlook on their level of economic, food, and livelihood security when various shifts occur in terms of the quality and quantity of the water-food nexus. Consequently, this provides the information necessary to make decisions and thus optimally manage local nexus resources. However, we have to acknowledge that the quality of the survey instrument always affects data resulting from this approach. Such quality includes the steps undertaken to develop the tool [25] and their limited spatial and temporal applications [26].

3.2. Ontology Engineering

Scholars have proposed methods and frameworks supporting interdisciplinary and transdisciplinary approaches in the field of team science. However, the methods and research designs for reasonably, effectively assessing the processes and outcomes of team science have not been sufficiently developed [27]. How do we facilitate collaboration using interdisciplinary and transdisciplinary approaches? Defila and Di Giulio [28] stated that the existence of many different frames, or definitions of the problem, suggests a need to develop shared goals and language, while Defila *et al*. [29] showed that those who achieved a synthesis also succeeded in identifying a common language and a collective theoretical basis.

Ontology Engineering is one of the base technologies in semantic web technology, where the Internet is used to create a knowledge base that computers can deal with directly by means of adding metadata, (*i.e.*, semantic information for computers, as annotations to information resources on the World Wide Web) [30,31]. An ontology consists of concepts and relationships that are used to describe the target world. It provides common terms, concepts, and semantics by which users can represent the contents with minimum ambiguity and interpersonal variation of expression. Construction of a well-designed ontology presents an explicit understanding of the system.

An ontology can deal with a model, an indicator system, or an analytical framework rather than a case itself. The main steps using an ontology are: (1) Sharing the definition of a term; (2) Sharing the relationship between items; (3) Sharing the relationship between models/indicator systems/analytical frameworks; and (4) Sharing the relationship between a defined term and a metadata item. The relationship between the WEF nexus model (Figure 1) and the ontology of sustainability science/social-ecological systems (SS–SES; please see below) corresponds to the relationship between the model and the ontology. Figure 3 illustrates these relationships.

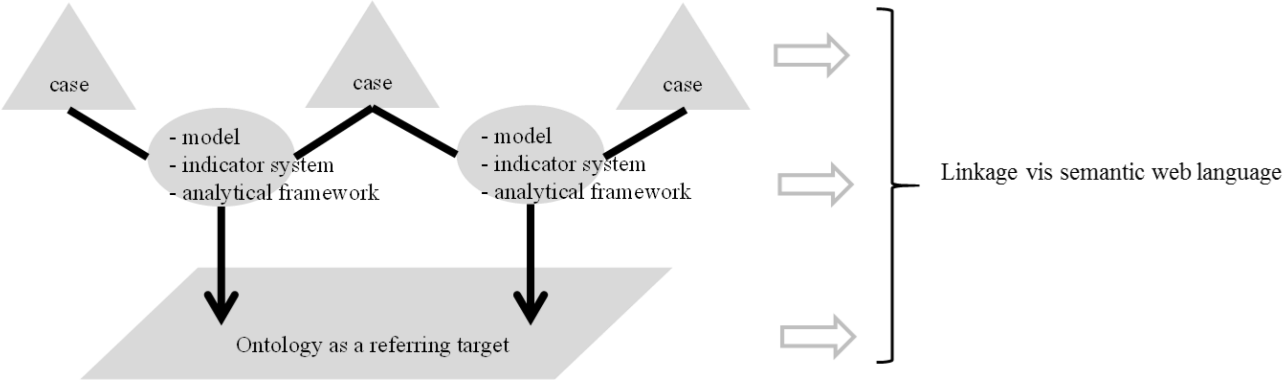

Figure 3. Mutual relationships structured by cases, models and ontology.

We used Ontology Engineering in Obama City and Beppu City (see above), building on a set of questions defined for those contexts. Figure 4 displays a conceptual map focusing on water, generated from the SS-SESs ontology [32,33]. This map shows that agriculture, fisheries and human life are the hubs that connect water, energy and food. By exploring the causal chains in the conceptual map, we can identify the question to be analyzed.

Combining the exploratory questions and the ontology dealing with the nexus should facilitate our ability to establish the issue for further examination and share it among a variety of researchers or stakeholders.

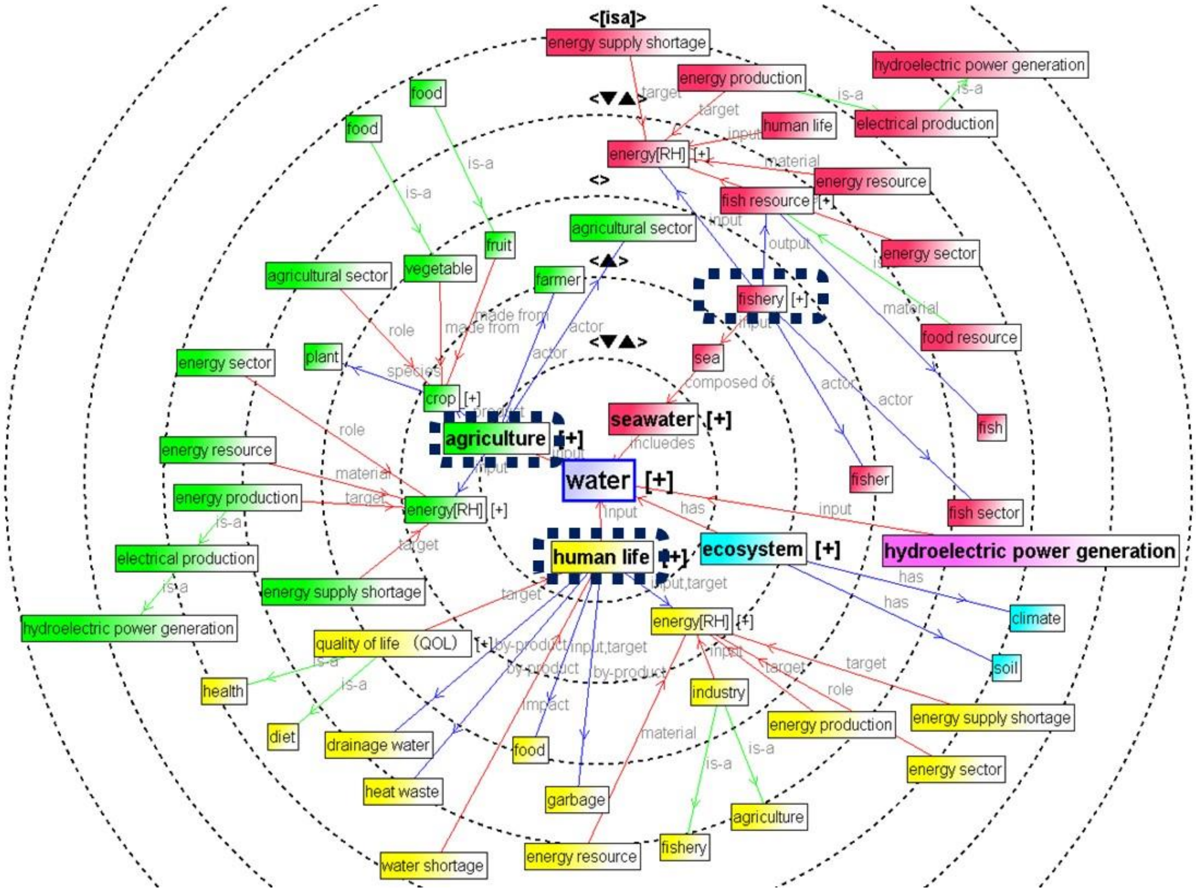

Figure 4. Conceptual map focusing on water.

3.3. Integrated Maps

An Integrated Map is an overlay of various single maps, and it can be used as a method to support the implementation of synthesized policies between the land and the sea. In contrast to sectoral management and monodisciplinary research approaches (which often focus on a single ecological system), an integrated map informs policies capable of restoring and maintaining the interdependence between the land and the sea.

Creation of an integrated map brings many benefits. Firstly, it can be used to incorporate individual research results into maps as integrated methods for interdisciplinary research approach to enhance mutual understanding between members. Secondly, it can be used to unify data, information and knowledge on maps to visualize and disseminate the current status of environment and utilization in river basins and coasts to stakeholders. Thirdly, an integrated map can facilitate the identification of key nexus issues, such as the impact that nutrient flows have for coastal ecosystem. Fourth, Integrated Maps can be used as a transdisciplinary method, engaging stakeholders and policy-makers to discuss through an integrated map how to implement integrated management of land and coastal areas. For an example of an Integrated Map created for Beppu Bay, see Annex.

It is possible to create a site-specific Integrated Map at the local level to visualize the current conditions of water, energy and food resources, as well as resource users. However, it would be challenging to create an Integrated Map at the national or global level. In addition, an Integrated Map shows a static condition, not future scenarios, which limits the map's utility to demonstrate inter-scale, inter-generational and inter-area circumstances.

4. Quantitative Methods to Examine the Nexus

Along with three qualitative methods, we took a combined approach using four quantitative methods: Physical Models; BCA; Integrated Indices; and Optimization Management Models. We used various kinds of quantitative methods, especially by the W-E and W-F nexus teams to analyze the interlinkages of the water-energy and/or water-food systems; this helped us understand the complexities of WEF nexus systems.

Furthermore, we presented the specific per-site results in several forms but normalized them to allow for direct comparison with other results at different project locations in the Asia-Pacific region. This makes it possible to decide on optimal policies regarding the sustainable management of water, energy, and food, not only for project members, but also for stakeholders.

4.1. Physical Models

A physical model simulates a biological or ecological system using mathematical formalizations of that system's physical properties. Such models are often used to predict the influence of a variety of factors on a complex system. In the context of water, we are often interested in how both exogenous (e.g., droughts, sea level rise, natural disasters) and endogenous (e.g., groundwater extraction, surface water diversion, water pollution) factors ultimately affect resource quality and availability over time.

To address questions about human-environmental security in the context of the WEF nexus, we developed a physical water model as part of RIHN's WEFN project. Based on a representation of water balance (the SHER model) and a three-dimensional groundwater simulation (the SEAWAT model). Using data collected daily, the SHER model can calculate water balance components such as groundwater recharge, river discharge, and surface runoff with precipitation and evapotranspiration. The SEAWAT model consists of the modular finite-difference flow model (MODFLOW) and the modular 3-D multi-species transport model (MT3DMS), which can simulate water and dissolved material transport by using the advection-diffusion equation. The web-link for the modeling methods can be viewed at http://water.usgs.gov/ogw/modflow/.

Thus far, we have calibrated the physical model described above using data from Obama City. The primary issue currently facing Obama City is how to allocate groundwater among multiple uses, including for domestic purposes, melting snow (groundwater has a constant temperature throughout the year), as well as providing the necessary inputs to the nearshore fishery resources via submarine groundwater discharge. Results from this modeling exercise will allow us to consider how various future land use and climate change scenarios will affect water balance components such as recharge, runoff, and river discharge, in order to inform water management and land use decisions in Obama City. We intend to use these outcomes to help parameterize the economic models that we are developing to allocate groundwater in the most optimum way possible for these various uses over time.

Integrated physical models (such as those that measure water balance), and hydrological parameters (such as water exchange between rivers and groundwater, and groundwater discharge into the ocean) are useful methods for hydrologists. Material transport (including nutrients from the land to the ocean by rivers and groundwater) is important for fisheries. Hydrology, fisheries, and geochemical and biochemical information can be applied to this integrated physical model in an interdisciplinary way. To complete the transdisciplinary process, decision makers should be able to employ this model along with other stakeholders, such as scientists and business sectors, to decide on optimal policies for sustainable water and ecological management. This integrated physical model can deal with both the water-food and the water-energy nexuses. For the water-food nexus, we need additional data to link it with fisheries; however, we can obtain the basic components of water balance and geochemical parameters including chlorophyll-a with this model. For the water-energy nexus, the model can illustrate the connection between groundwater and subsurface temperature, which is important for heat pumping and geothermal energy.

Integrated physical models can simulate the balance between water, energy, and food production; therefore, simulations based on potential future scenarios can be useful for decision makers. However, the results of integrated model simulation without social and local knowledge may lead people to misconstrue the model's results if the numbers from simulations are unrealistic for political, economic and other reasons.

4.2. Benefit-Cost Analysis

BCA allows us to gauge an environmental project or investment by comparing an activity's economic benefits with its economic costs, usually over some fixed time horizon. BCA can be used to appraise a scheme's economic merit, or to compare the net benefits of competing projects. BCA examines potential changes to the ecosystem, with the objective of increasing social welfare.

One way to carry out BCA is to use benefit-cost models (BCMs), which assess the desirability of a proposed policy or project, either independently or ranked according to highest net benefit if selecting from a range of alternatives. BCMs can be used in the context of evaluating WEF nexus project to clearly consider the trade-offs in a particular region where one or more of the WEF elements will be utilized. The researcher begins the analysis by identifying all the potential benefits and costs of a particular action, regardless of whether he/she can quantify or monetize them. This step is usually conducted in partnership or consultation with stakeholders in the region of interest.

Once the time horizon for analysis is selected, we can calculate the net present value of quantifiable benefits and costs. Because nexus-related problems are typically dynamic, it is important to consider the timing and magnitude of benefits and costs. When monetized benefits largely exceed monetized costs, policy and management implications may be more straightforward than when monetized benefits fall short of monetized costs. In the latter case, the results can be interpreted to mean that if the non-monetized benefits are at least as large as the difference in shortfall between monetized costs and benefits, then the project or policy passes the benefit-cost test over the selected time horizon.

We developed a BCM to analyze the construction of a new dike between the Pacific Ocean and Otsuchi's coastline. In 2011, the Tohoku earthquake and tsunami completely destroyed a six-meter dike, and the Japanese government started to build a new 14-meter dike to replace the old one. While the project will be extremely costly in terms of construction expenses, the potential benefits associated with protecting lives and material property are also expected to be substantial. BCA is a method for evaluating the potential gap between these elements.

In terms of pros, the largest expected component will be avoided damages from another Tohoku-like event (future estimates for damage range from USD 50 million [34] to USD 210 million [35]). Other, much smaller potential benefits include ecotourism and tourism-related benefits that might be realized via the Itoyo Sanctuary Park, which is being planned to protect the nationally protected "itoyo" fish species.

On the cost side, the largest component will be the current and future construction expenditures involved in building the dike. In addition to construction costs, annual operation and maintenance expenses will be calculated and discounted for the appropriate time horizon. Similar costs will be collected for the Itoyo Sanctuary Park, though these are expected to be insignificant compared to the larger building costs of the dike. Another important component of the cost portion is ecological losses. Erecting the dike is expected to result in a 100% loss of the area's mudflat habitat, which would lead to economic losses in terms of the oyster, abalone, and seaweed fisheries. We calculated typical (or average) total annual profits from each of these fisheries and included them in the losses as a result of building the dike.

The WEF nexus is inherently about trade-offs. BCA enables researchers to provide decision-makers with information regarding the consequences of these trade-offs and to explicitly examine the net benefits of decisions in order to allocate scarce resources (such as water) toward food or energy. In addition, to improve understanding of the trade-offs, BCA makes the costs and benefits accrued over individual time periods transparent.

4.3. Integrated Index

A number of studies have shown that a mix of sociology, geography, and natural science is required to effectively analyze the relationship between people and their surrounding environment, e.g., [36–38]. Often, a key research objective aims to understand how people cope and develop, given prevailing social inequities and environmental stresses, which are typically area-specific [39].

Indicators are methods used to quantitatively describe and operationalize any system, no matter how inherently complex [40,41]. Indicators have served as an operational representation of various social and environmental characteristics, wherein measurable variables are used to create each indicator in order to quantify the system's overall characteristics in an analysis. To investigate and gauge the social system, MacGregor and Fenton [42] identified five indicator classes (informative, predictive, problem-oriented, program-evaluation, and target-delineation), which can be used to describe or model the different social sub-systems. Informative indicator types describe the social system, while predictive types model describe the social system's various components.

We employed indicators to assess the security of the human-environmental system in Laguna de Bay, using approach similar to the one presented in [41]. The objective was to identify indicators for measuring human-environmental security in Laguna, with a particular focus on the interconnection between food and water. This method is contextual and dynamic, and hence needs to be approached on a case-by-case basis. Common indicators for different environments are difficult to achieve because they should be strongly linked to the issue and objective for measurement and tailored specifically for the research area. Although not covered in this study, there is a strong interconnection between water and food with energy. The lake that supports the fisheries has been providing water that turns the turbines of the hydro-electric plants that supplement the region's energy supply. We believe this might entail a different approach for indicator development because energy operates on a different spatial scale.

Prior to selecting the indicator, we created a profile with help from local experts to establish area-specific information on physical and social characteristics. This profile included: the hazards that pose a risk to security of the social and natural environment; the susceptibility of the coupled system based on its intrinsic conditions (e.g., special needs populations, proximity to the hazard source); and the consequences based on the hazard effects.

An objective is formed and the approach to meet it is established within the target communities and their respective human and environmental values, the hazards that threaten their human values, and the means for mitigating their negative effects. We referred to the objective to develop the indicators.

The general dimensions for analyzing human-environmental security within the interconnections of water and food consisted of social, environmental, economic, governance, and risk components. For each dimension, specific indicators are identified based on prevailing indicators of the World Governance Index (WGI), the World Development Index (WDI), and the United Nations Development Programme's (UNDP) Human Development Index (HDI). Annex is an example of the indicators selected for the social dimensions to analyze the water-food nexus.

Based on our preliminary observations, an indicator-based assessment of the water-food nexus at the local level has allowed us to incorporate households' views and knowledge into our analysis of the effects of shifts from the water-food nexus to the human-environmental system. This is useful for minimizing bias assessment of social and environmental conditions at the study sites. However, we observed that this could also be challenging due to the unavailability of reliable and pertinent data. In this case, gathering responses at the household level and quantifying them based on a scale to gauge conditions has been substantial in the process of indicator-based assessment [25].

4.4. Optimization Management Models

While the BCM is an appropriate framework when the objective is to evaluate a project's independent or comparative desirability, a different approach is needed when the goal is to determine optimal allocation of a resource that has linkages to many other resources and may also cross physical, political, and administrative boundaries. In such situations, the Optimization Management Model provides one possible method to look at optimal resource allocation. Such a framework is invariant to the extent of transboundary interlinkages, as the objective is to maximize the net present value of total welfare. Once the optimal allocation is identified, however, the most effective way to incentivize behavior that approximates that social optimum can vary greatly depending on the particular situation.

We used the Optimization Management Model to study groundwater allocation problem in Obama City. Water has traditionally been thought of as a common property resource in the area, with publicly provided groundwater pumps and wells throughout the city. However, it is of interest how groundwater extraction influences the availability of SGD, as well as the fisheries. Such changes may lead to different management actions and policies regarding groundwater use in Obama City.

In order to address these questions, RIHN researchers developed an economic optimization framework that allows us to consider aquifer dynamics in response to a variety of different controls. The main model's control variables are pumping groundwater for domestic use and pumping groundwater for melting snow, since the groundwater remains at a constant temperature throughout the year. In response to these changes in pumping, the aquifer head level will be drawn down, thereby decreasing water pressure and subsequently changing the amount of SGD available in the nearshore. The optimization framework allows us to describe these linkages between groundwater pumping and the resulting dynamics of the aquifer, and optimize by choosing the benefit-maximizing levels of groundwater pumping for domestic and snow-melting uses during every period on the time horizon. For detailed explanation of the framework, see Annex.

While important trade-offs can be qualitatively identified using the theoretical optimization framework developed above, calculating the actual trajectories of optimal resource extraction and stock levels requires numerical methods. When the problem is relatively simple, applying a standard gradient method will often lead to the net present value (NPV) maximizing solution. However, as the complexity of the problem increases (for example, when the number of interlinked resources increases), a more complex, nonlinear programming algorithm may be required. Therefore, depending on the particular situation (e.g., the resource system's complexity, s strict or flexible project deadline, computational capability, data availability, the types of research/policy questions being addressed) then a BCM, optimization model, or a combination of the two may be most suitable.

An Optimization Management Model allows researchers to explicitly represent the interaction of natural resources, which is key to understanding trade-offs inherent in the WEF nexus. Decisions to draw down one resource often affect other resources, as well as the social welfare of the community of interest. For example, the decision to use groundwater for fisheries rather than agriculture depends on the production costs of both fish and agriculture, including energy. Economic optimization allows the researcher to determine how to allocate scarce resources over time, when doing so has consequences for the surrounding ecosystem and society.

5. Discussion

In this section, we discuss our experience on developing and using various integrated methods to address the WEF nexus. The main advantage of integrated methods is their ability to synthesize team-based production collected by individual scientists in different disciplines. Integrated methods are necessary to link the ideas and actions of numerous stakeholders from different sectors in light of distinct temporal and spatial scales. Both vertical and horizontal dimensions should be considered to reduce trade-offs and conflicts, and optimize the linkages within the WEF clusters.

In Table 3, we re-categorized and synthesized different methods to provide a critical reflection from an Ontology Engineering perspective. The methods we developed are shown in bold letters. We began by grouping methods according to how the target or objective of the research was expected to be achieved. A perspective-oriented approach uses information from a survey, analysis, or assessment, often in a forward-looking or predictive manner, in order to meet the research target. In other words, the method focuses on what could be understood. The state-oriented approach, on the other hand, aims to grasp the system in its current state; that is, it determines what should be understood about the target itself. We further sub-categorized these methods according to dimension/unit systems, and the integrated methods described in this paper each cover one or more of those dimensions (e.g., spatial, physical, monetary). In summary, we collected data from team-based production using each of the monodisciplinary approaches in order to create site-specific integrated methods.

Table 3. We re-categorized each method from the ontology engineering perspective.

How the Target World Exists	How to Recognize the Target	Dimension/ Unit System	Individual Method	Integrated Method
Target system	√ Perspective-oriented √ What to be understood √ Format-oriented	Spatial	Map	Integrated Maps
		Physical	Physical Models	Integrated Physical Models
		Monetary	Cost Analysis	Benefit-Cost Analysis
			Benefit Analysis	Economic Optimization Models
		Non-unified unit	Indicator	Integrated indices
	√ State-oriented √ What to understand √ Content-oriented	Context-dependent	Specific	Comprehensive
			Questionnaire surveys	Interviewing

A remaining challenge is to develop integrated methods for linking the ideas and actions of various stakeholders from different sectors, while also considering distinct temporal and spatial scales, including vertical and horizontal dimensions (Figure 5). Ways of connecting local nexus issues within a community to broader national and global nexus issues (the vertical dimension) are often missing from site-specific case studies. At the same time, it is important to understand how an incident related to WEF resources and resource users in one case study area could affect other case study areas (the horizontal dimension). Finally, we should also consider how current events are likely to impact future WEF resources and resource users on a temporal scale.

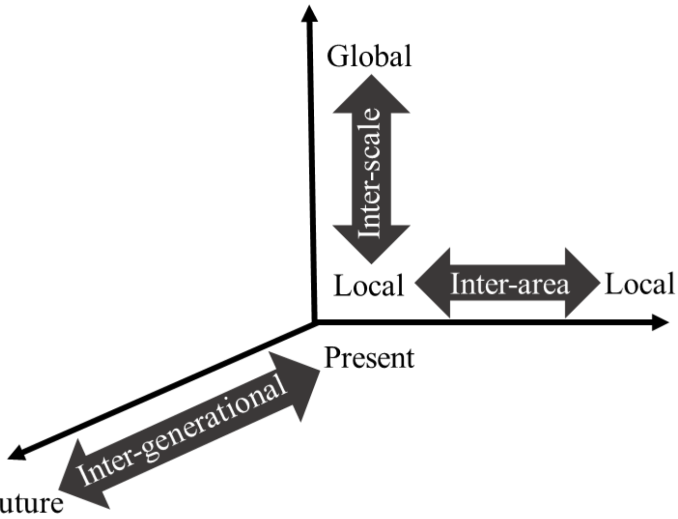

Figure 5. Relationships between targets on different spatial and temporal scales.

6. Conclusions

This article has provided a comparative analysis of various integrated methods that we used under the RIHN WEFN project in order to analyze the WEF nexus. We classified the integrated methods as qualitative and quantitative that contribute to both interdisciplinary and transdisciplinary research. Our approach employs the concepts of co-design and co-production to link the ideas and actions of numerous stakeholders from distinct sectors considering different temporal and spatial scales, including vertical and horizontal dimensions to achieve sustainable development.

Qualitative methods that we analyzed consisted of Questionnaire Surveys, Ontology Engineering and Integrated Map, while quantitative methods included Physical Models, BCA, Integrated Indices, and Optimization Management Models. We discussed our experiences using all of these methods based on case studies from research sites in Japan and the Philippines.

To take the approach of co-design and co-production through the project process, each method should be developed as a science-policy interface method, although each one has different uses at various stages. Ontology Engineering would be the most useful for designing the project during initiation stage to build a list of common concepts of term; the linkages of each term among stakeholders included researchers and practitioners. In addition, Ontology Engineering could be used at the policy planning stage to assess whether the policy/plan would cover all disciplines including natural sciences, social sciences and humanities, and sectors such as water, energy, and food (in order to address the key issues that are originally identified during the initiation stage). Questionnaire Surveys would be more useful for collecting information to analyze WEF interlinkages when few data exist; then, it would help to identify the key issues during the initiation stage. Integrated Maps can provide an opportunity to share knowledge showing actual conditions at a spatial scale among stakeholders during the policy planning stage. BCA and an Optimization Management Model would play important roles in clarifying trade-offs during the initiation stage, creating and providing policy options during the policy planning stage. Physical models could be quite essential to understand WEF nexus systems; if it were developed to clarify interlinkages between physical conditions of water, energy and food, as well as human activities by working with social scientists, then, it could be used to address the key issues more holistically during the policy planning stage. Using an Integrated Index can be a discipline-free method, which could incorporate and integrate each result with different disciplines, then evaluate trade-offs during the policy planning stage. At the same time, interdisciplinary team members themselves could be interpreters or coordinators for science-policy interface, using those approaches when they have a commitment to both science and society from the initiating stage.

From the perspective of spatial and temporal scales, although we covered spatial, physical and economic dimensions, our approach is somewhat limited in terms of vertical and horizontal elements, as well as on a temporal scale to address the WEF nexus. To address these challenges, it can be possible to use global data such as a global model to set our site-specific case studies within a global context on vertical spatial scale [44]. In addition, the creation of future scenarios further integrating each integrated method mentioned in this paper must be a challenge, however this will make it happen to analyze WEF nexus based on temporal scale [45]. While our case study areas focused on relatively small water bodies in Japan and the Philippines, we believe that all the methods can also apply in other contexts, including large transboundary rivers. The most important is first of all to understand the context and its specific characteristics and then recognize the key issues and related problems. Finally, it is key to select the most appropriate method(s) to analyze those issues. Overall, we conclude that developing integrated methods to link different scales and to achieve multi-dimensional targets is an important area for future research at both the case study level and in large river basin areas.

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Author Contributions

Aiko Endo and Izumi Tsurita reviewed WEF nexus practices and studies; Kimberly Burnett and Christopher Wada developed the BCA and Optimization Management Models; Pedcris M. Orencio conducted and analyzed the results of Questionnaire Surveys; Terukazu Kumazawa contributed to the section on Ontology Engineering as well as the discussion; Aiko Endo and Akira Ishii designed the Integrated Map; Makoto Taniguchi contributed to the section on Physical Models; Pedcris M. Orencio developed the Integrated Index with support from all authors. Although Aiko Endo and Kimberly Burnett conceived this paper, this research was conducted by an interdisciplinary team under the RIHN WEFN project performed this research. In order to assess human-environmental security, they aimed to develop integrated methods to synthesize and harmonize each project member’s discipline and set of research skills.

Conflicts of Interest

The authors declare no conflict of interest.

Appendix

A. Integrated Map in Beppu Bay

The Basic Act on Water Cycle (enacted in 2014) and the Basic Act on Ocean Policy, (enacted in 2007) guide Japan’s current water and coastal management. The former aims to re-establish the view that water is an integral part of water circulation and to promote integrated measures with respect to the water cycle. The latter broadly defines coasts as any areas where the land and sea interact. Water and coastal management thus requires an integrated approach.

It has gradually become clear that SGD plays an important role in the cycling of dissolved materials and is now viewed as one of the water cycle’s invisible channels [43]. The map in Figure A1 overlays the actual conditions of use of the Hirata River, the Hiya River basin and Beppu Bay, with visually observed locations of spring water (in crossed pink lines).

Different bodies charged with overseeing specific targets oversee Japan’s coastlines. The observed locations of spring water have been identified in both commercial port areas (in purple), which fall under the jurisdiction of the Coast Act (first enacted in 1956 and amended 1999), as well as common fisheries right areas (in light green), which fall under the Fishery Act. SGD has not been managed to date, because it occurs along the policy border between terrestrial and coastal areas. In order to clarify the dimensions where conflicts of interest emerge among stakeholders, effective administration will require interdisciplinary studies to reconsider the spheres and boundaries of water circulation handled by each ministry and agency, and the relationships between these actors.

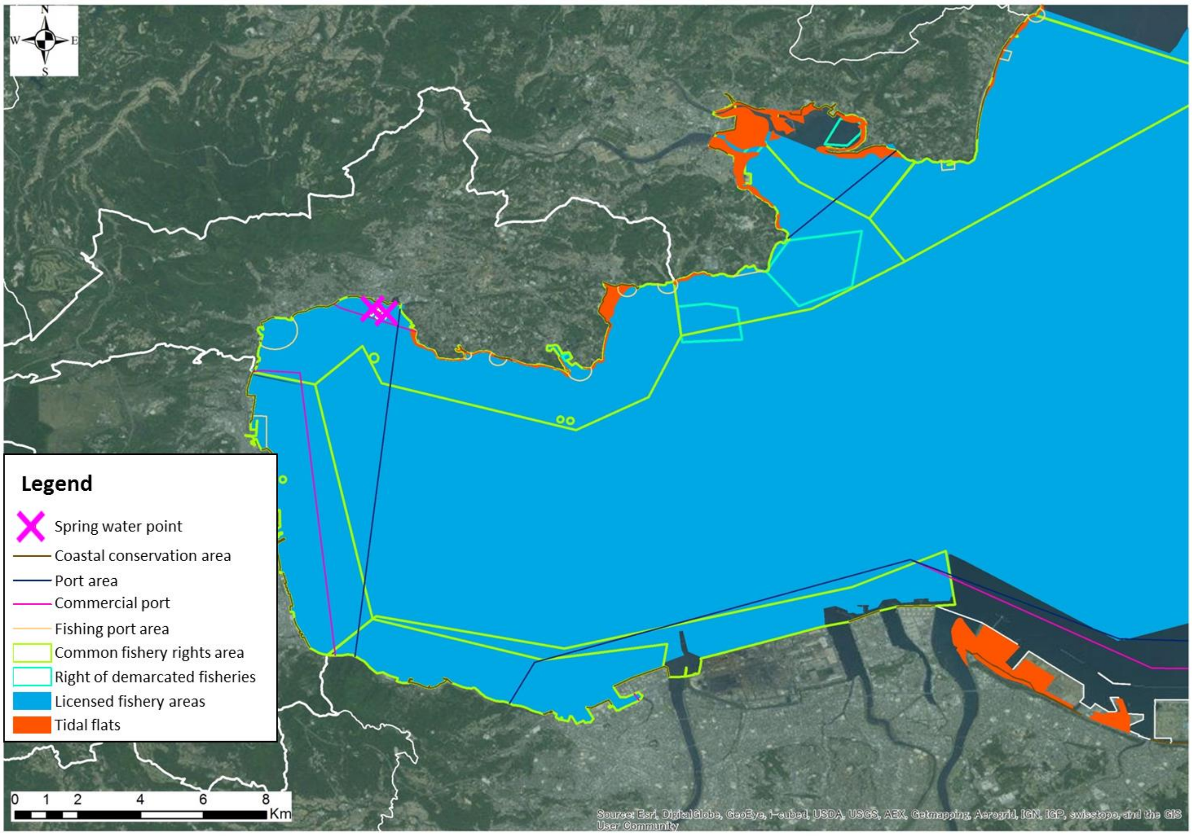

Figure A1. Beppu Bay—Multiple overlay map. Source: [44].

B. Social Indicators for Lagunade Bay

The Table A1 below shows selected indicators of the social component for the analysis of water and food nexus in Laguna de Bay. We identified the indicators based on the objective, within a specific boundary. Each boundary corresponds to a specific dimension and is referred to when distinguishing the indicators.

In general, social indicators are chosen based on their measurability when downscaled at the local level. The availability of real data for valuation at this level is one of the major concerns for establishing a quantitative measure. Nonetheless, household surveys that can be rapidly executed could be explored to develop the quantitative values. The use of the Likert scale to gauge household socio-economic data, with reference to a range of values, was very useful in the process of identifying, evaluating, and measuring indicators, e.g., [25]. This is an important component of metric development that is required to create a human-environmental security index, which, like the WGI, the WDI and the HDI, could portray the security of the coupled system in the research area.

Table S1.

Component	Indicators	Variables	Tentative Values
Social	Food sufficiency rates	% of protein needs sourced from fisheries	Total required dietary allowance (RDA) protein need per individual
		% of protein needs met	Total RDA of protein needed per individual
	Water sufficiency rates	% water demand supplied locally	80% of demand per end user is supplied
	Health status	% of mortality rates of adults, women and children	Major cause of mortality
		access to hospital services	Standard hospital beds for size of population
		% occurrence of water-borne diseases	50% of children and female population are affected by water-borne diseases
	Change in the population	% population growth rate	Annual national growth rate
		% population density	Mean standard limit of population density
	Transportation	Passenger cars	Availability of passenger vehicles for public transport per standard population
	Communication	Mobile phone/TELCO subscriptions	80% of population has access to TELCO subscriptions

C. Description of the Optimization Management Model in Obama City

Figure A2 displays the general framework used to study Obama City's optimal groundwater management. The central resource of interest in the framework is the groundwater aquifer, illustrated by the blue box in the center of the flow chart. Aquifer volume $X_h(h)$ is a function of head level h, which will be changed via the controls (in red): groundwater quantity pumped for households q_H at a cost of $c_w(h)$ and the quantity of groundwater pumped to melt snow q_S, also at a cost of $c_w(h)$. Distribution costs for each use are given by c_{DH} and c_{DS}, respectively. The third control variable in the model is the quantity of fish caught q_F, harvested at a cost of $c_F(X_F)$. Aside from the aquifer state variable, this framework includes the fishery stock, given in orange by X_F, which is governed by the growth function $G(X_F, h)$. In this framework, the primary stock of groundwater directly affects the growth of the fish stock via SGD, which is a function of head level $SGD(h)$. Benefits for all uses of groundwater are shown in green: domestic benefits B_H, snow-melting benefits B_S, and fishery benefits B_F.

The framework allows researchers to understand the multiple trade-offs working against each other in the model. As more groundwater is used for one of the aboveground uses (domestic or melting snow), less is available to support fishery production in the nearshore region via submarine discharge. The optimal allocation of water will depend on the marginal benefits accrued under each of these uses, as well as the marginal costs for utilizing each one. These benefits and costs will change over time in response to their respective time paths, described in Equations (2) and (3). The objective is then to choose the optimal time paths of groundwater pumping for each use to maximize total NPV from all three uses of groundwater: domestic, melting snow, and fishery production. Equation (1) describes this goal mathematically.

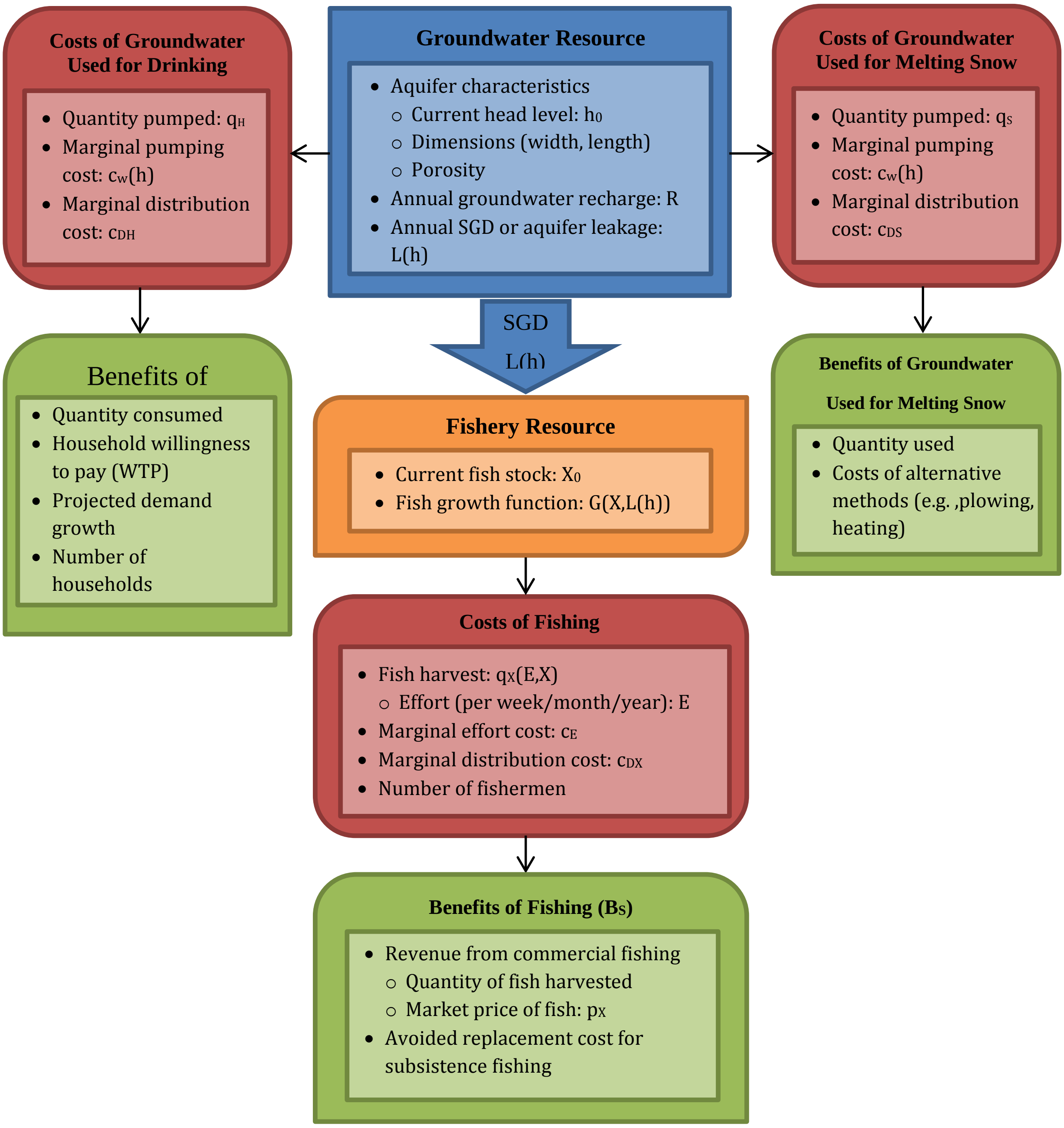

Figure S2. Groundwater optimization model for Obama City, Japan.

$$\begin{gathered}\text{Max } (B - C) \text{ over time} \\ \text{subject to } dh/dt = \text{Recharge} - \text{SGD}(h) - (q_H + q_S) \\ dX_F/dt = \text{G}(X_F,h) - q_F\end{gathered} \tag{1}$$

where

$$B = B_H(q_H) + B_S(q_S) + B_F(q_F) \tag{2}$$

$$C = [c_W(h) + c_{DH}]q_H + [c_W(h) + c_{DS}]q_S + [c_F(X_F) + c_{DF}]q_F \tag{3}$$

When the problem is transboundary in nature, there may be multiple benefit and cost functions for each end use, *i.e.*, the B and C-functions would be indexed not only by end-use but also by region or country. Although that complicates the mathematics, the underlying methodology remains the same. Once the optimal allocation is determined, payments for benefits or compensation for costs can be used to incentivize transboundary socially optimal outcomes. In this case, the commercial fishermen might give up a portion of their expected benefits to cover the cost to the service provider (the users of the aquifer) of ensuring the continued provision of the valuable SGD. This may require substituting groundwater use with costlier alternative freshwater sources (e.g., recycled wastewater).

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