frontiers in Water

ORIGINAL RESEARCH
published: 12 October 2021
doi: 10.3389/frwa.2021.713000

# Methodology for Nexus Approach Toward Sustainable Use of Geothermal Hot Spring Resources

*Aiko Endo*[1]*, *Makoto Yamada*[2], *Kenshi Baba*[3], *Yuji Miyashita*[4], *Ryo Sugimoto*[5], *Akira Ishii*[6], *Jun Nishijima*[7], *Masahiko Fujii*[8], *Takaaki Kato*[9], *Hideki Hamamoto*[10], *Michinori Kimura*[11], *Terukazu Kumazawa*[12], *Naoki Masuhara*[13] and *Hisami Honda*[14]

[1] Center for Global Change and Earth Observations, Michigan State University, East Lansing, MI, United States, [2] Faculty of Economics, Ryukoku University, Kyoto, Japan, [3] Faculty of Environmental Studies, Tokyo City University, Yokohama, Japan, [4] Research Division, Hot Springs Research Institute of Kanagawa Prefecture, Odawara, Japan, [5] Faculty of Marine Science and Technology, Fukui Prefectural University, Obama, Japan, [6] Infrastructure Space Digitalization Unit, Research Institute for Infrastructure Paradigm Shift, Yachiyo Engineering Co., LTD., Tokyo, Japan, [7] Faculty of Engineering, Kyushu University, Fukuoka, Japan, [8] Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Japan, [9] Faculty of Environmental Engineering, The University of Kitakyushu, Kitakyushu, Japan, [10] Center for Environmental Science in Saitama, Kazo, Japan, [11] Systems Analysis Division, Lake Biwa Environmental Research Institute, Otsu, Japan, [12] RIHN Center, Research Institute for Humanity and Nature, Kyoto, Japan, [13] School of Human Science and Environment, University of Hyogo, Himeji, Japan, [14] Department of Agriculture, Forestry and Fisheries, Fukui Prefectural Government, Fukui, Japan

OPEN ACCESS

**Edited by:**
Mohammad Al-Saidi,
Qatar University, Qatar

**Reviewed by:**
Christopher Wada,
University of Hawaii, United States
Fanxin Meng,
Beijing Normal University, China
Janez Susnik,
IHE Delft Institute for Water Education, Netherlands

***Correspondence:**
Aiko Endo
endoaiko@msu.edu

**Specialty section:**
This article was submitted to Water and Human Systems, a section of the journal Frontiers in Water

**Received:** 21 May 2021
**Accepted:** 08 September 2021
**Published:** 12 October 2021

**Citation:**
Endo A, Yamada M, Baba K, Miyashita Y, Sugimoto R, Ishii A, Nishijima J, Fujii M, Kato T, Hamamoto H, Kimura M, Kumazawa T, Masuhara N and Honda H (2021) Methodology for Nexus Approach Toward Sustainable Use of Geothermal Hot Spring Resources. Front. Water 3:713000. doi: 10.3389/frwa.2021.713000

This study has developed a methodology for the nexus approach by integrating interdisciplinary and transdisciplinary concepts and qualitative and quantitative mixed methods into the process of the systems thinking approach. The nexus approach was institutionalized in two projects using the location specific case study of Beppu, Japan where a set of interconnected issues in using geothermal hot spring resources have emerged due to the promotion of geothermal energy development under low-carbon policies at global and national levels. The interlinkages among geothermal hot spring resources, including heat, steam, nutrients, and drainage between land and coastal systems were analyzed to improve decision- and policy-making. This study discusses (1) how different discipline-oriented methods and data are integrated, (2) how much of the targeted water-energy-food nexus systems are understood using the nexus approach, and (3) how far does the nexus approach influence changes in the policy agenda and human behavior regarding sustainable geothermal hot spring resources use. The nexus approach facilitated the sequential integration of individual methods and data to better explain the causal linkages focusing on water-energy-food resources in the human-nature systems in Beppu. The proposed policy recommendations are based on the local government initiative for continuing to conduct citizen participatory surveys on geothermal hot spring resources. Transferring the developed methodology will help to effectively develop geothermal hot spring resources and compliment the current national renewable energy and natural resource policies and management.

**Keywords: water-energy-food nexus, nexus methodology, geothermal resources, hot spring, renewable energy, interdisciplinary, transdisciplinary, integration**

# INTRODUCTION

## Current Discussion on the WEF Nexus

The interdependencies and tradeoffs among energy, food, and water resource systems and sectors have become apparent with the background of socio-economic and climate events triggered in the early 2000's. The global energy crisis, with increasing oil prices in 2007 and biofuel production, was the impetus for the global food crisis in 2007 and 2008 (Allouche et al., 2014). Severe drought in the USA in 2007, 2008, and 2012, and the extreme heatwaves in Europe in 2003, 2006, and 2009 increased electricity generation and therefore water demand for thermal power plant cooling. This resulted in output reductions or total shut down at several power plants owing to limitations of water availability or water rights, as well as policies related to avoiding the violation of the thermal pollution limits (DeNooyer et al., 2016; Webber, 2017; Gjorgiev and Sansavini, 2018). Securing water resources will be both constraints and opportunities for businesses, as well as private investors and the financial industries (Pandey and Sangam Shrestha, 2017). Recent study shows that the water-energy nexus has increasingly been the focus of water-energy-food (WEF) nexus studies (Endo et al., 2020). Triggering events and several driving factors have enhanced this trend, such as (1) the occurrence of extreme climate, weather events, and disasters; (2) technological breakthroughs; (3) enhancements to regional energy and economic cooperation, as well as the integration of energy security, considering water security; (4) large-scale infrastructure development for water and energy in developing countries; (5) the identification of tradeoffs among water, energy, and low-carbon policies among different levels; (6) targeting multiple global goals, such as the Sustainable Development Goals.

Managing tradeoffs among resources systems and different interests, and scale and power gaps among socio-economic sectors, has shaped the global agenda, known as the WEF nexus, which has been discussed at the international level, such as the World Economic Forum and United Nations, as potential decision- and policy-making tool.

The nexus approach, conceptualized at the 2011 Nexus Conference in Bonn, Germany, consists of two dimensions namely interdisciplinary and transdisciplinary. The interdisciplinary dimension addresses the complexity of the linkages among water, energy, and food resource systems and sectors by highlighting the tradeoffs and synergies. The transdisciplinary dimension enhances the cooperation with diverse groups of stakeholders and improves governance across sectors by translating systems thinking into government policy-making processes and balancing different user goals and interests (Allan, 2003; Bazilian et al., 2011; Hoff, 2011; Lawford et al., 2013; Ringler et al., 2013; The Food and Agriculture Organization of the United Nations (FAO), 2014; Keskinen et al., 2015; Scott et al., 2015; Kurian, 2017). Various discourses, such as integrated water resources management (IWRM) (Benson et al., 2015), social-ecological systems approach (Pandey and Sangam Shrestha, 2017; Gain et al., 2021), and the incorporation of systems thinking, have largely influenced the concepts of the nexus. The nexus approach aims to balance the social, environmental, and economic dimensions of sustainable development. These dimensions include understanding human-nature interactions in ecosystems (Al-Saidi and Elagib, 2017; Kurian et al., 2018); implementing more holistic policies and regulatory designs for economic efficiency, resource efficiency, improved livelihood options, and public health (Bazilian et al., 2011); managing interdependencies between resource and policy systems and among the diverse actors shaping these systems (Stein et al., 2018); identifying critical linkages that determine the system behavior, including human behavior, and recognizing key leverage points for policy options (Alcamo, 2015). After the 2011 Bonn conference, the WEF nexus discourse has been implemented across many academic disciplines and has witnessed geographic expansion, along with tool and method development, as an interdisciplinary and integrated approach; however, a well-established nexus methodology, combining both interdisciplinary and transdisciplinary approaches, does not currently exist (Endo et al., 2020). Interdisciplinary, qualitative, and quantitative mixed methods, as well as incorporating transdisciplinary or participatory approaches, are prerequisites for addressing the physical and social aspects of water, energy, and food systems (Albrecht et al., 2018).

Ongoing discussions and challenges have characterized the nexus approach, highlighting the second dimension as an essential component for applying this approach. Nexus governance is weak (Pahl-Wostl et al., 2018), poorly conceptualized (Al-Saidi and Elagib, 2017), and disconnected from decision- and policy-making processes, which has resulted from fragmentation across the water, energy, and food sectors (Weitz et al., 2017), as well as different policy levels. Studies that empirically examined how governance actors understand the nexus concept, how these actors are linked, and what policy actions they recommend remain limited (White et al., 2017). One example is the absence, incoherence, and gaps in policy arrangements between the global acceleration of renewal energy development based on low-carbon policies and local practices. From a climate and energy justice perspective, donor-driven hydropower projects have impacted ecosystems and local livelihoods in the Mekong region (Siemenpuu Foundation, 2021); this appears to have reduced the emphasis on the security of local natural resources and livelihoods (Käkönen and Kaisti, 2012). Food, water, and energy have never been conceptually separated for farmers and fishermen in many rural communities (Allouche et al., 2014), or in river watersheds, including coastal areas where non-academic forms of knowledge on local resources and management of the local area exists. Understanding the interlinkages and tradeoffs in natural and social systems requires the recognition of local knowledge and the rights and interests of local stakeholders (Weitz et al., 2017), consideration of local cultures and behavioral changes related to the use of human resources, and the involvement of local communities and various other stakeholder groups during the implementation process (Pahl-Wostl, 2019). A specific understanding of the complexity in the local trade-offs and interconnectedness of the nexus requires an in-depth case study (Hamidov and Katharina Helming, 2020). Moreover, an effective local-to-global WEF resource management will help to achieve the national and global targets of WEF security (Purwanto, 2021). To address these challenges, the nexus approach was applied in this study to context specific governance issues using a local-level location-based case study (White et al., 2017) in Japan.

## Objectives

This study aims to develop a methodology for the nexus approach by integrating interdisciplinary and transdisciplinary concepts and qualitative and quantitative mixed methods into the process of the systems thinking approach under two projects. The first project, titled "Human-Environmental Security in the Asia-Pacific Ring of Fire: Water-Energy-Food Nexus" (Fiscal Year 2013–2017), which had two primary objectives: (A) to understand the complexity of the WEF resource system and (B) to create policy options to highlight the trade-offs among resources, solve conflicts among resource users using scientific evidence and uncertainty, and maximize human-environmental security. The second project was the "Development of the Methodology for the Integrated Future Scenario Building with Trans-disciplinary Approach" (Fiscal Year 2019–2020), which developed a methodology for scenario building as a transdisciplinary approach. In this study, the nexus approach was institutionalized in the courses of the two projects using the location-specific case study of Beppu, Japan where a set of interconnected issues in using geothermal hot spring resources have emerged due to the promotion of geothermal energy development under low-carbon policies at global and national levels. We analyzed the interlinkages in geothermal resources, including heat, steam, nutrients, and drainage (as a cascade use of energy, water, or food sources) between land (underground and river systems) and coastal systems, to provide a reference for decision- and policy-making processes when managing the tradeoffs among stakeholders. This study discusses (1) how different discipline-oriented methods and data are integrated, (2) whether the methodology developed for the nexus approach is useful for understanding the targeted natural and social systems, or rather how much of the targeted WEF nexus systems are understood using the methodology developed for the nexus approach, and (3) how far does the nexus approach influence changes in the policy agenda and human behavior regarding sustainable geothermal hot spring resources use.

## Study Area

In the 2010 Basic Plan on Energy Supply and Demand (Basic Energy Plan), a Japanese energy policy aimed to achieve the following goals by 2030: (1) increase the self-sufficiency ratio in the primary energy supply from 18 to 36%, (2) increase the percentage of electricity generation from nuclear and renewable energy from 34 to 70%, and (3) increase the percentage of total electricity generation from nuclear power to 50%. However, the 2011 tsunami and earthquake revealed vulnerabilities in the Japanese energy system and dysfunctions related to security and public administration. Nuclear power plants have currently ceased operation while nuclear reactors are being tested to conform to new regulatory standards introduced in July 2013. As of March 15, 2021, only 9 out of 60 power plants were operational while 24 are expected to be decommissioned (Agency for Natural Resources and Energy of Ministry of Economy, Trade and Industry (METI), 2021a). Consequently, the self-sufficiency ratio for the primary energy supply declined from 19.6% in 2010 to 8.4% in 2016. Japan became increasingly dependent on imported fossil fuels, resulting in increased fuel costs, electricity bills, and $CO_2$ emissions between 2011 and 2013 (Agency for Natural Resources and Energy of Ministry of Economy, Trade and Industry (METI), 2021b). In 2020, the Japanese government announced the objective of carbon neutrality by 2050 by promoting the development of low-carbon, low-emissions, and domestic-grown energy production, such as nuclear, offshore wind power, and hydrogen, since the energy sector accounts for 85 and 93% of the total greenhouse gas and $CO_2$ emissions, respectively (Agency for Natural Resources and Energy of Ministry of Economy, Trade and Industry (METI), 2021c). For a disaster scenario(s), the new plan aims to build a distributed energy system by combining small-scale renewable energy sources at the local level.

Japan, characterized by dozens of volcanoes and approximately 28,000 hot springs, possesses significant geothermal resources and currently ranks third in geothermal energy potential (Yousefi and Mortazavi, 2018); however, geothermal energy occupied only 0.3% of the total renewable energy production in 2019, which is expected to increase to 1.0–1.1% by 2030. The challenges associated with geothermal energy development in Japan are as follows: (1) limited development areas since most potential geothermal areas are located in designated national and quasi-national parks characterized by strict environmental protection regulations, (2) high costs and long-term development which are associated with high-risk investments, and (3) potential conflicts between energy developers and local hot spring resorts, who have concerns over the influences that development may have on hot spring resources (Agency for Natural Resources and Energy of Ministry of Economy, Trade and Industry (METI), 2021c).

Beppu (**Figure 1**), the focus region of this study, is a major hot spring resort area for bathing, which receives more than 4 million domestic and foreign tourists per year. The city has the largest number of hot spring sources (2,288) in Japan, and the total quantity of discharged hot spring water is 87,550 L/min (Oita Prefecture, 2021). Hot springs that originate at Mt. Tsurumi, in western Beppu, flow into the urban sector. The spring water has higher temperatures in mountainous areas than in the lowlands, reaching to over 90°C (**Figure 1**). The use of the hot springs has significantly changed in recent years. Small-scale geothermal energy development (< 15,000 kW), which can benefit from a higher rate in the feed-in tariff (FIT) scheme for renewable energy introduced in 2012, has led to geothermal hot spring electricity development. The resulting increase in the pumping of geothermal hot spring water may influence natural systems, including underground systems, such as the groundwater flow pathways, quality, storage, level, and temperature. Changes in the underground system may cause changes in the broader coastal environment, including the submarine groundwater discharge (SGD) rate, nutrient input, seawater temperature, primary production, and fishery resources. Additionally, the development of hot spring energy facilities may alter local river and coastal ecosystems which is a concern

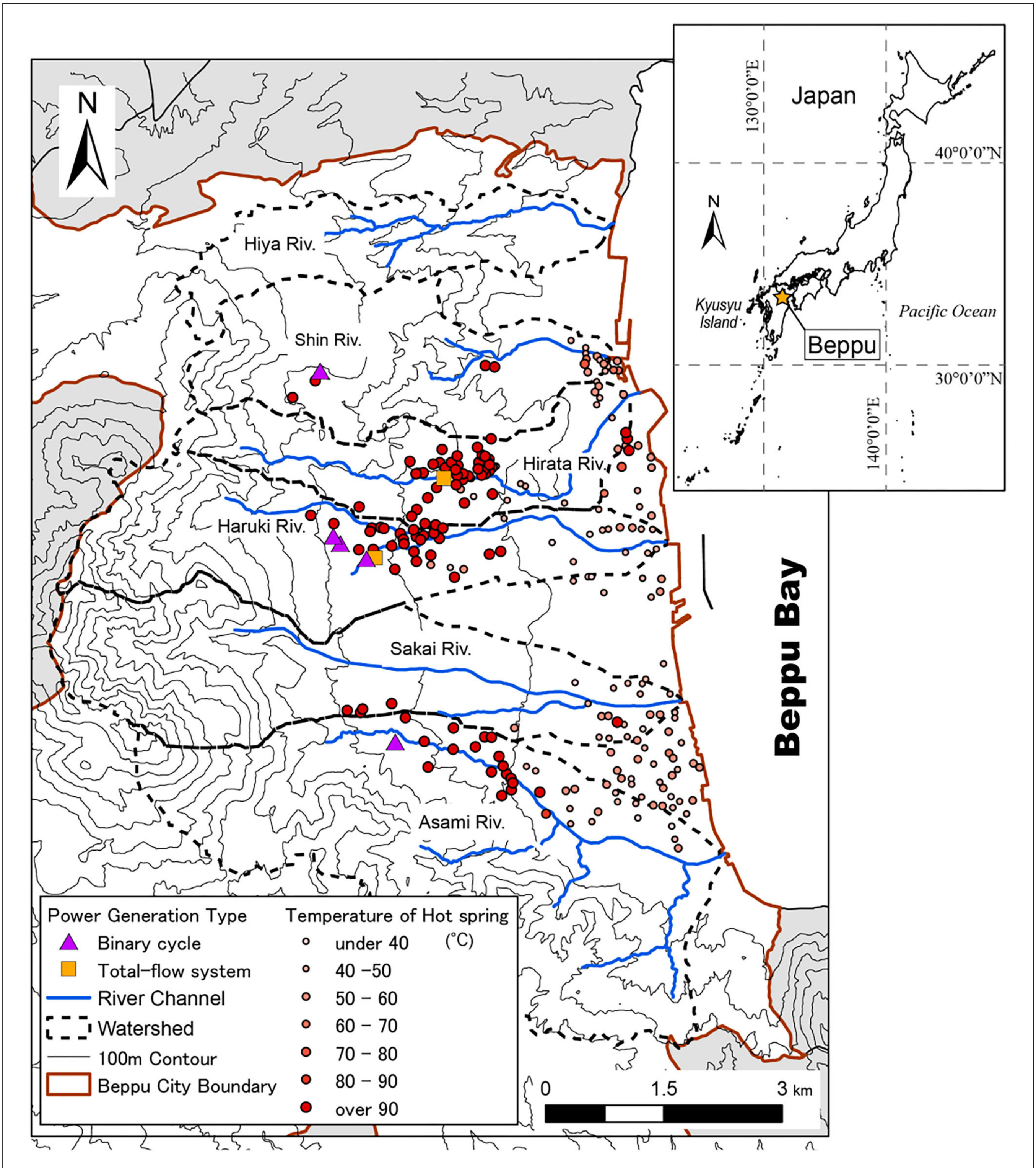


**FIGURE 1 |** Distribution of the hot springs and hot spring power plants with their associated temperatures in six river basins in the Beppu area (Yusa et al., 1989, 1990).

for local stakeholders (**Figure 2**). Local hot spring resorts have stated their concerns over the changing quantity, quality, such as chemical components which affect the health benefits of hot spring bathing, and temperature of geothermal hot spring resources. Finally, coastal fishermen have also vocally expressed their concerns over geothermal resource development. Drainage

**FIGURE 2 |** Graphical presentation for targeted water-energy-food nexus between land and coastal areas in Beppu, Japan.

water from hot spring resorts and power generation facilities is discharged, along with household wastewater, into four rivers (the Shin, Hirata, Haruki, and Asami rivers), which all flow into the Beppu Bay. Nile Tilapia (*Oreochromis niloticus*), which is tropical and non-native species to Japan, has been observed over the past few years.

## MATERIALS AND METHODS

### Design for WEF Nexus Approach

**Figure 3** illustrates the causal linkages in the targeted natural and social systems and the targeted boundary of the systems affecting the project in Beppu for each team. The teams were classified as follows: underground and river systems (the water-energy nexus team, T2), coastal systems (the water-food nexus team, T3), and social systems focusing on stakeholders (the stakeholder analysis team, T4). The socio-cultural team (T1) reviewed the socio-cultural significance of hot spring resources while the interdisciplinary studies team (T5) developed interdisciplinary methods. Each team, led by a multidisciplinary expert, was expected to adopt multi-, cross-, and interdisciplinary approaches (Keskinen, 2010). The members not only performed disciplinary research, but also transcended the boundaries of their team to generate co-production of knowledge, and developed networks between each team and the project sites by acting a science-policy-society interface.

### Nexus Methodology

The process of systems thinking (Alcamo, 2015) was tailored and institutionalized by incorporating interdisciplinary (Repko and Szostak, 2008) and transdisciplinary approaches into the project design and roadmap by combining quantitative and qualitative methods, tools, and data to understand the WEF nexus system in Beppu (**Figure 4**).

In the projects, the interdisciplinary approach was a knowledge production process that addressed complex research topics. Holistic and systemic perspectives were applied to select a research topic, and academic experts from various disciplines were involved to determine whether any existing data, methods, tools, concepts, and/or theories could be shared

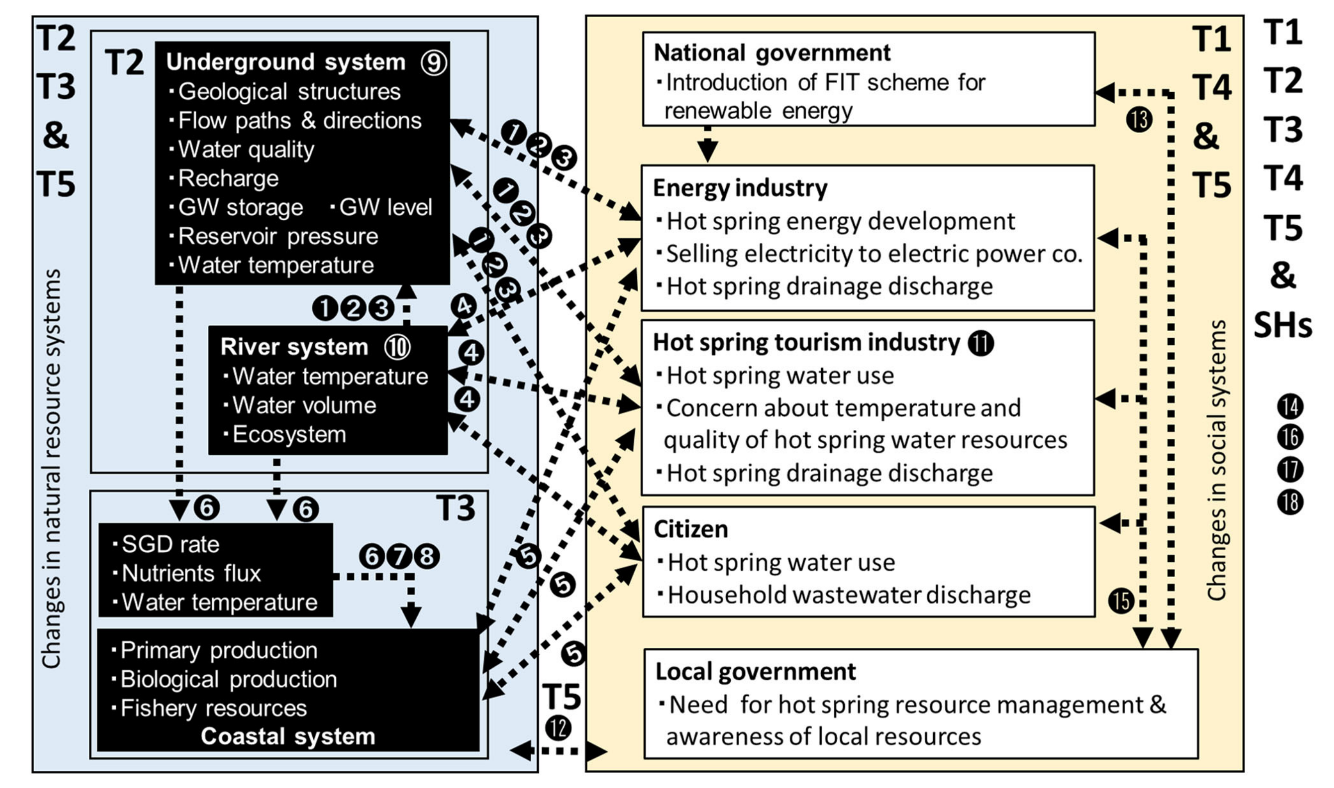


**FIGURE 3 |** Targeted natural and social systems, and targeted boundary of the five teams (T1–T5) in Beppu, Japan. Arrows demonstrate the causal linkages, while the numbers (①-⑱) indicate the methods applied and outputs in Beppu in **Table 1**. GW, groundwater; SGD, submarine groundwater discharge; FIT, feed-in tariff; SHs, stakeholders.

and integrated, or new ideas were to be created (National Academy of Sciences, 2005; Klein, 2008; Repko and Szostak, 2008; Keskinen, 2010). The transdisciplinary approach was a knowledge production process incorporating non-academic forms of knowledge to address dynamic issues. More holistic and systemic perspectives were applied by working with academic and non-academic stakeholders in various sectors to better understand the interactions between nature and society by shifting from the idea of science about society to science for and within society (Keskinen, 2010).

The numbers in **Figures 3**, **4** and **Table 1** represent the individual methods applied throughout the projects. **Figure 4** shows a roadmap of the project using these methods, as well as how the data and methods were shared and integrated among the five teams.

In the first step, the nexus system map was qualitatively described (**Figure 3**) to select targeted systems, such as land and coastal areas for natural systems, social systems, including stakeholders and institutions, and targeted tradeoffs among the resources and sectors. The map also helped to identify the research boundaries, as well as connectivity points among the five teams. In the second step, we quantified the natural systems on land (①②③⑨⑩), social systems (⑪⑮), and the linkages between the land and coastal systems (⑥⑦⑧), and further developed the qualitative nexus system map to logically and theoretically describe the linkages between natural and social systems and identify tradeoffs among resources and sectors (⑫). In addition, the policy gaps among the cross-sectors and multi-levels in the social system were qualitatively clarified (⑬). In the third step, we identified the critical linkages to determine the behaviors between the land and coastal systems (⑥⑦⑧), as well as the natural and social systems, such as the impacts of the use of hot spring resources, including drainage, on the environment, using quantitative models and simulations (①②③④⑤). We created scenarios by integrating local and expert knowledge for the transdisciplinary approach (⑭). In the final step, we identified the key leverage points, provided narrative scenarios as policy options (⑭), and recommended policies (⑱) for the sustainable use of geothermal hot spring resources.

## Water-Energy Nexus

T2 quantitatively assessed the water-energy nexus in terrestrial systems using two geophysical models and estimation of the renewable energy potential. First, a geophysical modeling framework based on previous geochemical studies performed in Beppu (Osawa et al., 1994; Osawa and Yusa, 1996) was applied to understand hot spring production mechanisms in relation to the geological structures, flow paths and directions, aquifers, temperatures, and heat sources. A three-dimensional (3-D) geological groundwater flow model using a microtremor array exploration method was developed to understand the relationships between the geological structures and hot spring

**TABLE 1 |** Methods applied and outputs in Beppu.

| No. in Figure 2 | Disciplines | Methods and outputs |
|---|---|---|
| **Interdisciplinary approach** | | |
| 1 | Geophysics | 3-D geological groundwater flow model |
| 2 | Geophysics | Hydrothermal model and simulation for quantitative scenario (for deep underground) |
| 3 | Hydrology, Geophysics | Integrated water balance model and simulation for quantitative scenario (for shallow underground) |
| 4 | Biogeochemistry | Analysis of impact of hot spring drainage on river ecosystems |
| 5 | Fish biology | Analysis of impact of hot spring drainage on fish community |
| 6 | Physics, Biogeochemistry, Biology | $^{222}$Rn mapping to visualize SGD impacts and field incubation for phytoplankton primary productivity |
| 7 | Physics, Biogeochemistry, Biology, Hydrology | Analysis of the linkage between SGD and biological production |
| 8 | Fish biology | Analysis of influence of SGD on fish community |
| 9 | Geophysics | Shallow geothermal potential map |
| 10 | Hydrology, Geography | Potential of electricity from small hydropower operations |
| 11 | Environmental economics | CBA for hot spring water |
| 12 | Systems engineering | WEF nexus domain ontology and nexus system maps |
| 13 | Policy studies | Cross-sector and multi-level policy analysis |
| **Transdisciplinary approach** | | |
| 14 | Policy science, Environmental policy analysis | Scenario building, consisting of stakeholder analysis, stakeholder meetings, Delphi method, and scenario workshop |
| 15 | Structure analysis | Social network analysis |
| 16 | Citizen science, Science, Technology and society | Citizen participatory surveys |
| 17 | Geographic information | Hot spring web maps |
| 18 | Policy studies | Policy recommendations |

flow paths (Miyashita, 2018) ((1)). Next, a natural state hydrothermal model was constructed using TOUGH2 to identify the hot spring water flow paths and up-flow zones (targeted at −700 to 700 m), and via aquifer monitoring using repeated hybrid microgravity measurements. Hot spring temperatures and reservoir pressure distributions at various depths (targeted at −2,000 to 1,000 m) were then simulated from 1950 to 2030 to predict the impact that water use has on the water production sustainability at a hot spring aquifer (Nishijima et al., 2018) ((2)).

Second, this study assessed the possibility of applying a geothermal heat exchanger (GHE) system using shallow geothermal heat energy for air conditioning based on a thermal that used geological, groundwater, and subsurface temperature data collected by T5 (Hamamoto et al., 2018) ((9)). Additionally, the potential for small-hydropower (SHP) electricity generation was estimated and mapped from hydrological and geographical perspectives, including possible changes in climate (precipitation) or social factors, such as land use patterns or local populations (Tanabe, 2015; Fujii et al., 2017) ((10)).

## Water-Food Nexus

T3 conducted physical, biogeochemical, and biological surveys to quantitatively address the water-food nexus by examining the interlinkages between the groundwater, specifically the SGD, and fishery resources along the nearshore coast of Beppu Bay. Previous studies have revealed a strong link between primary production and yields from fisheries (Nixon, 1988). Accordingly, the following hypothesis was formulated: changes in the SGD rate causes a change in the nutrient flux, resulting in variations in the primary production and ultimately in the fishery resources. First, the relationship between the $^{222}$Rn activity (as a tracer of the SGD) and phytoplankton primary productivity along the nearshore coast of Beppu Bay was assessed to determine the impact of the SGD on the primary production ((6)). Next, to ascertain the quantity of nutrients, including the dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN), supplied via the SGD, the water and nutrient flux from the SGD, river water, and groundwater at a small spatial scale along the Hiji coast of the inner Beppu Bay was examined (Honda et al., 2015; Sugimoto et al., 2017) ((6)). Based on these results and quantitative modeling developed by T5, the potential biological production supported by nutrients delivered via the SGD in the coastal sea was calculated according to the methods of Burnett et al. (2018) ((7)). Finally, the influence of the SGD on the fishery community was investigated using underwater photographs captured at 1-min intervals for 2–3 h at points near the SGD and locations where no SGD was observed along the Hiji coast (Shoji and Tominaga, 2018) ((8)).

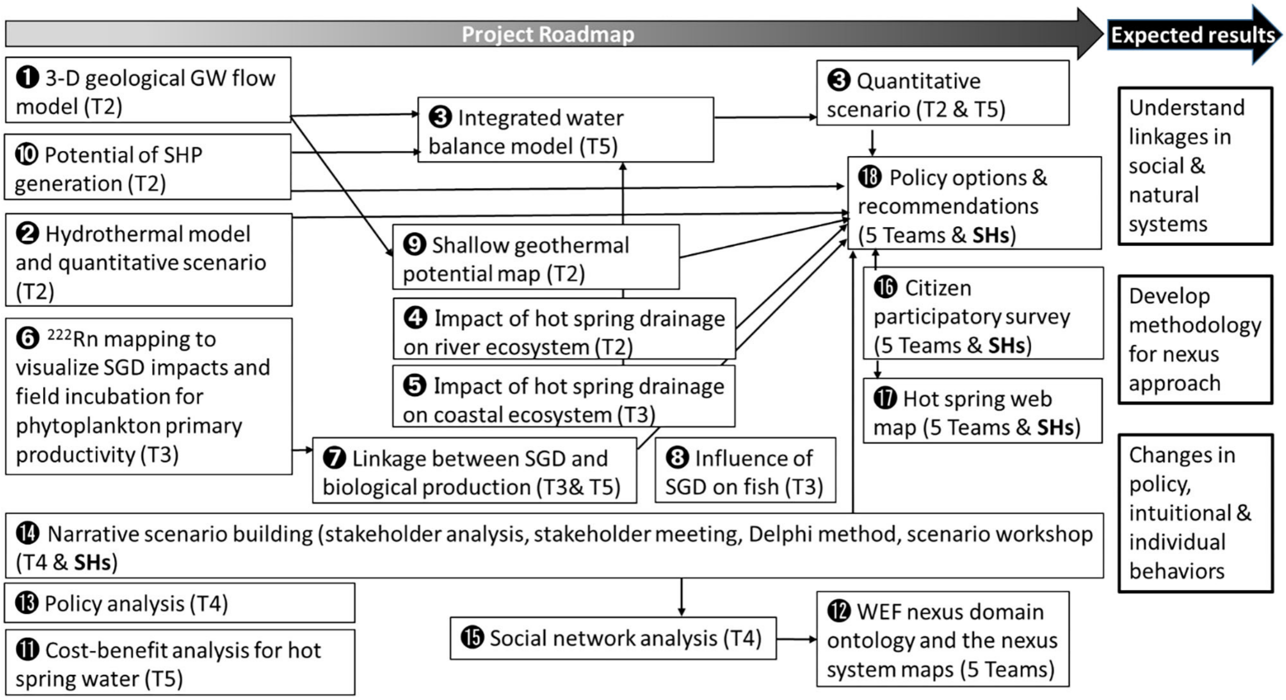


**FIGURE 4 |** Roadmap of the project using the methods applied and data integrated within the five teams in Beppu for the development of the methodology for the nexus approach. The numbers (①-⑱) indicate the methods applied and outputs in Beppu in **Table 1**, while the arrows indicate the connectivity among each method and output among the five teams. SHs, stakeholders; SGD, submarine groundwater discharge; WEF, water-energy-food.

### Water-Energy-Food Nexus

We first analyzed the impact of thermal energy on river ecosystems based on biogeochemical research. Nile Tilapia, which is tropical and non-native species to Japan, was used as a target to better understand the impact of the temperature of the hot springs drainage. The survey items comprised the water and air temperatures, electrical conductivity, and flow rates at twelve points along the Hirata River (Yamada et al., 2018) (④). Second, we analyzed the impact of the hot springs drainage on the coastal fishery resources based on fish community research. Underwater photographs were captured at 1-min intervals for 1 h at points with and without hot spring drainage inflow into the Kamekawa fishing port in Beppu Bay during the winter (January 26, 2017) and summer seasons (August 31, 2017) (Shoji, 2018) (⑤). Third, we used a cost-benefit analysis (CBA) was to determine the potential for cascading hot spring energy at different temperatures from 100 to 35°C, as well as the quality profiles of the steam, heat, and hot spring water (Kamio and Kato, 2018) (⑪).

## Interdisciplinary-Based Integrated Approach

T5 developed the WEF nexus domain ontology database and WEF nexus system maps as interdisciplinary-based integrated tools to describe a target WEF nexus domain world, including the causal linkages and trade-off relationships between WEF resources and their stakeholders, as well as to understand the subsequent complexity of the WEF nexus systems. An ontology engineering method, a qualitative technique, was applied for the replicability of the WEF nexus domain ontology and map. The software HOZO (http://www.hozo.jp/), based on the fundamental theories of ontology engineering for capturing the essential conceptual structure of the target world, was used (Endo et al., 2018) (⑫).

Next, an integrated water balance model was created using the general-purpose terrestrial fluid-FLOW simulator (GETFLOWS) by integrating the groundwater yield data, quantity of surface water use monitored by local governments, and geological structure data from the 3-D geological ground water flow model. River flow observation data were used to calculate the potential SHP generation and as verification data to build the model. Quantitative scenarios were developed for the quantity, temperature, and quality of the groundwater, including the hot spring water, to predict the magnitude of groundwater storage and groundwater temperature distribution (Ishii et al., 2018) (③).

## Transdisciplinary-Based Integrated Approach

T4 covered the social sectors and systems targeting stakeholders in Beppu. First, the gaps between cross-sector and multi-level policies for hot spring management were identified for policy coherence (⑬). A scenario building methodology, consisting of a stakeholder analysis, including a stakeholder network analysis,

**TABLE 2** | Number of event participants and collected data.

| Year | No. of participants | No. of data points collected |
|---|---|---|
| 2016 | 47 | 48 |
| 2017 | 53 | 48 |
| 2018 | 49 | 24 |
| 2019 | 69 | 54 |
| 2020 | N/A* | 39 |

*Due to COVID-19, the survey was only conducted by local city government employees.

stakeholder meetings, and the Delphi method to integrate expert and local knowledge, was developed to create narrative scenarios and address future uncertainties regarding the sustainable use of geothermal resources (Baba et al., 2018; Masuhara and Baba, 2021) ((14)). The social network analysis method was applied to visualize latent relationships among the stakeholders of geothermal resources and identify the shared understanding of such resources for the stakeholders in Beppu based on the results of the stakeholder analysis (Kimura et al., 2017) ((15)).

Concurrently, citizen participatory events to engage stakeholders, enhance mutual learning between local stakeholders and researchers, and build a long-term management system for hot spring resources in Beppu were created to follow the transdisciplinary approach: (1) participatory citizen hot spring surveys were conducted from 2016 to 2020 ((16)), (2) a citizen-centered monitoring system for long-term monitoring was initiated in 2019, and (3) scientific data were geographically collected, unified, and visualized online based on the survey results (**Table 2**) ((17)). Formal policy recommendations were then suggested to the Mayor of Beppu in March 2018 at the end of the project as a reference for policy- and decision-making for the sustainable use of geothermal hot spring resources ((18)).

# RESULTS

## Interdisciplinary Approach

### Geophysical Models and Simulations

Changes in the hot spring water temperature and reservoir pressure distribution between 1950 and 2030 were simulated based on the developed hydrothermal model ((2)) based on previous studies that demonstrated a hot spring water yield of 50,000 t/d (Yusa et al., 1975). Although no significant change was observed in the temperature, the model showed that the continued use of 50,000 t of hot spring water per day until 2030 is not sustainable owing to a reduction in the reservoir pressure.

A 3-D geological groundwater flow model ((1)) was developed to demonstrate the relationships between the geological structures and two types (Ca-Mg-$HCO_3$ and Na-Cl) of hot spring flow directions at depths of 100–500 m in the northern and southern parts of Beppu (Miyashita, 2018). The data in the geological structure model was used to validate the previous geochemical studies performed in Beppu (Osawa et al., 1994; Osawa and Yusa, 1996), and was incorporated into an integrated water cycle analysis and hydrothermal model ((3)) to simulate hot groundwater flow and predict how the use of spring water for energy development in mountainous areas will affect the spring resources used by resorts in the low altitude areas. Consequently, quantitative scenarios regarding groundwater storage quantities and temperature distributions were simulated, assuming a hot spring water yield of 50,000 t/d (Yusa et al., 1975). To consider climate change, a scenario analysis was conducted for years with the minimum (1994), average (2008), and maximum (1993) annual precipitation observed over the past 40 years (1977–2016). The results showed that the groundwater storage quantity during the years with the maximum, average, and minimum annual precipitation was +0.5, −2.4, and −6.8 million $m^3$/year, respectively. Therefore, if the annual precipitation is below the current average or the use of hot springs increases in the future, the groundwater storage will decrease. Hence, the deterioration of the water environment and exhaustion of hot spring resources remains concern. In contrast, the temperature distribution in the depth direction for the four major hot springs was almost identical for years with the maximum, average, and minimum annual precipitation; changes in the precipitation and water use on land had a negligible influence on the heat source of the hot spring water resources (Ishii et al., 2018).

### Renewable Energy Potential

The potential of applying GHEs in underground systems to create a shallow geothermal potential map ((9)), as well as the SHP in river systems ((10)) to build a combination of a system of small-scale renewable energy sources at the local scale were examined. The results illustrated the potential for using GHEs in the northern and southern parts of Beppu, where the subsurface temperature is $< 30°C$ at a depth of 10 m. For space cooling operations, GHE is a better option than an air source heat pump system when the subsurface temperature is $< 30°C$ (**Figure 5**) (Yasukawa et al., 2009; Hamamoto et al., 2018).

The potential for SHP generation in May, July, September, November, and December in the six river basins (i.e., the Sakai, Haruki, Hirata, Shin, Asami, and Hiya basins) throughout Beppu was estimated based on direct measurements of the water levels. The SHP generation potential is higher during the summer (52,550 kWh in July) in the Hirata River and during the winter (90,928 kWh in December) in the Asami River (Tanabe, 2015; Fujii et al., 2017).

### Water-Food Nexus Between Land and Coastal Areas

Changes in the interlinkages between the underground and coastal systems were assessed. First, the interlinkages between the $^{222}$Rn activity (as a tracer of the SGD) and phytoplankton primary production along the nearshore coast of Beppu Bay was examined. The *in situ* primary productivity in the surface seawater had a positive correlation with the *ex situ* primary productivity on land, indicating that the nutrient availability determines the phytoplankton primary productivity. The biomass-specific primary productivity demonstrated a significant relationship with the $^{222}$Rn activity, but not with the *in situ* primary productivity ((6)). Nutrient transport via SGD was examined at a small spatial scale along the Hiji

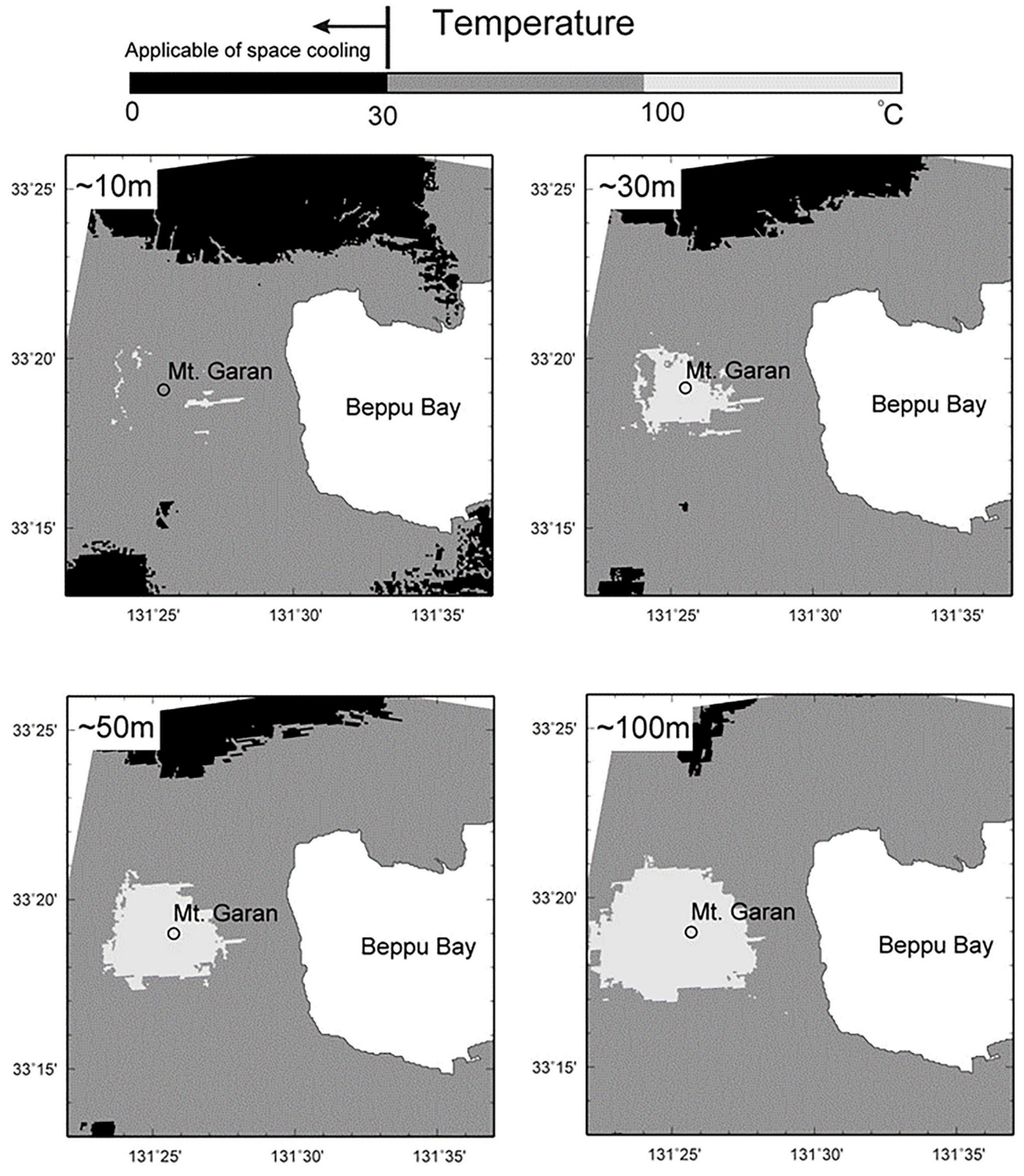


**FIGURE 5 |** Evaluation of the applicable area for GHE systems. GHE, geothermal heat exchanger.

coast in inner Beppu Bay; compared with other locations, nutrient concentrations around the SGD point were higher for the DIP and DIN. This implies that SGD is the main source of nutrients along the Hiji coast. Additionally, SGD-supplied nutrients contribute significantly to primary production (⑥). The linkage between the SGD and fishery resources was also analyzed along the Hiji coast; a higher abundance of fish adjacent to the SGD point was observed. Overall, these results indicate major linkages between the SGD and fishery resources ((8)). The potential biological productivity of tertiary consumers supported by SGD can reach 3,304 kg C/y based on the quantitative modeling results ((7)).

## Impact of Hot Spring Drainage on Aquatic Ecosystems

Changes in river systems caused by drainage from hot springs used for power generation and resorts were assessed ((4)). The inflow of hot spring drainage increased the temperature of the river water in the Hirata River. At points where hot spring drainage mixes with river water, the estimated quantity of thermal energy required to increase the temperature of the river water from its initial state (17.4°C, flow rate of 0.16 $m^3$/s) to its warmed state (27.7°C, flow rate of 0.38 $m^3$/s) was approximately 6,700 kW. This change in temperature in the river due to heat inflow creates an environment in which Nile Tilapia, a species foreign to Japan, can thrive. The lower and upper lethal temperatures for Nile tilapia are 11–12°C and 42°C, respectively, with preferred temperatures of 31–36°C (The Food and Agriculture Organization of the United Nations (FAO), 2015). Hence, the river water temperature is likely favorable for Nile tilapia based on the balance between the temperature and quantity of hot spring drainage inflow. The dominant species in the Hiya River, not yet affected by hot spring drainage, is the Barcheek goby (*Rhinogobius giurinus*). Therefore, the quantity and average temperature of hot spring drainage should be modified to reduce the impact of hot spring drainage on river ecosystems (Yamada et al., 2018).

The impact of hot spring drainage on coastal fishery resources was also analyzed. Greenfish (*Girella punctate*) and Pearl-spot chromis (*Chromis notate*) in winter and greenfish (*Girella punctate*) and black sea bream (*Acanthopagrus schlegelii*) in summer were identified. A higher abundance of fish at points with hot spring drainage inflow was observed in both the winter and summer. In addition to the high water temperatures, the terrestrial nutrients supplied via hot spring drainage likely have an influence on the primary production and subsequent fish production (Shoji, 2018) ((5)).

## Cascade Use of Heat and Steam From Hot Spring Resources

In collaboration with the Chinetsu Kanko Lab Emma, a stakeholder in the local hot spring tourism industry was conducted to assess the cascade uses of the heat and steam from hot spring water resources by installing a geothermal system in a strawberry greenhouse 15 m in length, 12 m in width, and 9 m in height ((11)). A comparison between the costs of using a geothermal system and electricity cost reduction by applying CBA demonstrated that the geothermal system contributed to an electricity savings of 7,800 kWh between December 2016 and March 2017. Minimum and maximum hourly temperatures during this period was −2.2 and 22.7°C, respectively. The target temperatures in the greenhouse were 24°C during the daytime and 9°C during the night. A simple heat transfer model was used to evaluate sunlight heat input, geothermal input, and heat release to the outside air. A 4% reduction rate was assumed for obtaining the present values of costs and benefits. The geothermal system also contributed to reducing the number of air conditioning units in a greenhouse from seven to six. The total cost reduction over 10 years of winter operation using the geothermal system was ∼2 million yen, almost compensating for the cost of installing and maintaining the system. Therefore, the economic benefit of the electricity savings and air conditioning capacity using the geothermal system exceeded its initial and operational costs since it also cooled the greenhouse during the summer (Kamio and Kato, 2018). The greenhouse is located in a densely populated area and is smaller than many commercial agricultural productions that uses geothermal energy in Japan reported by Okumura (2017). Our cost benefit analysis has shown that even this small-scale operation can produce positive benefits.

## Visualizing the Water-Energy-Food Nexus in Natural and Social Systems

The causal linkages between WEF resources and their stakeholders in targeted natural and social systems in Beppu (**Figure 3**) were described with project members from each team. Then the WEF nexus domain ontology database was developed to define the concepts and sub-concepts of the trade-offs relating to WEF. The following tradeoffs were identified in Beppu: (A) trade-off in hot spring use between water, heat, steam, nutrients, and drainage; (B) trade-off in water use between food and energy production on land and in the ecosystem, including fishery resources in coastal areas; (C) trade-off in water temperature between fish species in river ecosystems; and (D) trade-off in hot spring water between use by hot spring resorts and hot spring power generation. Subsequently, the network analysis method to identify key concepts acting as linkage hubs in the target WEF nexus domain ontology was applied. Finally, the WEF nexus system maps were designed and visualized by centering the identified key concepts of water, energy and food (Endo et al., 2018). **Figure 6** demonstrates the paths centering on the concept of "hot spring" as a linkage hub toward the concepts of energy and food ((12)).

## Cross-Sector and Multi-Level Policy Gaps

The Hot Spring Act at the national level under the authority of the Ministry of Environment (MOE) controls the hot spring water resources for bathing. This act protects hot spring water resources; however, it does not regulate the use of hot spring water resources as a geothermal resource for energy development. Therefore, the MOE established guidelines for the effective use of hot spring heat in 2019. In contrast, Agency for Natural Resources and Energy of METI is the primary authority for promoting renewable energy, including geothermal energy. Due to a 40-year conflict over geothermal energy development in the national parks between the METI and MOE, new development was hindered. Owing to the 2011 Japanese energy crisis, the MOE clarified possible areas for new geothermal development in the national parks.

The Hot Spring Act authorizes prefectural governments to approve the development of hot spring water resources.

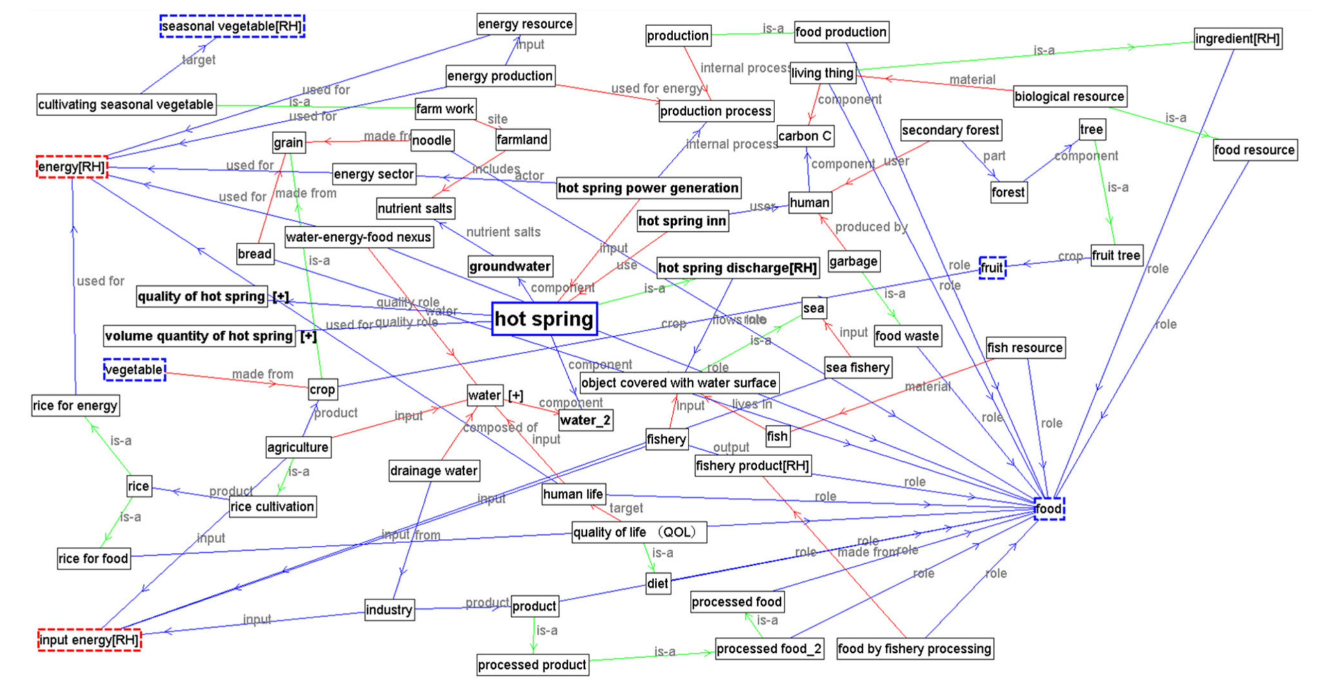


FIGURE 6 | The "hot spring"-water-energy-food nexus system map centering on the concept of "hot spring."

Currently, 14 prefectural governments have established installation targets for geothermal power generation, including hot spring power generation (Masuhara and Baba, 2017). For Oita Prefecture (the location of Beppu City), the Hot Springs Division of the Environmental Council, under the prefectural ordinance, issued drilling or digging development permits for geothermal power generation. Twenty-six geothermal power generation operations began from 2012 to 2017, with the introduction of the FIT scheme. At the city level, Beppu City, which has no authority to approve development permits for bathing and energy development, issued a 2016 municipal ordinance to enhance the co-existence between hot spring power generation development and hot spring bathing. This ordinance was amended in 2018, mandating that hot spring water resource power operations must consult with local inhabitants prior to development (Masuhara and Baba, 2017) ((13)).

## Transdisciplinary Approach

### Stakeholder Analysis

A future scenario building method ((14)) was applied to integrate local and expert knowledge through four steps, finally establishing complete narrative scenarios for the future of Beppu. First, stakeholder analysis was conducted to create an agenda by determining the problems to be addressed by policies from the perspectives of the stakeholders. Semi-structured interviews were conducted to collect the interests, attitudes, and local knowledge of the stakeholders on the hot spring resources. Targeted stakeholders were initially nominated by local officials and then further identified using snowball sampling to obtain 36 stakeholders, including local governments, proprietors of hot spring inns and hot spring sources, tourism organizations, energy developers, financial institutions, local NGOs, and citizen groups.

### Social Network Analysis

The social network analysis method was applied to visualize the latent relationships among the stakeholders related to the geothermal resources in Beppu based on the results of the stakeholder analysis ((15)). **Figure 7** shows the degree centrality index, calculated using the node with the most numerous relationships as the center of the network. Nodes with higher and lower indices are arranged at the center and periphery, respectively. A private enterprise, which previously developed and installed small-scale geothermal power generation operations, was at the center, with the highest degree of centrality. Hot spring resort owners, hot spring source owners, and local governments responsible for managing hot spring water resources possessed low degrees of centrality and were thus located at the periphery of the network. Accordingly, hot spring energy development was at the center of the stakeholder network, sharing interests with other stakeholders in Beppu (Kimura et al., 2017).

### Building Narrative Scenarios

A stakeholder meeting was then held to share the results of the aforementioned analysis, where 73 narratives were drafted, with 54, 11, and 8 narratives for hot springs, geothermal power, and community change, respectively. The narratives were evaluated according to their certainty and severity by 9 experts from the project using the Delphi method to integrate expert and local

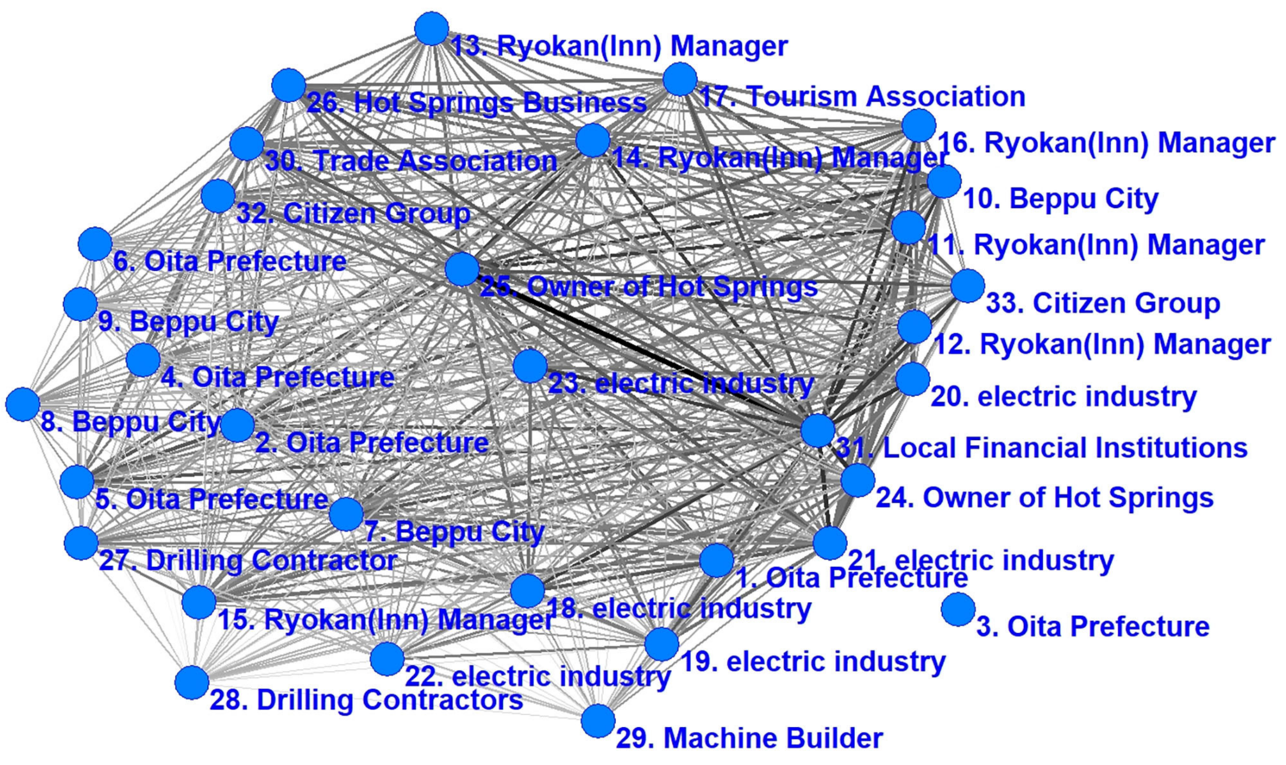


**FIGURE 7 |** Relationships among the stakeholders related to the geothermal resources in Beppu using social network analysis (Kimura et al., 2017).

knowledge by verifying the logical validity and probability of the collected expert knowledge. The specialized field experts were classified as follows: five in the natural sciences (one each in renewable energy, hot spring science, geothermal science, geofluid chemistry, and groundwater hydrology) and four in the humanities and social sciences (one each in tourism/hot spring culture, fishery economics, environmental planning, and resource theory). In 2017, two Delphi surveys were conducted, where the scores on the certainty and importance of each of these narratives across a five-point scale were provided by the experts, with suggestions/commentary in each survey on modifying each narrative, or the deletion or addition of new narratives. In 2018, the results of the second Delphi survey for the mean and variance values were classified; the stories were summarized, supplemented with explanations and future scenario plans for better understanding among the stakeholders. In November 2019, a scenario workshop was held with ∼25 participants, including those surveyed, as well as a hot spring enthusiast group, known as the "Hot Spring Meister."

The future scenario options imagined for Beppu City ca. 2040 were described in a text format with three story groups: (A) base stories, (B) important stories to be examined, and (C) stories to be monitored. The base stories are a group of stories where both the certainty and importance are higher than the average score provided by the experts, consisting of five stories: (A1) increase in migrants and settlers in Beppu, (A2) change in hot spring tourism, (A3) increase in hot spring water pumping, (A4) impact of increase in hot spring water resources, and (A5) increase in the interest of local food production and consumption, as well as cascade uses of hot spring resources. Stories to be examined included four with high importance and low certainty: (B1) challenges associated with the management of hot spring sources, (B2) change in the tourism industry, (B3) activation of volcanoes, and (B4) change in hot spring resources. Stories monitored included those with both low importance and certainty, which should nonetheless be of concern, as follows: (C1) progress on new and alternative drilling techniques, (C2) increase in bathing taxes, which segregates hot spring resorts into winners and losers, and (C3) stabilization in the total quantity of pumped hot spring water. The conclusions of each story were confirmed during the course of this study. The final revised future scenarios were published in a leaflet and shared among the concerned parties (**Figure 8**) (Baba et al., 2018; Masuhara and Baba, 2021) ((14)).

## Citizen Participatory Surveys and Hot Spring Web Maps

A citizen participatory survey was organized by the Research Institute for Humanity and Nature (RIHN), the Beppu city government, Beppu Onsen Geo-Museum, Beppu City Ryokan Hotel Association, and the Institute for Geothermal Sciences of Kyoto University. The participatory citizen survey has two aims: to provide local stakeholders (including students)

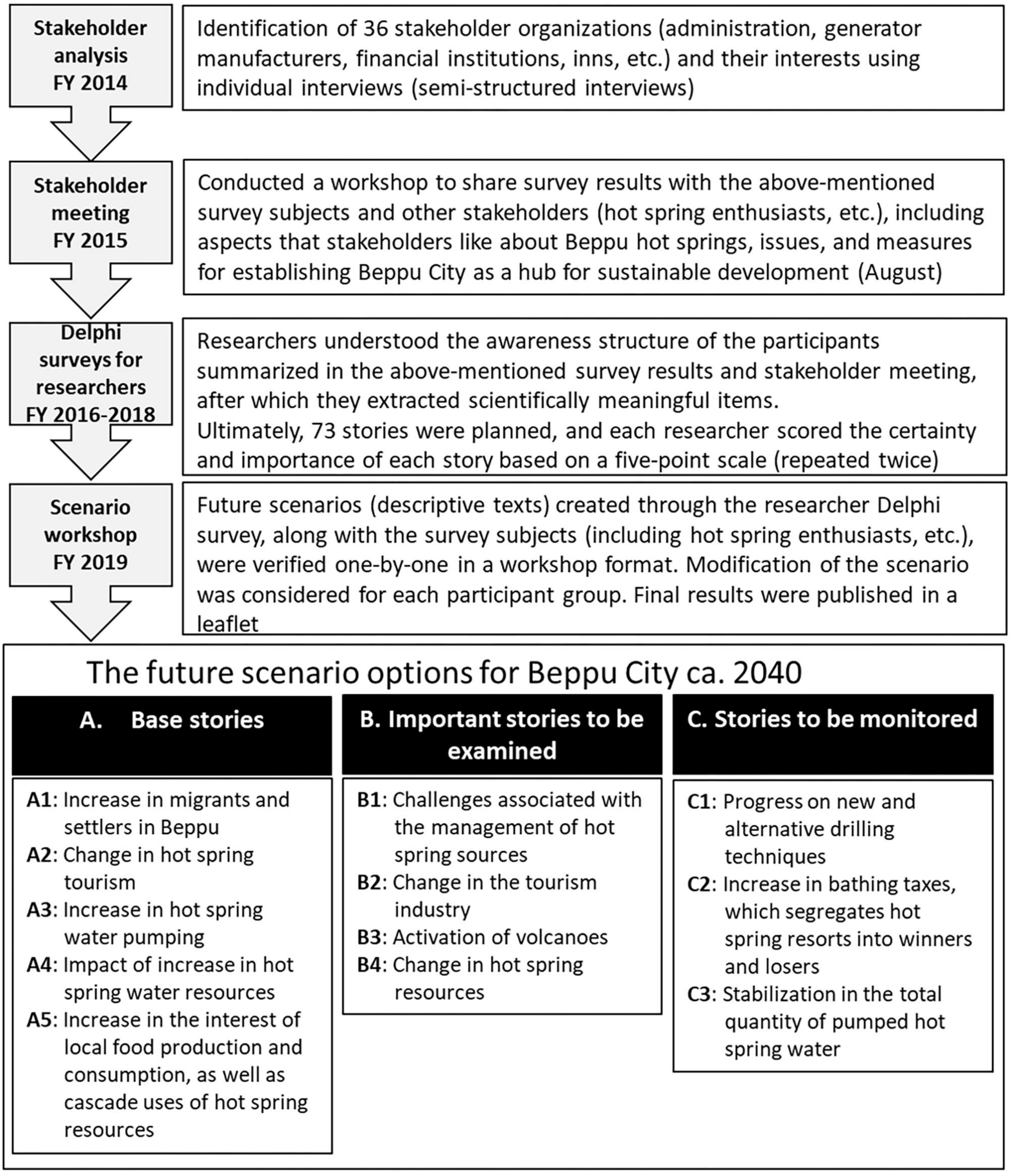


**FIGURE 8 |** Procedure for building future scenarios in Beppu City and future scenario options for ca. 2040.

with experience in collecting scientific data on hot spring water using scientific instruments, including the temperature, electrical conductivity, pH, and dissolved chemical components, and enable them to understand the scientific interpretation process. Project researchers also gained local knowledge from the participants through mutual learning and joint

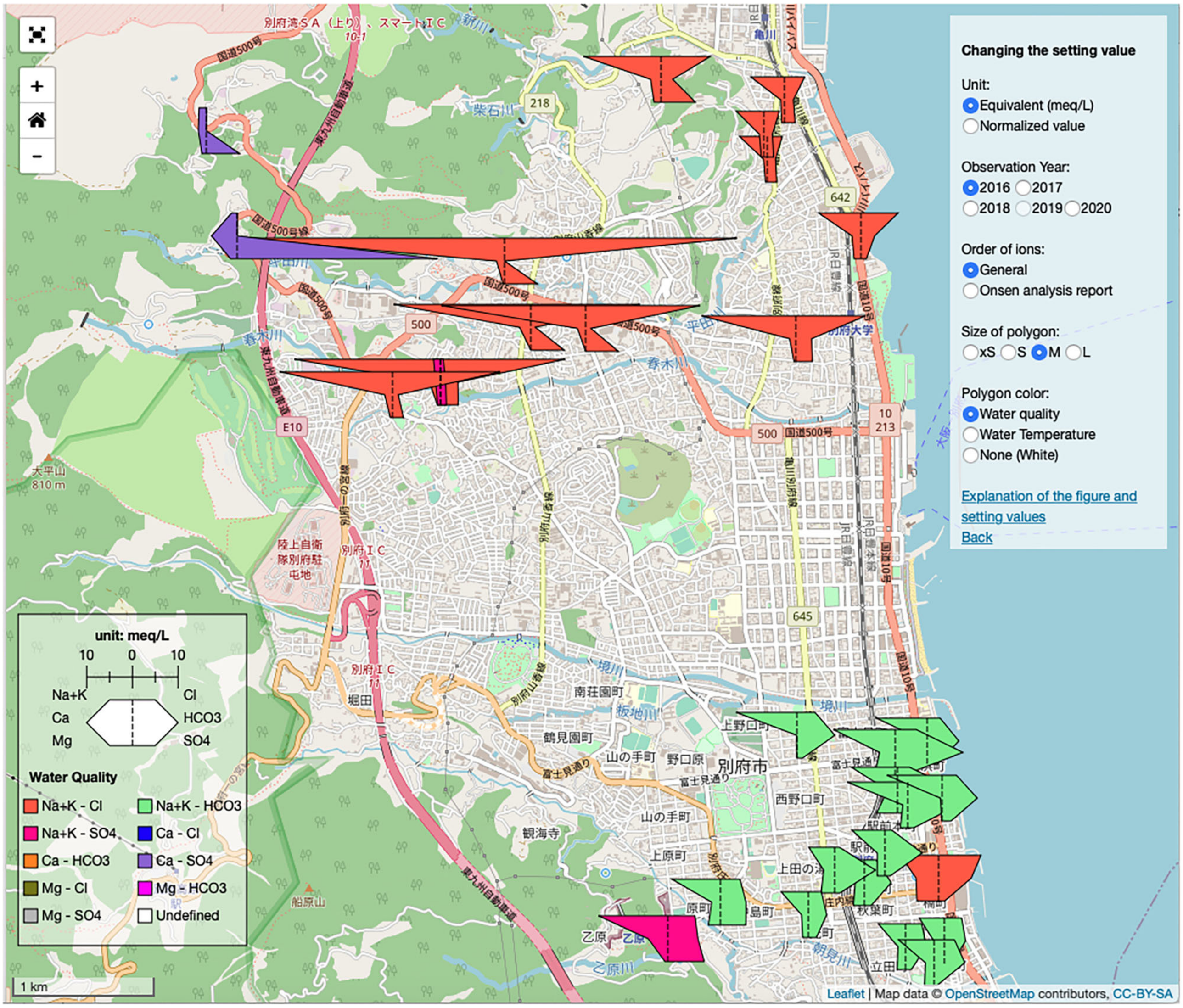


**FIGURE 9 |** Data collected in the 2017 citizen participatory survey, with 38 out of the 48 points displayed online (http://www.wefn.net/beppu/). The hexagrams in the map show the type of hot spring (Na + K, Ca, Mg, Cl, $HCO_3$, and $SO_4$). The setting of the unit, sample collection year, ion arrangement, and polygon size and color are changeable.

activities; and to analyze the collected hot spring water data since large-scale sampling and analysis of the hot spring water resources in Beppu have not been conducted since 1989–1990. The citizen participatory surveys have been consecutively conducted in 2018, 2019, and 2020; these surveys are funded by the local government of Beppu City with the completion of the project. They have included educational events for children during the 2019 summer holidays; local stakeholders have begun to lead this event since 2019 (16).

Data collected by citizen participatory events were uploaded to the website, shared with participants in a visual manner, and displayed geographically online (https://www.wefn.net/beppu/hexaMap_en.html) (**Figure 9**). Following the participatory survey in 2017, local citizens were trained on how to monitor hot spring water resources, working with the local city government and the Onsen Meister Association to establish a long-term monitoring system (Yamada and Oh, 2018) (17).

## Policy Recommendations

Policy recommendations for the sustainable use of hot spring resources were presented directly to the Mayor of Beppu at the end of the project (18). Our recommendations were addressed future challenges for scientific research and those for the local government and its citizens. For the scientific challenges, we first recommended the incorporation of nexus-specific tools and methods into government policy-making processes. For example, the integrated modeling framework for determining the total volume control of hot spring water resources and regulating the development of protected areas should be refined by the continuous collection of data on temperature, pressure, changes in gravity, chemical components, and underground geological structures because long-term effects cannot be predicted or detected throughout a 5-year project period. Second, translating scientific evidence and uncertainties into local government policies is necessary. For instance, the linkage between water resources (including hot spring drainage) and aquatic ecosystems (including fishery resources) should be further examined by analyzing nutrients and primary production in the water to enhance food security and wastewater management. For governance challenges, we recommended (1) regularly updating and properly managing hot spring registration ledgers; (2) building a long-term monitoring system and collecting data through co-production activities via the institutionalization of local government upper-level policies; (3) diversifying the use of hot spring resources, including heat, steam, nutrients, and drainage; (4) establishing a distributed energy system that combines small-scale renewable energy sources, including small hydropower operations and GHEs, at the local level. In response to recommendations issued in 2018, citizen participatory events have been funded by the local city government after the completion of the project. Furthermore, a budget for the continuation of scientific research that focuses on hot spring underground water resources has been allocated for 4 years, beginning in 2020.

# DISCUSSION

## How Are Different Discipline-Oriented Methods and Data Integrated for Interdisciplinary and Transdisciplinary Approaches?

The WEF nexus approach is not entirely novel, rather, it is one of the integrated approaches such as IWRM (Keskinen, 2010) to natural resource use and management, or the components consisting a holistic integrated approach focusing on water, energy and food resources to understand human-nature interactions. The concept of the integrated approach was proposed in the report "Our Common Future," prepared for the World Commission on Environment and Development in 1987, when the concept of sustainable development was introduced. The report indicated that "we should span the globe, and pull together to formulate an interdisciplinary, integrated approach to global concerns and our common future." However, no clear indication as to how to integrate it for practicing integrated approach has been proposed. There are a few studies focusing on the nexus approach discussing integration along various components. Roidt and Avellan (2019) used 27 indicators consisting of components of integrated management including a holistic systems approach, the participation and inclusion of stakeholders, and interdisciplinarity and/or transdisciplinary manner, to understand the feature of WEF nexus. Al-Saidi and Elagib (2017) identified three types of integrations with examples of analysis and methods used in the WEF nexus studies to understand issue integration, that is, incorporation, cross-linking, and assimilation.

This section reviews the developed methodology consisting of discipline-oriented methods from the point of integration including causal, sequential, horizontal, and conceptual integrations (Henry, 2017). The projects resulted in individual academic publications which contributed to the discipline-oriented academic communities, however, no single discipline or method alone can explain the sequential events and the results precipitated by distant factors, which might completely change the whole system indirectly. The causal integration can help to determine the targeted natural and social systems and the related disciplines and methods for research topic selection, which, in this case, is sustainable geothermal hot spring resource use and management (**Figure 3**). The sequential integration can be institutionalized to the project roadmap to converge the data and methods and enhance the interdisciplinary collaboration among teams for building quantitative and narrative scenarios and shaping policy recommendations (**Figure 4**). The horizontal integration should be analyzed when multiple methods are used to understand the underground systems for sharing the data (**Figure 10**, gray arrows) and validating previous studies (**Figure 10**, black arrow). Lastly, the conceptual integration is used during transdisciplinary-formed knowledge production such as narrative scenario building by incorporating non-scientific forms of knowledge within and beyond the life span of the project. Multiple integrated approaches can be addressed partially and selectively to understand the causal linkages and human-nature interactions based on context specific case studies. The developed methodology for the nexus approach contributes to the integration of discipline-oriented methods and data for inter- and transdisciplinary approaches.

## How Much of the Targeted Water-Energy-Food Nexus Systems Are Understood by Using the Developed Methodology for Nexus Approach?

There are several challenges that remain in terms of developing methodologies for the nexus approach to understand the linkages and overcome the tradeoffs among resource systems in Beppu. First, to address tradeoffs in hot spring use among water, heat, and steam, we developed quantitative models to predict the sustainability of future geothermal hot spring resources, including changes in the temperature and pressure. As there was no alternative data available, we used data published in 1975 (Yusa et al., 1975), which has not been updated for more than 40 years, despite changes in the conditions and use of the hot spring resources. These changes encompass social changes, such as the number of tourists and the initiation of electricity production using hot spring steam. Moreover, comprehensive sampling and analysis of the hot spring water resources in Beppu have not been conducted since 1989–1990. Improving the accuracy of the quantitative models is critical for addressing future uncertainties associated with geothermal hot spring resources.

Second, to address the tradeoffs in water use between food and energy production on land and within the ecosystem, including

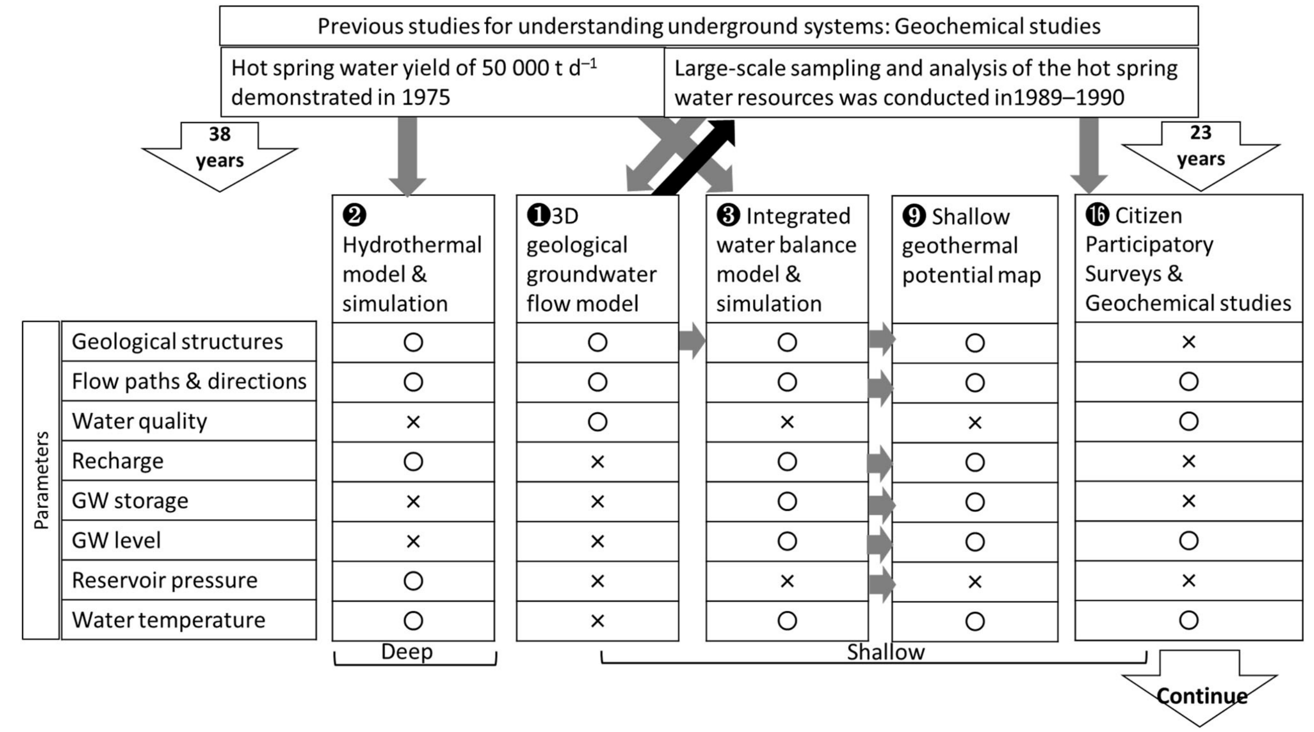


**FIGURE 10 |** Horizontal integration with different methods for better understanding of the underground system. GW, groundwater.

fishery resources along coastal areas, we quantified the linkages among the SGD, nutrients, and primary production. However, further studies are required to analyze the quantitative and qualitative linkages between the primary production and fishery resources by (1) comparing fish biomass at points with and without SGD inflow, (2) tracing material flows that derive from SGD to fish species using stable isotopes, and (3) assessing the impacts of temporal and spatial variabilities in the SGD rate on fish biomass, including fish catch. We also identified the critical linkages between hot spring drainage and coastal fishery resources. Further analyses of fish feeding habits at points with and without hot spring drainage inflow are required to determine whether hot spring drainage supplies critical terrestrial nutrients (Shoji, 2018).

Third, the developed methodology has still not been optimized for geothermal hot spring resources at larger scales. The techno-economic approach, including the life-cycle assessment, should be applied to enhance the cascade use of heat, steam, nutrients, and drainage of geothermal hot spring resources at different temperatures to co-optimize renewable energy, food production, and bathing. This could contribute to the formation of a distributed energy system by combining small-scale renewable energy sources such as SHP and GHE at the local level.

Furthermore, natural science disciplines dominated the scientific methods applied in Beppu to understand the WEF nexus systems. This is due to global trends in WEF nexus research. The Earth Science community initially promoted the WEF nexus to understand the planetary system; they have proactively invited social scientists to address global-scale environmental challenges that have become more interrelated, complicated, and uncertain (Leck et al., 2015). The social science experts played a key role in the latter half of the projects, implementing the second dimension of the nexus approach, including the construction of the narrative scenarios. However, the integration of more social science approaches can better explain the social system by (1) identifying the social, economic, and organizational conditions that enable the sustainable use of hot spring resources by local communities, including the introduction of environmental taxes to control the use of hot spring resources, aside from the existing hot spring tax, and (2) measuring the monetary value of the multi-functionality of the geothermal resources for an area-level cost-benefit comparison. In addition, Japan has a unique history of hot spring resource uses, as compared with other countries, such as Iceland, which have promoted geothermal energy development (Itadera, 2012; Covarrubias, 2019). The interdisciplinary and transdisciplinary approaches in the systems thinking process should incorporate more humanity sciences methods, including history, cultural studies, and pre-existing local practices, such as community-based geothermal hot spring resources management.

Finally, the developed scenarios did not consider pandemics such as COVID-19, which has had a significant impact since 2020, leading to a significant decrease in the number of domestic and foreign tourists. Future scenarios should be developed to consider cases of extrinsic change caused by extreme events (Masuhara and Baba, 2021).

### How Far Does the Nexus Approach Influence Changes in the Policy Agenda and Institutional/Human Behavior for Sustainable Geothermal Hot Spring Resources Use?

In Japan, policy and institutional frameworks that follow the WEF nexus approach do not currently exist at the national and local levels, despite the adoption of integrated resources management approaches, such as the IWRM, at different governmental levels. At the global level, the Global Water Partnership (GWP), which defined the IWRM concept, has adopted the water-energy-food-environment nexus approach into their strategy for targeting Sustainable Development Goal 6.5 (GWP, 2019). At the national level in Japan, the basic act on the water cycle (enacted in 2014) targets hot spring water as a water resource, rather than an energy resource. This implies that the nexus issues targeted in Beppu were out of the scope of the IWRM in Japan. Furthermore, we identified the gaps in policies among the cross-sectors and multi-levels of geothermal energy development in Japan. These gaps may be driven by political interests, which were beyond the scope of the two projects. Although the nexus approach does not currently exist at national and local levels in Japan, we used it as an umbrella concept to institutionalize the developed methodology into the discussion and policy processes within the local government system of Beppu City. The proposed policy recommendations resulted in the allocation of a budget for continued citizen participatory surveys and geochemical studies to establish a long-term monitoring system for geothermal hot spring resources that will continue after project completion. Furthermore, since 2019, city government has independently started to lead events on citizen participatory surveys within the scope of the RIHN nexus project. We must further consider the challenges associated with involving more diverse generations and stakeholders in these events to promote their interests in local resources management and build a locally led long-term management system to combat future uncertainty. We were unable to determine how and by what quantity the two projects, using the framework of the nexus approach, have changed the policy agendas, as well as the behaviors of the institutional and individual stakeholders, which intricately depend on each other. The Beppu initiative shaped by collaborating scientists, the local government, and local citizens can be applied as a model solution to other hot spring resorts for sustainable use and management of geothermal hot spring resources across Japan.

## CONCLUSIONS

We developed a methodology for the application of the nexus approach based on systems thinking, integrating interdisciplinary and transdisciplinary concepts and qualitative and quantitate mixed methods, for the sustainable use of geothermal hot spring resources at the local-scale in Beppu, Japan. Our results suggest that the use of the developed methodology explained the interlinkages among water, energy, and food resource systems and sectors in Beppu. However, several challenges remain, such as optimizing resource systems at a wider scale, changing policy agendas to complement cross-sector and multi-level gaps, and managing the tradeoffs in resource use and sectors, which are related to institutional and individual behaviors. At the national scale, Japan faces several challenges with the development of geothermal energy for enhancing the use of renewable energy. The transferability and scalability of the qualitative and quantitative single mixed methods and/or the developed methodology for the application of the nexus approach can be replicated and/or adjusted at different sites (Endo et al., 2020). Using a location-based case study, propagating the methodology and local initiatives from a bottom-up approach will compliment current national renewable energy and natural resource policies and management based on specific issues.

## DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because Data sharing not applicable. Requests to access the datasets should be directed to Aiko Endo, endoaiko@msu.edu.

## AUTHOR CONTRIBUTIONS

AE contributed to the Introduction, Materials and Methods, Results, Discussion, and Conclusion. MY analyzed the impact that hot spring drainage has on river ecosystems, led the citizen participatory surveys, and created the hot spring web maps. KB and NM conducted the stakeholder analysis and established the methodology for narrative scenario building. YM developed the 3-D geological groundwater flow model. RS and HHo analyzed the linkages among the SGD, nutrient flux, and primary production between land and coastal areas. AI developed an integrated water balance model and simulations for quantitative scenarios. JN developed a hydrothermal model and simulations for quantitative scenarios. MF calculated and mapped the potential electricity generation from small hydropower operations for development of renewable energy. TKa used the CBA for the cascade use of hot spring resources for energy, food, and water. HHa applied the GHE system to calculate the shallow geothermal potential. MK conducted a social network analysis and visualized the relationships of the stakeholders. TKu developed the WEF nexus domain ontology and visualized the nexus system maps while collaborating with AE, MY, MK, and TKa. NM analyzed and identified the cross-sector and multi-level policy gaps. All authors contributed to the Discussion and Conclusion sections.

## FUNDING

This study was conducted under the following projects funded by the RIHN: Human Environmental Security in Asia-Pacific Ring of Fire: Water-Energy-Food Nexus (No. 14200097; Fiscal Year 2013–2017) and Development of the Methodology for Integrated Future Scenario Building with Trans-disciplinary Approach (No.

14200144; Fiscal Year 2019). This study was also supported by the 2018 Program 2, Fair Use and Management of Diverse Resources, and by the Multidisciplinary Collaborative Projects, Change of Local Communities and Reconstruction of Community Cultures after Disasters in Japanese Archipelago, which was organized by the National Institutes for the Humanities in 2021.

## ACKNOWLEDGMENTS

We acknowledge Professors Makoto Taniguchi (RIHN) and Shinji Osawa (Kyoto University), who provided useful advice throughout the course of the project; Doctors Jun Shoji and Tomohiro Oh, who contributed to the two projects in Beppu; and Ms. Takako Okamoto and Mr. Shun Teramoto, who assisted the project as secretariat members. We also acknowledge Dr. Shigeki Senna (National Research Institute for Earth Science and Disaster Prevention) for help with microtremor data analysis. Finally, we thank local government employees, including Mr. Shuzo Shiraishi and Mr. Kenichiro Nakamura, and local stakeholders, including Mr. Junichiro Yuki and Mr. Yoshinobu Kamijo, who supported the two projects in Beppu.

## REFERENCES

Agency for Natural Resources and Energy of Ministry of Economy, Trade and Industry (METI) (2021b). *Renewable Energy*. Available online at: https://www.enecho.meti.go.jp/category/saving_and_new/saiene/renewable/outline/index.html (accessed April 3, 2021).

Agency for Natural Resources and Energy of Ministry of Economy, Trade and Industry (METI) (2021c). *Future Renewable Energy Policy*. Available online at: https://www.meti.go.jp/shingikai/enecho/denryoku_gas/saisei_kano/pdf/025_01_00.pdf (accessed April 3, 2021).

Agency for Natural Resources and Energy of Ministry of Economy, Trade and Industry (METI) (2021a). *Current Condition of Operations and Construction of Nuclear Power Plants in Japan*. Available online at: http://www.ene100.jp/www/wp-content/uploads/zumen/4-1-3.pdf (accessed April 3, 2021).

Albrecht, T. R., Crootof, A., and Scott, C. A. (2018). The water-energy-food Nexus: A systematic review of methods for nexus assessment. *Environ. Res. Lett*. 13:043002. doi: 10.1088/1748-9326/aaa9c6

Alcamo, J. (2015). *Systems Thinking for Advancing a Nexus Approach to Water, Soil and Waste*. Lecture Series, No. 2, UNU-Flores.

Allan, J. A. (2003). Virtual water-the water, food, trade nexus, useful concept or misleading metaphor? *Water Internat*. 28, 106–113. doi: 10.1080/02508060.2003.9724812

Allouche, J., Middleton, C., and Gyawal, D. (2014). *Nexus Nirvana or Nexus Nullity? A Dynamic Approach to Security and Sustainability in the Water-Energy-Food Nexus*. STEPS Working Paper 63. Brighton: STEPS Centre.

Al-Saidi, M., and Elagib, N. A. (2017). Towards understanding the integrative approach of the water, energy and food nexus. *Sci. Total Env*. 574, 1131–1139. doi: 10.1016/j.scitotenv.2016.09.046

Baba, K., Masuhara, N., and Kimura, M. (2018). "Scenario-based approach to local water-energy-food nexus issues with experts and stakeholders," in *The Water-Energy-Food Nexus Human-Environmental Security in the Asia-Pacific Ring of Fire*, eds A. Endo and T. Oh (Gateway East: Springer). doi: 10.1007/978-981-10-7383-0_22

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., et al. (2011). Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* 39, 7896–7906. doi: 10.1016/j.enpol.2011.09.039

Benson, D., Gain, A. K., and Rouillard, J. J. (2015). Water governance in a comparative perspective: from IWRM to a "Nexus" approach? *Water Altern*. 8, 756–773. Available online at: https://www.water-alternatives.org/index.php/alldoc/articles/vol8/v8issue1/275-a8-1-8

Burnett, K. M., Wada, C. A., Taniguchi, M., Sugimoto, R., and Tahara, D. (2018). Evaluating the tradeoffs between groundwater pumping for snow-melting and nearshore fishery productivity in Obama City, Japan. *Water* 10:1556. doi: 10.3390/w10111556

Covarrubias, M. (2019). The nexus between water, energy and food in cities: towards conceptualizing socio-material interconnections. *Sustain. Sci*. 14, 277–287. doi: 10.1007/s11625-018-0591-0

DeNooyer, T. A., Peschel, J. M., Zhang, Z., and Stillwell, A. S. (2016). Integrating water resources and power generation: The energy-water nexus in Illinois. *Appl. Energy* 162, 363–371. doi: 10.1016/j.apenergy.2015.10.071

Endo, A., Kumazawa, T., Kimura, M., Yamada, M., Kato, T., and Kozaki, K. (2018). Describing and visualizing a water-energy-food nexus system. *Water* 10:1245. doi: 10.3390/w10091245

Endo, A., Yamada, M., Miyashita, Y., Sugimoto, R., Ishii, A., Nishijima, J., et al. (2020). Dynamics of water-energy-food nexus methodology, methods, and tools. *Curr. Opin. Environ. Sci. Health* 13, 46–60. doi: 10.1016/j.coesh.2019.10.004

Fujii, M., Tanabe, S., Yamada, M., Mishima, T., Sawadate, T., and Ohsawa, S. (2017). Assessment of the potential for developing mini/micro hydropower: A case study in Beppu City, Japan. *J. Hydrol. Reg. Stud*. 11, 107–116. doi: 10.1016/j.ejrh.2015.10.007

Gain, A. K., Sarwar Hossain, M. D., Benson, D., Di Baldassarre, G., Giupponi, C., and Huq, N. (2021). Social-ecological system approaches for water resources management. *Int. J. Sustain. Dev. World* 28, 109–124. doi: 10.1080/13504509.2020.1780647

Gjorgiev, B., and Sansavini, G. (2018). Electrical power generation under policy constrained water-energy nexus. *Appl. Energy* 210, 568–579. doi: 10.1016/j.apenergy.2017.09.011

GWP (2019). *Mobilising for a Water Secure World. Strategy 2020-2025*. Stockholm: GWP.

Hamamoto, H., Miyashita, Y., and Tahara, D. (2018). "Evaluation of the shallow geothermal potential for a ground-source heat exchanger: A case study in Obama Plain, Fukui Prefecture, Japan," in *The Water-Energy-Food Nexus: Human-Environmental Security in the Asia-Pacific Ring of Fire*, eds A. Endo and T. Oh (Gateway East: Springer). doi: 10.1007/978-981-10-7383-0_6

Hamidov, A., and Katharina Helming, K. (2020). Sustainability considerations in water-energy-food nexus research in irrigated agriculture. *Sustainability* 12:6274. doi: 10.3390/su12156274

Henry, S. (2017). "Interdisciplinary in the fields of law, justice, and criminology," in *The Oxford Handbook of Interdisciplinarity, Second Edition*, eds R. Frodeman, J. T. Klein, and R. C. S. Pacheco (New York, NY: Oxford University Press). doi: 10.1093/oxfordhb/9780198733522.013.32

Hoff, H. (2011). *Understanding the Nexus. Background Paper for the Bonn Conference 2011: the Water-energy-food Security Nexus*. Stockholm: Stockholm Environment Institute.

Honda, H., Osawa, S., Sugimoto, R., Hen, T., Mishima, T., Yamada, M., et al. (2015). *Submarine Groundwater Discharge and Nutrients State of Around Coastal Seawater*. Japan Geoscience Union Meeting, Makuhari, Chiba, Japan.

Ishii, A., Miyashita, Y., Yamada, M., Honda, H., Sugimoto, R., Osawa, S., et al. (2018). "Understanding of water, energy and food nexus using integrated water cycle analysis model in Beppu Bay," in *Water-Energy-Food Nexus on Geothermal Energy Resources*, eds K. Baba, N. Masuhara, A. Endo (Tokyo: Kindaikagakusha).

Itadera, K. (2012). Visit note in Iceland (Iceland wo tazunete). *Catfish Lett.* 62, 28–32.

Käkönen, M., and Kaisti, H. (2012). The world bank, laos and renewable energy revolution in the making: challenges in alleviating poverty and mitigating climate change. *Forum Dev. Stud.* 39, 159–184. doi: 10.1080/08039410.2012.657668

Kamio, M., and Kato, T. (2018). "Reducing environmental burden of greenhouse strawberry production by geothermal use," in *Water-Energy-Food Nexus on Geothermal Energy Resources*, eds K. Baba, N. Masuhara, and A. Endo (Tokyo: Kindaikagakusha).

Keskinen, M. (2010). *Bringing Back The Common Sense? Integrated Approaches in Water Management: Lessons Learnt from the Mekong*. [Dissertation]. [Espoo, Finland]: Aalto University.

Keskinen, M., Someth, P., Salmivaara, A., and Kummu, M. (2015). Water-energy-food nexus in a transboundary river basin: The case of Tonle Sap Lake, Mekong river basin. *Water* 7, 5416–5436. doi: 10.3390/w7105416

Kimura, M., Masuhara, N., and Baba, K. (2017). Visualization of potential social network focusing on common recognition of small scale distributed geothermal power plant stakeholders in Beppu City, Oita Prefecture. *J. Environ. Sci*. 30, 325–335. doi: 10.11353/sesj.30.325

Klein, J. T. (2008). Evaluation of interdisciplinary and transdisciplinary research: A literature review. *Am. J. Prevent. Med*. 35, 116–123. doi: 10.1016/j.amepre.2008.05.010

Kurian, M. (2017). The water-energy-food nexus Trade-off thresholds and transdisciplinary approaches to sustainable development. *Env. Sci. Policy*. 68, 97–106. doi: 10.1016/j.envsci.2016.11.006

Kurian, M., Portney, K. E., Rappold, G., Hannibal, B., and Gebrechorkos, S. H. (2018). "Governance of water-energy-food nexus: a social network analysis approach to understanding agency behaviour," in *Managing Water, Soil and Waste Resources to Achieve Sustainable Development Goals*, eds S. Hülsmann and R. Ardakanian (Cham: Springer). doi: 10.1007/978-3-319-75163-4_6

Lawford, R., Bogardi, J., Marx, S., Jain, S., Wostl, C. P., Knüppe, K., et al. (2013). Basin perspectives on the water-energy-food security nexus. *Curr. Opin. Environ. Sustain*. 5, 607–616. doi: 10.1016/j.cosust.2013.11.005

Leck, H., Conway, D., Bradshaw, M., and Rees, J. (2015). Tracing the water-energy-food nexus: description, theory and practice. *Geogr Compass* 9, 445–460. doi: 10.1111/gec3.12222

Masuhara, M., and Baba, K. (2017). *Current Situation of Resource Potential, Development Targets, Regulations and Conflicts of Geothermal Energy in Japan*. Third World Congress and Expo on Green Energy, Berlin, Germany.

Masuhara, N., and Baba, K. (2021). Achievements and challenges of interdisciplinary and transdisciplinary approaches to water and energy nexus -case study of scenario planning for hot spring/tourism and geothermal issues in Beppu City. *J. Environ. Sci*. 34, 66–79. doi: 10.11353/sesj.34.66

Miyashita, Y. (2018). "Elucidation of Beppu Onsen aquifer by microtremor survey," in *Water-Energy-Food Nexus on Geothermal Energy Resources*, eds K. Baba, N. Masuhara, and A. Endo (Tokyo: Kindaikagakusha).

National Academy of Sciences (2005). *National Academy of Engineering and Institute of Medicine*. Washington, DC: Facilitating Interdisciplinary Research, National Academic Press.

Nishijima, J., Naritomi, K., Sofyan, Y., Ohsawa, S., and Fujimitsu, Y. (2018). "Monitoring hot spring aquifer using repeat hybrid micro-gravity measurements in Beppu Geothermal Field, Japan," in *The Water-Energy-Food Nexus: Human-Environmental Security in the Asia-Pacific Ring of Fire*, eds A. Endo and T. Oh (Gateway East: Springer). doi: 10.1007/978-981-10-7383-0_5

Nixon, S. W. (1988). Physical energy inputs and the comparative ecology of lake and marine ecosystems. *Limnol. Oceanogr*. 33, 1005–1025. doi: 10.4319/lo.1988.33.4part2.1005

Oita Prefecture (2021). *Data of Hot Spring*. Available online at: http://www.pref.oita.jp/site/onsen/onsen-date.html (accessed April 12, 2021).

Okumura, T. (2017). *Case Studies in Hydrothermal Use and Geothermal Binary Power Generation in Japan*. Available online at: https://www.enaa.or.jp/?fname=gec_h29_3_2.pdf (accessed July 30, 2021).

Osawa, S., and Yusa, Y. (1996). *Study on Flow Path of Underground Hot Spring Water in Beppu Northern Area Estimated From Chemical Components of Hot Spring Water, Geothermal Fluid Flow Process and Underground Structure*. Beppu: Research on Grants for Scientific Research Result Report.

Osawa, S., Yusa, Y., and Kitaoka, S. (1994). Flow path of thermal groundwaters in the southern part of Beppu, Japan. *J. Hot Spring Sci*. 44, 199–208.

Pahl-Wostl, C. (2019). Governance of the water-energy-food security nexus: A multi-level coordination challenge. *Environ. Sci. Policy* 92, 356–367. doi: 10.1016/j.envsci.2017.07.017

Pahl-Wostl, C., Bhadurib, A., and Brunsc, A. (2018). The Nexus of water, energy and food - An environmental governance perspective. *Environ. Sci. Policy* 90, 161–163. doi: 10.1016/j.envsci.2018.06.021

Pandey, V. P., and Sangam Shrestha, S. (2017). "Evolution of the nexus as a policy and development discourse," in *Water-Energy-Food Nexus Principles and Practices*, eds P. A. Salam, S. Shrestha, V. P. Pandey, and A. K. Anal (Washington DC: Wiley). doi: 10.1002/9781119243175.ch2

Purwanto, A. (2021). *Grasping the Water, Energy, and Food Security Nexus in the Local Context Case Study: Karawang Regency, Indonesia*. [Dissertation]. [Delft]: Wageningen University.

Repko, A. F., and Szostak, R. (2008). *Interdisciplinary Research: Process and Theory*. Thousand Oaks, CA: SAGE.

Ringler, R., Bhaduri, A., and Lawford, R. (2013). The nexus across water, energy, land and food (WELF): Potential for improved resource use efficiency? *Curr. Opin. Environ. Sustain*. 5, 617–624. doi: 10.1016/j.cosust.2013.11.002

Roidt, M., and Avellan, T. (2019). Learning from integrated management approaches to implement the Nexus. *J. Environ. Manage*. 237, 609–616. doi: 10.1016/j.jenvman.2019.02.106

Scott, C., Kurian, M., and Wescoat, J. (2015). "The water-energy-food nexus: enhancing adaptive capacity to complex global challenges," in *Governing the Nexus: Water, Soil and Waste Resources Considering Global Change*, eds M. Kurian and R. Ardakanian (Dordrecht: Springer). doi: 10.1007/978-3-319-05747-7_2

Shoji, J. (2018). "The impacts of hot spring drainage on fishery resources," in *Water-Energy-Food Nexus regarding Geothermal Resource*, eds K. Baba, N. Masuhara, A. Endo (Tokyo: Kindaikagakusya).

Shoji, J., and Tominaga, O. (2018). "Relationships between submarine groundwater discharge and coastal fisheries as a water-food nexus," in *The Water-Energy-Food Nexus: Human-Environmental Security in the Asia-Pacific Ring of Fire*, eds A. Endo and T. Oh (Gateway East: Springer), 117–131. doi: 10.1007/978-981-10-7383-0_9

Siemenpuu Foundation (2021). *Climate and Energy Justice*. Available online at: https://www.siemenpuu.org/en/funding/energy (accessed January 26, 2021).

Stein, C., Pahl-Wostl, C., and Barron, J. (2018). Towards a relational understanding of the water-energy-food nexus: an analysis of embeddedness and governance in the Upper Blue Nile region of Ethiopia. *Environ. Sci. Policy* 90, 173–182. doi: 10.1016/j.envsci.2018.01.018

Sugimoto, R., Kitagawa, K., Nishi, S., Honda, H., Yamada, M., Kobayashi, S., et al. (2017). Phytoplankton primary productivity around submarine groundwater discharge in nearshore coasts. *Mar. Ecol. Prog. Ser*. 563, 25–33. doi: 10.3354/meps11980

Tanabe, S. (2015). *Assessment of the Potential of Developing Mini/Micro Hydropower*. [Master's Thesis]. [Sapporo, Hokkaido]: Hokkaido University (in Japanese).

The Food and Agriculture Organization of the United Nations (FAO) (2014). *The Water-Energy-Food Nexus: A New Approach in Support of Food Security and Sustainable Agriculture*. Available online at: http://www.fao.org/nr/water/docs/FAOnexusconcept.pdf (accessed April 2, 2021).

The Food and Agriculture Organization of the United Nations (FAO) (2015). *FAO Fisheries & Aquaculture - Cultured Aquatic Species Information Programme - Oreochromis Niloticus. Linnaeus, 1758*. Available online at: http://www.fao.org/fishery/culturedspecies/Oreochromis_niloticus/en (accessed April 2, 2021).

Webber, M. E. (2017). "Water for electricity generation in the United States," in *Competition for Water Resources*, eds J. R. Ziolkowska and J. M. Peterson (Amsterdam: Elsevier). doi: 10.1016/B978-0-12-803237-4.00012-4

Weitz, N., Strambo, C., Kemp-Benedict, E., and Nilssona, M. (2017). Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance. *Global Environ. Change* 45, 165–173. doi: 10.1016/j.gloenvcha.2017.06.006

White, D., Jones, J., Maciejewski, R., Aggarwal, R., and Mascaro, G. (2017). Stakeholder analysis for the food-energy-water nexus in Phoenix, Arizona: Implications for nexus governance. *Sustainability* 9:2204. doi: 10.3390/su9122204

Yamada, M., Honda, H., Mishima, T., Ohsawa, S., and Shoji, J. (2018). "Tradeoff between hot spring use and river ecosystem: The case of Beppu City, Oita Prefecture, Japan," in *The Water-Energy-Food Nexus: Human-Environmental Security in the Asia-Pacific Ring of Fire*, eds A. Endo and T. Oh (Gateway East: Springer). doi: 10.1007/978-981-10-7383-0_10

Yamada, M., and Oh, T. (2018). "The citizen participatory hot spring survey in Beppu city," in *Water-Energy-Food Nexus Regarding Geothermal Resource*, eds K. Baba, N. Masuhara, A. Endo (Tokyo: Kindaikagakusya).

Yasukawa, K., Takashima, I., Uchida, Y., Tenma, N., and Lorphensri, O. (2009). Geothermal heat pump application for space cooling in Kamphaengphet, Thailand. *Bullet. Geolog. Surv. Japan* 60, 491–501. doi: 10.9795/bullgsj.60.491

Yousefi, H., and Mortazavi, S. M. (2018). "A Review on Robustness of Geothermal Energy in Japan," in *Proceedings of the 43rd Workshop on Geothermal Reservoir Engineering-Stanford University, Stanford* (California).

Yusa, Y., Kamiyama, K., and Kawano, T. (1989). Long-term change in chemical composition of hot spring in the southern part of Beppu area (2). *Rep. Oita Prefecture Hot Spring Res. Soc.* 40, 21–29.

Yusa, Y., Kamiyama, K., and Kawano, T. (1990). Long-term change in chemical composition of hot spring in the northern part of Beppu area (2). *Rep. Oita Prefecture Hot Spring Res. Soc.* 41, 13–24.

Yusa, Y., Noda, T., and Kitaoka, K. (1975). Discharge of water, heat and chemical substances through a hydrothermal system-Beppu hydrothermal system. *J. Soc. Eng. Mineral Springs* 10, 94–108.

**Conflict of Interest:** AI was employed by Yachiyo Engineering Co., LTD.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Publisher's Note:** All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.