Case Study

Examining the Food-Energy-Water-Environment Nexus in Transboundary River Basins through a Human Dimension Lens: Columbia River Basin

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Abstract: Previous food-energy-water-environment (FEWE) nexus studies have primarily focused on technical aspects, such as data analysis and model development. However, to inform policy and the resulting management of resources in politically complex transboundary systems, nontechnical human factors in the FEWE nexus should also be considered. This paper explores the human dimension of the FEWE nexus in the Columbia River basin between the US and Canada. We hosted a workshop with regional government agencies to review and evaluate current policies and management of the *institutional aspect* of FEWE resources. We then surveyed residents from both the US and Canada, who share transboundary water resources in the region, to evaluate their awareness of the FEWE nexus and its related policies, representing the *residential aspect*. The outcomes of the workshop showed that (1) a consensus of common metrics for all sectors (food, energy, water, and environment) can provide a uniform basis for cross-sectoral comparison; (2) it is critical to have adaptive management and interagency coordination mechanisms; and (3) the support of local residents is key to successful policy implementation. The survey results suggested that residents understand a strong relationship between water and energy sustainability. Females and renters showed stronger support for policies related to FEWE sustainability. Combining knowledge from the workshop and survey will support the development of a more realistic modeling framework. **DOI: 10.1061/(ASCE)WR.1943-5452.0001461.** © *2021 American Society of Civil Engineers.*

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Introduction

With a growing population, economic development, and the increasing impact of extreme climatic events, challenges in maintaining food, energy, and water security have become public concerns. These rising demands intensify the nexus, or linkages, between the food, energy, and water sectors. In recent years, water, energy, and food linkages have been strongly promoted as a global research agenda to analyze sustainable development goals (Siddiqi et al. 2013; Leck et al. 2015). In addition, it is a critical challenge to (1) develop policies that support the sustainability of food, energy, and water resources; (2) provide access to these resources for all levels of society; and (3) maintain a healthy environment (Fasel et al. 2016; Karabulut et al. 2019; Simpson and Jewitt 2019; Larkin et al. 2020). A better understanding of interactions among food-energy-water-environment (FEWE) sectors and how they are entangled within human society can facilitate more efficient and sustainable resource allocation and use. Traditionally, nexus issues have been evaluated by independent analyses of the water, energy, or food sectors; however, several studies have shown that single-sector planning and decisions are likely to lead to unsustainable development (Bizikova et al. 2013; Rees 2013; Smajgl et al. 2016). By recognizing the interdependence of FEWE nexus components, policies can be designed to focus on the needs of multiple and often interdependent sectors.

To fully explore the entire FEWE nexus, political and institutional realities should also be considered. These realities are especially critical for transboundary systems, like river basins that flow through different sovereignties. Approximately 40% of the world's population lives in these basins (UN Water 2008), and they require energy, drinking water, and food (through agricultural activities) to be supported by the rivers. Keskinen and Varis (2016) indicated that the nexus approach could provide new strategies for the management of resources and transboundary cooperation. De Strasser et al. (2016) also pointed out that using a nexus approach could enhance resource efficiency and good governance in transboundary basins. Previous studies have focused on technical and physical aspects of the FEWE nexus in transboundary river basins (Bach et al. 2014; Keskinen et al. 2015; Keskinen and Varis 2016; De Strasser et al. 2016; Yang et al. 2016b), but few studies had evaluated social perspectives (i.e., connections between policy and public opinion among these four sectors) in their methodology.

To address this gap, recent research has highlighted institutional relationships among these sectors and engaged local stakeholders in research on the FEWE nexus (Harvey 2014; Boas et al. 2016; Smajgl et al. 2016; Givens et al. 2018; Hargrove and Heyman 2020). Previous researchers have conducted workshops and invited stakeholders to share their specific expertise in FEWE nexus management (Mohtar and Daher 2016; White et al. 2017; Sušnik et al. 2018; Badham et al. 2019). Others have developed web-based tools to support FEWE nexus decision-making in a complex societal context (Zeng et al. 2012; Abdullaev and Rakhmatullaev 2014;

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Babbar-Sebens et al. 2015). These studies examined the *institutional aspect* of the FEWE nexus because most participants in the workshops or tool users were government employees or policymakers. In this study, we define the institutional aspect as the response of different government agencies to the FEWE nexus challenge. Other studies have tried to explore the *residential aspect* of the FEWE nexus, which we define as an awareness of relevant FEWE policies by local residents. An example of this approach was demonstrated by Portney et al. (2018). They conducted a national public opinion survey on the FEW nexus to evaluate resident understanding and awareness of nexus issues. Few studies, to the best of our knowledge, have combined these two aspects together to explore the human dimension of the FEWE nexus in a single system (e.g., a transboundary river basin). We think that these two aspects are complementary, and combining them will (1) provide a more comprehensive view of the FEWE nexus and (2) potentially enable reconciliation of priorities from different groups, leading to better management of food, energy, and water resources.

This paper presents a case study using a framework to explore both the institutional and residential aspects of the FEWE nexus in a transboundary system: the Columbia River basin (CRB). Following the structured public participation concept from Shared Vision Planning (USACE 2007), we conducted a workshop to facilitate in-depth conversations with stakeholders from government agencies that cover the food, energy, water, and environmental sectors. This workshop can help us review and evaluate the current management of FEWE resources as well as identify institutional and legal barriers. We also conducted a large-scale survey in the basin to collect resident opinions on related FEWE policies. We then compared the results from the workshop and the survey to identify points of convergence.

The structure of the paper is as follows: we briefly introduce the background of food, energy, water, and environmental sectors in the CRB in the "Study Area" section; we describe the methods used to explore the institutional (workshop) and residential (survey) aspects of the FEWE nexus in the "Method" section; we show workshop and survey results in the "Result" section; we discuss the potential knowledge transfer to other basins and limitations in the "Discussion" section; and finally, we present conclusions in the "Conclusion" section.

Study Area

The Columbia River is North America's fourth-longest river; it drains an area of 567,000 km^2 and covers portions of seven western states (Washington, Oregon, Idaho, Montana, Wyoming, Nevada, and Utah) in the US and the Canadian province of British Columbia (Fig. 1). It originates in the Rocky Mountains of British Columbia,

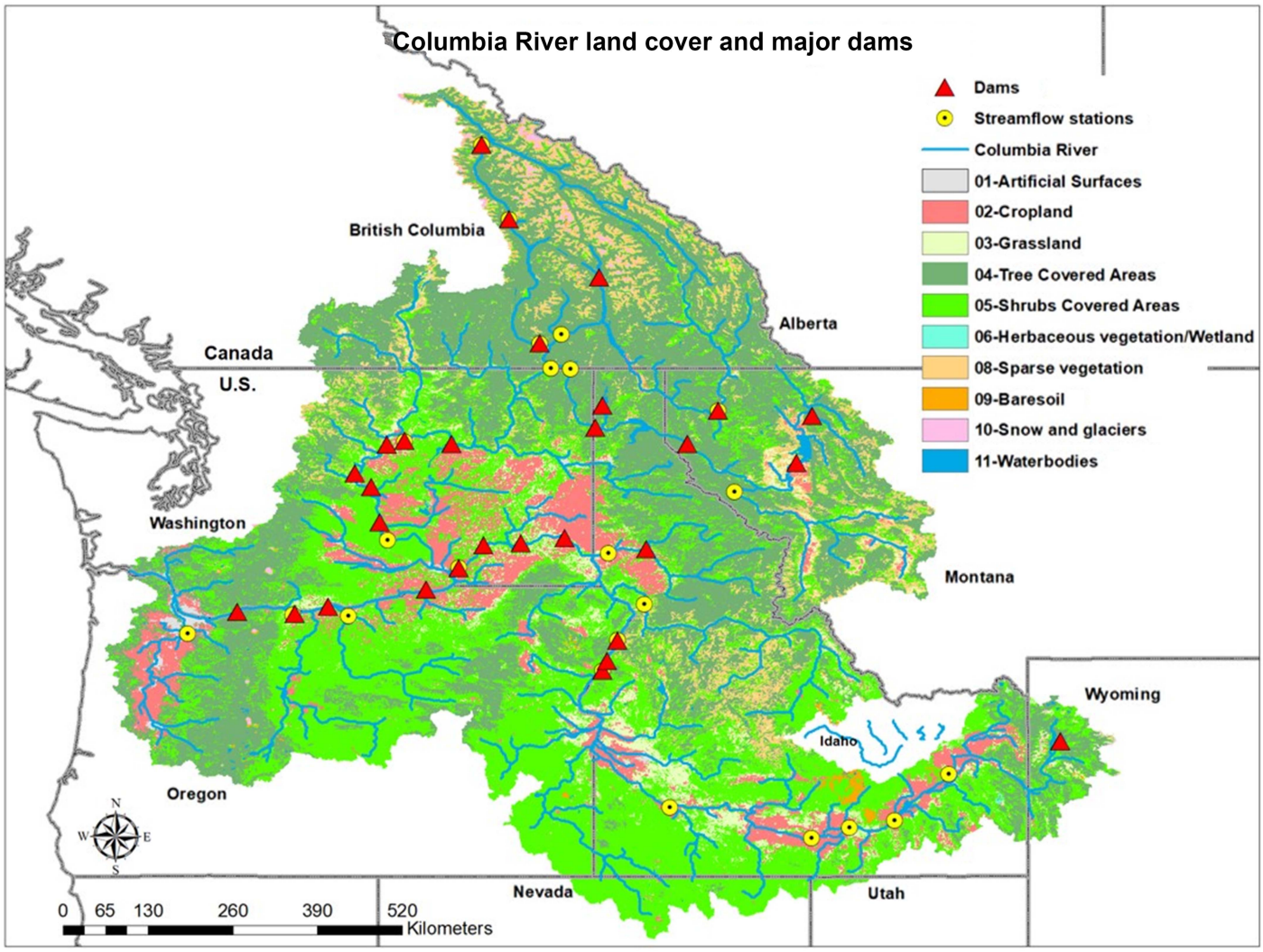

Fig. 1. Columbia River basin boundary, land cover, and major dams.

Idaho, Montana, and Wyoming and then flows through Washington and Oregon before entering the Pacific Ocean.

Food

Agriculture generates thousands of jobs and billions of dollars in revenue every year; hence, it is deeply tied to the livelihoods of many people (USDA 2020). In some rural areas, agriculture is the primary engine for economic growth. Today, approximately 5.1 million acres of farmlands are irrigated with water from the Columbia River and its tributaries (Brunell 2018). The largest areas of irrigated acreage are in southern Idaho, eastern Washington, and eastern Oregon. Nearly all of the potatoes, sugar beets, hops, fruit, vegetables, and mint grown in the CRB are irrigated, as are large crops of hay and grain (National Research Council 2004). Irrigation is the largest consumptive use of water in the CRB (Northwest Power and Conservation Council 2019b).

Energy

The Columbia River features a high hydraulic head gradient (large water surface drop over a short distance) (Bonneville Power Administration 2001). This feature has been exploited to produce hydroelectricity, which represents up to 80% of the electricity produced in the Pacific Northwest. The hydroelectricity produced in the CRB can support more than 13 million households. Because hydropower is one of the cheapest energy sources, most Pacific Northwest residents have significantly lower electric bills than residents of other parts of the United States and Canada (Foundation for Water and Energy Education 2020).

Water

The Columbia River has an annual average runoff of approximately 250 billion m^3 per year, with roughly 25% of the volume originating in the Canadian portion of the basin (Bureau of Reclamation 2016). The Columbia River system has over 400 dams with multiple objectives, including irrigation, water supply, hydropower production, streamflow regulation, and flood risk management. However, the dams in the CRB also negatively impact the ecosystem (Bureau of Reclamation 2016).

Environment

Dams interrupt the migration of several anadromous fish, such as salmon and steelhead, between the Pacific Ocean and freshwater tributaries (Northwest Power and Conservation Council 2019a). The CRB once hosted the largest salmon runs on earth, with more than 30 million salmon returning to spawn each year; today, only a fraction returns to CRB due to hundreds of dams along the Columbia River corridor (Michel 2018). Salmon populations are tied to the health of multiple ecosystems, including estuaries, coastal areas, and rivers. For the health of the CRB ecosystem, operations in some dams have been modified to increase flows and the spill of water through the dams, move juvenile fish downstream faster, and barge juvenile fish around the dams (Bureau of Reclamation 2016).

FEWE Management

The current transboundary FEWE nexus management in the CRB is partially guided by the Columbia River Treaty (CRT), which was established in 1964 between Canada and the United States. The CRT governs dam development and operation along the river for the benefit of power production (energy sector) and flood control (water sector). The CRT provides the US with rights and obligations that are carried out by two federal agencies: the Bonneville Power Administration and the USACE. Canada's rights and obligations are managed by the Canadian Federal Cabinet: the British Columbia Hydro and Power Authority. The CRT has no specific end date. Either the United States or Canada can terminate most provisions of the CRT (except flood control operations) if written notice is filed no less than ten years in advance. When the treaty was ratified, the United States paid $64.4 million to Canada for flood control benefits. These flood control operations are scheduled to end in 2024 and transition to a *called-upon* operation. A called-upon operation is a flood control regime that requires the US to make effective use of all related storage before calling on Canada to help to avoid potential flood damages. The US must also pay Canada for called-upon operations (Metcalfe 2018), although these costs are not well-defined in the current treaty. To date, both the US and Canada have indicated an interest in renegotiating the treaty.

When the CRT was established in 1964, policymakers did not explicitly consider the rights and responsibilities of tribes and residents. Additionally, the treaty did not address fishing, restoration, agriculture use, or water temperature changes. Renegotiations of the CRT should consider providing stream flows to promote anadromous and resident fish populations and minimize adverse effects on tribal resources (Stern 2019). Flows to improve ecosystems have been treated as a new treaty purpose by tribal and environmental groups. The renegotiation of CRT provides an opportunity to include the human dimension of the FEWE nexus in a formal agreement between two countries, and it will act as a standard for other transboundary basins to facilitate stakeholder collaboration and improve adaptive management to achieve multiple objectives.

Method

Institutional Aspect: Government Agencies Engagement Workshop for FEWE Management

To better understand how different government agencies currently manage FEWE resources and how current FEWE-related policy is prioritized by different agencies, a workshop was held in October 2018 in Seattle, Washington. This workshop brought together academics and FEWE stakeholders to discuss institutional, legal, and technological challenges in implementing the CRB's food, energy, water, and environmental nexus policies [Fig. 2(a)]. Ten participants attended the workshop: one from USACE, one from the US Bureau of Reclamation (BoR), one from the Northwest Power and Conservation Council (NPCC), one from the Washington Department of Fish and Wildlife, one from the Yakama Nation, one from the Pacific Northwest National Laboratory, and four from universities. The workshop was divided into four themes, which are shown in Fig. 2(b).

During *Metrics Definition* [Fig. 2(b)], scientists introduced the FEWE nexus concept and defined sustainability metrics for all four sectors. The food sector was defined as crop production, the energy sector as power supply and demand, the water sector as freshwater supply and flood control, and the environmental sector as ecosystem conservation, including fish and wildlife. Sustainability in this study considers the reliability, resilience, and vulnerability of these sectors. We used the concept of *deficit* to quantify these aspects in each of the four sectors (Loucks 1997; Sandoval-Solis et al. 2011; Yang et al. 2018a). A deficit refers to any gap between target and actual production, that is, resource demand and supply. The calculations for these deficits are provided in the Supplemental Materials. This

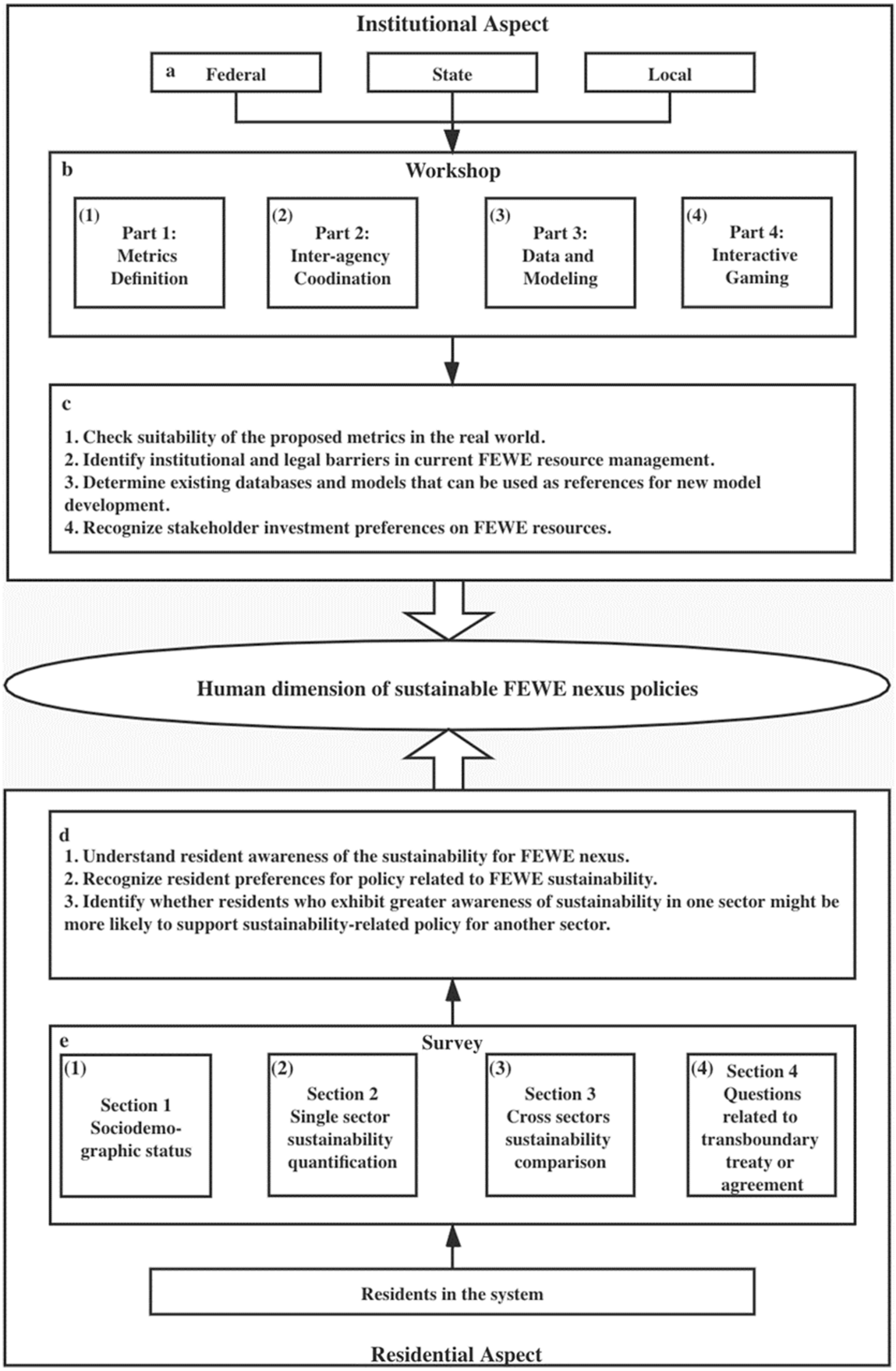

Fig. 2. Framework to explore the human dimension of FEWE nexus with both institutional and residential aspects: (a) indicates participants invited for the workshop; (b) shows four major themes discussed during the workshop; (c) lists the action items from the workshop to explore the human dimension of sustainable FEWE nexus policies; (d) lists the action items from the survey to explore the human dimension of sustainable FEWE nexus policies; and (e) summarizes the content of survey that was distributed to residents.

part of the workshop bridged the gap between academic research and government agencies about the main idea and concept applied in the FEWE nexus.

During the second part of the workshop, *Interagency Coordination* [Fig. 2(b)], scientists and stakeholders discussed existing adaptive management and interagency coordination in the CRB. We specifically focused on defining adaptive management from different agencies, as well as identifying communication channels between different agencies. These discussions will enable scientists to identify institutional and legal challenges in managing the future FEWE nexus.

The third part of the workshop, *Data and Modeling* [Fig. 2(b)], included a discussion of existing modeling frameworks and different databases related to the FEWE nexus in the CRB. These data and models can provide a technical understanding of connections within the FEWE nexus and serve as a foundation for policy decisions. This discussion enables scientists and government agencies to explore potential gaps in data collection or model development.

During *Interactive Gaming* [Fig. 2(b)], we used the method from Khan et al. (2017) to design an interactive role-playing game (Madani et al. 2017) that simulated the decision-making process for financial resource allocation. The biggest advantage of using the role-playing game was its fictional nature, which concentrates on presenting the information in an interactive way and providing a better intuitive understanding of complexity to stakeholders by relaxing requirements and providing suitable information for making defensible decisions (Craven et al. 2016). Our game uses a physical CRB map and four colors of page markers. The colors represent different sectors: yellow is food, orange is energy, blue is water, and pink is the environment. All participants were asked to invest USD 10 billion in the entire basin by physically tagging page markers ($1 billion per page marker) on the map of the CRB. The placement of these page markers represented the relative location of investment to mimic real-world investment decisions.

As shown in Fig. 2(c), by communicating with stakeholders during the entire workshop, scientists who study the FEWE nexus received real-world feedback on whether the concept or definition of metrics was meaningful to stakeholders. If a proposed metric is unsuitable for the real world due to institutional or legal barriers, stakeholders can help scientists make necessary modifications. Finally, interactive gaming helped scientists recognize stakeholder preferences and streamline research efforts to focus on different FEWE investments.

Residential Aspect: Survey of Resident Opinions on FEWE Policies

Policymakers should be aware of public opinions because the public can provide feedback to policies and guide policy decisions to coordinate with local preferences. Piemonti et al. (2013) showed an example of how a landowner's opinion of specific conservation criteria motivated policymakers to change their original decision in a prescribed watershed plan that was previously optimized for watershed-scale goals.

To understand the awareness of and opinions on the FEWE nexus among residents of the CRB, a large-scale survey was conducted. Survey responses were collected from March 2019 to May 2019, using the professional survey platform Qualtrics. The surveys were distributed to residents of Washington, Oregon, Idaho, Montana, and British Columbia in Qualtrics' database. We targeted anyone above age 20, regardless of their gender, race, occupation, or any other demographic information, which we defined as the general public. Of the 1,435 people who attempted the online survey, 543 completed it (443 in the US and 100 in Canada, and this ratio of Americans to Canadians reflects the population distribution in the basin). Our survey response rate was approximately 37.8%, which was slightly higher than the average response rate for an email survey (Shih and Fan 2009). About eight million people are estimated to live in the basin, and the total sample of 543 gave us a margin error of $\pm 4.5\%$ under the 95% confidence level. More details about this survey can be found in the Supplemental Materials.

The entire survey included four sections, with a total of 45 questions [Fig. 2(e)]. The first section asked respondents for sociodemographic information [Fig. 2(e)], such as their nationality, gender, housing status, education level, and other characteristics. The information collected from this section enabled us to correlate awareness of the FEWE nexus with different sociodemographic characteristics.

The second section included 12 questions that aimed to understand resident opinions about policies that can improve FEWE reliability, resilience, and vulnerability within a single sector [Fig. 2(e)]. The Likert scale was applied, and all questions were scored from 1 to 7, in which 1 meant respondents were extremely unlikely to support the policy, and 7 indicated respondents were extremely likely to support the policy. Reliability, resilience, and vulnerability were previously indicated as three aspects of sustainability in our research [connect to Metrics Definition of the institutional aspect in Fig. 2(b)]. We then used Spearman's rank-order correlation (Lehman et al. 2005) to examine how opinions about the sustainability of one sector were related to others. We used Spearman's correlation because it is the nonparametric version of the Pearson product-moment correlation (Walk and Rupp 2010). Spearman's correlation coefficient reflects the strength and direction of the association between two ranked variables (Mukaka 2012). Therefore, it can be used to identify whether a person who exhibited greater awareness of one sector might also exhibit greater awareness of another sector. We also classified respondents based on their sociodemographic status and then conducted a t-test (Rice 2006) with their answers in the second section. The independent t-test is an inferential statistical test that is used to determine whether there is a statistically significant difference between the means of two independent groups. Our null hypothesis for the t-test is that the difference of the mean score from any two groups (e.g., US versus Canada, male versus female, homeowners versus renters) is zero, and the p-value used for the t-test is 0.05. So, if the null hypothesis is rejected, we know there is a significant difference between the scores.

The third section contained 18 questions that were used to explore resident preferences for policies on reliability, resilience, and vulnerability across the four sectors [Fig. 2(e)]. These 18 questions could be divided into three portions that corresponded to three aspects of sustainability (reliability, resilience, and vulnerability). In each portion, two sectors were compared in a pair with six associated questions. For example, the food reliability policy was compared with the energy, water, and environmental reliability policy (three questions) to help us understand what the generic public's perceptions are on ranking their relative importance. Then we repeated this process for energy versus water and environment (two questions) and, finally, water versus environment (one question). Similarly, we can rank the relative importance of all four sectors for resilience and vulnerability using the same procedure. All questions received responses on a scale from 1 to 7, just like the questions in the second section. We used the aggregate score to rank resident preferences. For example, in the section about reliability, the respondent was asked whether improving food policy related to reliability is more important than energy policy. If the respondent selected 7—Completely Agree, then the food policy item received 7 points, and the energy policy item received 1 point. If the respondent selected 4—Neutral, both the food and energy policy

item each received 4 points. After six rounds of comparison in each portion, the aggregate score for four sectors was obtained. The results of this section helped us to rank resident support for a policy related to specific aspects of sustainability across four sectors.

Finally, the fourth section included a few questions about the CRT to explore whether familiarity with the CRT impacted resident opinions of related FEWE sustainability policies [Fig. 2(e)].

As shown in Fig. 2(d), we surveyed how awareness of sustainability varied across sociodemographic groups. This social science perspective helps scientists to explore how resident characteristics shape opinions about FEWE nexus sustainability (Givens et al. 2018). Moreover, the survey reflects resident preferences for individual policies related to reliability, resilience, and vulnerability across four sectors. This survey also provided information about whether a resident who exhibits greater awareness of sustainability in one sector is more likely to support sustainability-related policies for another sector.

Result

Government Agencies Engagement Workshop

We organize and summarize the major outcomes of the workshop in four noteworthy themes and highlight them as the subsection titles.

Common Metrics Definition

In the first part of the workshop, different participating agencies agreed that common metrics unify the calculation of reliability, resilience, and vulnerability in all FEWE sectors, enabling meaningful comparison. However, several participants stated that different agencies have their own metrics to evaluate planning performance related to the FEWE nexus. While the creation of common metrics is possible (and most likely welcomed) for planning purposes, it is challenging for day-to-day operations by multiple agencies. For example, when we raised a question about whether there is a targeted salmon population that any agencies used, a participant responded: "... It is very difficult to do because of so much uncertainty biologically. One thing we can do is to simulate river flows and reservoir elevation and infer travel times and survival [of the fish] with passages survival models and life cycle models ...."

Furthermore, some participants pointed out that current water and power systems in the CRB are designed to avoid deficits, which means that there is rarely a gap between resource supply and demand. Therefore, a method that focuses on deficit calculation might not be readily applicable, and further discussion about common metrics is still needed.

Lack of Interagency Coordination

One institutional barrier was highlighted in the second part of the workshop: agencies are driven by different missions and usually only focus on one system. Agencies can be legally limited from considering other systems. For example, when we asked whether USACE reservoirs consider irrigation as a secondary objective to their main flood control objective when a situation involves water rights, one response was the following: "Different agencies have different missions. So, to make sure the system can be operated as the system [we want], you have to negotiate the water right." Another response was the following: "... Water rights are something; it is difficult, and each state has its own laws. For example, we want extra water to increase the (instream) flows, and that needs to be negotiated and purchased from water banks .... It is very difficult ...."

However, real-world coordination still exists at different levels inside the government. There is international coordination between the US and Canada following the CRT. While the treaty created monthly reservoir operation rules, representatives from both countries hold a weekly meeting to discuss real-time reservoir release. At the federal government level of the US, dams under the BoR mostly focus on irrigation, although they will also coordinate with USACE dams for flood protection. At the US state level, there are coordinated meetings for the day-to-day and year-to-year operation for fish and wildlife conservation between Washington, Oregon, Idaho, and Montana. This interagency coordination in the CRB is not commonly observed in other transboundary river basins, especially in developing countries (Yang et al. 2014).

Workshop participants from different agencies also raised three questions for discussion: Who are the primary policymakers—federal or state agencies? How do federal law and that of individual riparian states differ? Where do federal and state jurisdictions overlap when FEWE nexus policies are implemented? Answers to these questions will help us clarify jurisdiction issues in all four sectors. By clarifying where overlaps and barriers occur, we can undertake focused efforts to overcome them to implement FEWE nexus policies. This information is also valuable for building a FEWE nexus modeling framework that considers physical constraints and institutional limitations. A better understanding of institutional and legal barriers can help scientists make better assumptions, possibly limiting systematic bias in the modeling results. Finally, participants also emphasized the need for smooth communication between government agencies and residents for the implementation of policies. Compared to other transboundary river basins, CRB provides different channels for these communications (British Columbia 2019; Upper Columbia Basin Environmental Collaborative 2020), but more effort might still be needed.

Exploring Existing Data and Modeling

During the third part of the workshop, participants discussed several existing modeling frameworks and available databases that aim to evaluate the energy, water, and environment sectors in the CRB. For example, the Model for Scale Adaptive River Transport (MOSART, Li et al. 2013) was used to simulate surface runoff, river flow, and water temperature under regular and extreme climate events like heatwaves, droughts, and floods. GENeration Evolution SYStem model (GENESYS, Northwest Power and Conservation Council 2016) was used to evaluate how climate change might impact the power market and water availability in the Northwest. During this discussion, participants also expressed a desire for a new modeling framework that could quantify adaptive management actions from different agencies and residents. A common definition of adaptive management is a learning-based process from stakeholders (Williams et al. 2009). Therefore, the new modeling framework should quantify this learning process. For example, the new modeling framework should allow government agencies to adjust their policies based on feedback from residents; residents can also adjust their actions/behaviors related to FEWE in response to different policies.

Incorporating qualitative data into the model was another discussion focus. This topic is aligned with one of the great challenges listed by Elsawah et al. (2020). Qualitative data usually provides a unique context for a specific case study and represents the sources of conflicting interests. For example, qualitative fish data were available from tribes beginning in the 19th century, and the number of fish has a direct linkage with the livelihood of tribes. One participant commented on this topic: "Tribes are definitely in a 'deficit' position .... [Both] invasive species or additional human encroachment into floodplains threaten the fish survival. If you

or any model want to represent the tribe's interests, I think you have to ask questions that [are] going to be very uncomfortable (and difficult) for the region to address [them] ...."

Results of Interactive Gaming

The outcomes of the activity completed in the fourth part of the workshop are shown in Fig. 3. The suggested investments focused on the water and environmental sectors, with minimal investment in energy. Also, most suggested investments were located in the main stem of the Columbia River, downstream of the Grand Coulee Dam. A relatively small number of workshop participants might have influenced the results, and they did not represent the comprehensive stakeholder list. For example, representatives from all states were not present, only one tribe was invited, and most importantly, there were not any participants from Canada. However, the aftergame discussion in the workshop confirmed that this result was realistic and shows that the focus of FEWE management in the CRB has shifted from hydroelectric power and flood control to ecosystem management and restoration (Allen 2019). Tribes and environmental groups have called for ecosystem functionality to be listed as a third purpose of the treaty, with equal importance to hydropower production and flood risk management (Stern 2019). During the discussion of incorporating qualitative data in the model, participants mentioned that cultural values might also influence investment decisions. For example, fish conservation is a religious belief of tribes because "human beings and animals should take care of each other since they made a deal with the creator." This belief would drive them to allocate financial resources to water and environmental sectors. These opinions are reflected in the results of our role-playing game for basin investments.

Survey of Resident Opinions

We present our analyses for the survey results and summarize them in three subsections: "Survey Results Statistics," "Single Sector Sustainability," and "Cross-Sector Sustainability Comparison."

Survey Result Statistics

The sociodemographic categories of respondents are shown in Fig. 4. In this study, we summarize the survey statistics, and the detailed questionnaire can be found in the Supplemental Materials. Most respondents were female (73.89%) and Caucasian or white (84.73%). The mean age in our sample was 40–49 years, and most respondents do not have a bachelor's degree. The mean household income among respondents was between USD 40,001 and USD 60,000 (CAD 52,001–78,000). To explore the human dimension of the FEWE nexus in the CRB, respondents were split into groups

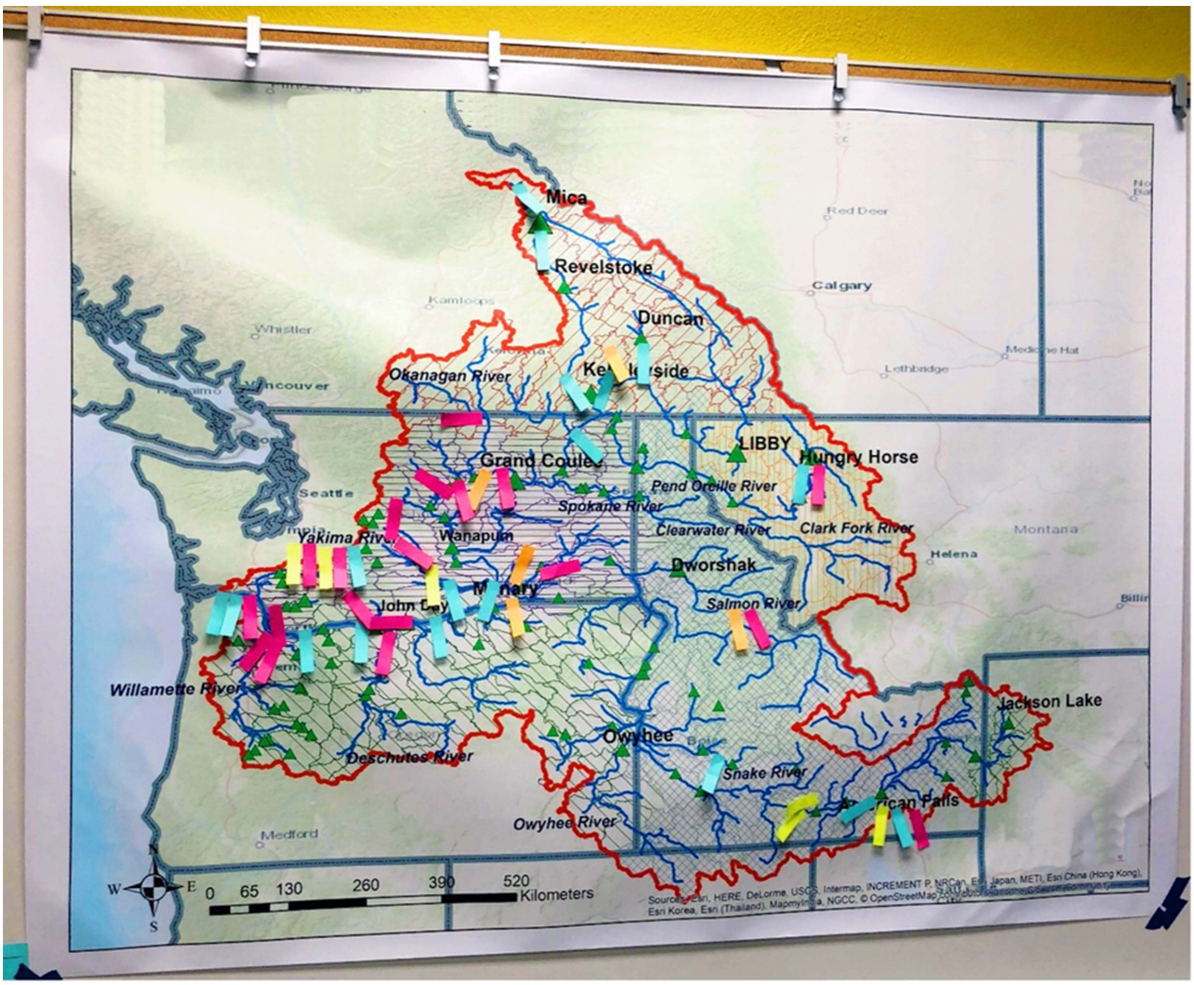

Fig. 3. Photo showing results of hypothetical basin-wide investment activities from workshop participants. Different sectors are represented. The location of the page markers corresponds to the relative location of investment. [Map sources: Esri, HERE, DeLorme, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), MapmyIndia, NGCC, © OpenStreetMap contributors, and the GIS User Community.]

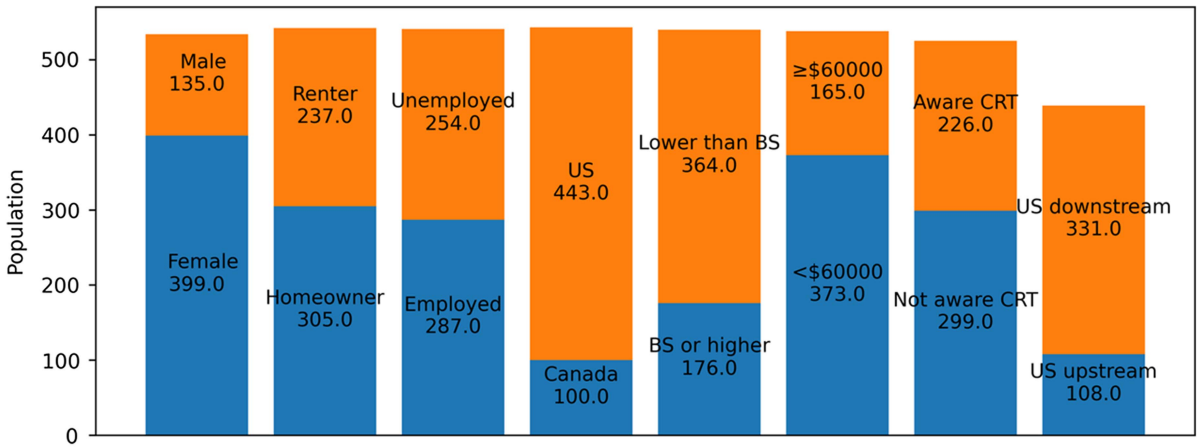

Fig. 4. Sample size of different sociodemographic categories. BS = bachelor's degree and CRT = Columbia River Treaty.

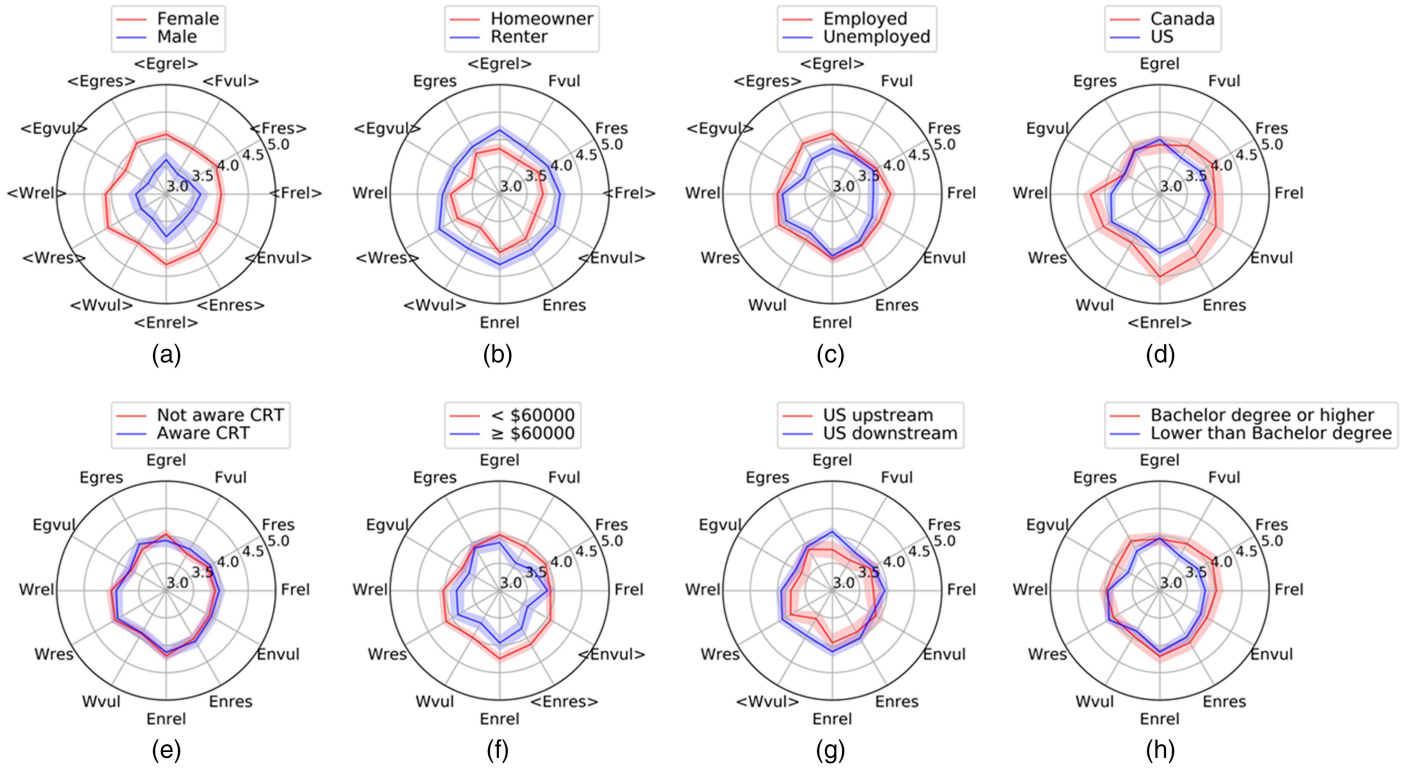

Fig. 5. Level of support for each aspect of sustainability: (a) gender; (b) homeownership; (c) employment; (d) nation; (e) CRT; (f) income; (g) US location; and (h) education. For clear reading, the original scale of 1–7 is zoomed to a scale of 3–5. Prefixes F-, En-, W-, and Eg- represent food, environment, water, and energy, respectively. Suffixes -vul, -res, and -rel represent vulnerability, resilience, and reliability, respectively. For example, Fvul = food vulnerability, Wres = water resilience, and Egrel = energy reliability. Solid lines represent mean values, and bands represent the standard error of the mean for corresponding groups in the legend. Brackets, <>, indicate a significant difference on specific policy; $p < 0.05$.

according to their different sociodemographic statuses in the following analyses.

Single Sector Sustainability

Fig. 5 shows detailed t-test results, with $p < 0.05$, which represent support for each aspect of sustainability from different groups. Solid lines represent the mean values, and bands represent the standard error of the mean. Fig. 5(a) shows significant differences between females and males in supporting sustainability policies. Females are more supportive of all policies related to FEWE sustainability in this study. This result was aligned with many previous studies (Glass et al. 2016; Johnsson-Latham 2007), which showed that females are more aware and concerned about sustainability issues than males. For example, Vernooy et al. (2006) pointed out that active and meaningful participation by females in the decision-making process regarding the use and management of natural resources is important. Yang et al. (2018b) also discussed how gender issues crossover with natural resources management (e.g., ecosystem services), and they highlighted that females prioritize supporting ecosystem services, like habitat conservation and sustainability.

Fig. 5(b) highlights different opinions of residents who are homeowners and renters. Renters maybe are more likely to support

policies about food reliability, energy reliability and vulnerability, water resilience and vulnerability, and environmental vulnerability. This may be because homeowners have more payments, such as property tax, real estate and legal fees, and mortgage interest, than renters (Fowler 2019). We hypothesize that homeowners might perceive that improved sustainability policies in the survey might increase state and province property taxes. Therefore, homeowners may be less willing to spend extra money on sustainability policies because these policies could negatively affect their personal finances. However, this hypothesis requires testing in future studies.

While gender and homeownership are the most significant factors that affect residents' opinions on almost all FEWE policies, other demographic factors will also affect how the general public supports FEWE policies but with more specific effects. Fig. 5(c) shows that employed people are more concerned about energy sustainability. This is echoing the concept that emphasizing employee contributions to sustainability goals has positive advantages for both the sustainability and profitability of companies, and it can change the way employees think and work to invest themselves in such efforts (Eccles et al. 2012). There is almost no difference between Canadians and Americans except for the policy about environmental reliability [Fig. 5(d)]. This result is aligned with previous studies that show that Canadians consider environmental problems in their top three priorities and strongly support environmental policies (Environics Institute for Survey Research 2018). The majority of people in BC believe economic growth should not jeopardize wild-salmon habitat, and a desire for new laws to strictly enforce salmon protection is combined with a willingness to pay higher taxes (Hume 2018). Household incomes only affect a resident's opinion on environmental resilience and vulnerability [Fig. 5(f)], and our results align with the findings by Cottrell (2003), which show that income is negatively related to environmental concerns. Residents from the US downstream region show stronger support for water vulnerability policies [Fig. 5(g)]. This may be due to a higher probability of downstream pollution. Finally, there were no significant differences in priorities based on education levels and knowledge of CRT [Figs. 5(e and h)].

We also conducted a correlation analysis to examine how opinions about sustainability in one sector were related to sustainability in other sectors. Based on different sociodemographic characteristics, including gender, household income, education level, and others, we explored correlations among different sectors in sociodemographic groups and visualized the results in Fig. 6. All correlations were significant at the $p < 0.001$ level. Darker colors indicate higher correlated values. In general, water–energy correlations were the highest, which was expected because 80% of the Pacific Northwest electricity comes from CRB dams. The highest water–energy correlation in our results was also observed in a previous survey of American adults (Portney et al. 2018). This study showed that people exhibited a greater understanding of the water–energy nexus than either the water–food nexus or the energy–food nexus. The correlation between food, energy, and water sectors and the environment were all relatively low, which might indicate that tradeoffs between environmental protection and resource use (e.g., modern agriculture uses many fertilizers for food production, and excess fertilizer could contaminate fish habitats; cheap and clean hydroelectricity from dams could fragment natural fish corridor) are unclear to local residents. There is a geographical difference in this correlation observed for the US upstream and the US downstream. Two upstream states in the US (Montana and Idaho) showed a strong correlation between environmental and the other three sectors compared to two downstream states (Oregon and Washington). This is likely because downstream states have recently undertaken efforts to improve the aquatic environment by modifying dam operations (Bureau of Reclamation 2020). Therefore, tradeoffs between the environment and the other three sectors are less obvious to residents.

Another major geographical difference occurred in the correlation between energy and environment between Canada and the US. Canada showed a significantly lower correlation in this pair compared to the US. According to the Columbia River Treaty—2019 Community Meetings Summary Report (British Columbia 2019), although local Canadians are concerned about the ecosystem and fish population, the connection between dam operation for hydropower and the impact of aquatic ecosystems has been less acknowledged in several community meetings. However, the debate of dam operation for hydropower or the ecosystem is a popular issue in several public meetings in the US (USACE 2020).

Cross-Sector Sustainability Comparison

We ranked different aspects of sustainability to compare resident priorities using section three of the survey; the results are shown in Fig. 7. For reliability, people were most supportive of policies impacting the food and water sectors; the food sector was always ranked first, and energy policies were ranked last. For resilience and vulnerability, people were most supportive of policies related to the water sector, while policies related to the environment were ranked last.

In general, these results suggested that people rank food and water policies higher, which was a fairly consistent observation, regardless of the respondent's gender, nationality, education level, household income, housing status, employment status, or awareness of CRT. Gantla et al. (2015) indicated that people in the Pacific Northwest are generally aware of the higher risk of food shortages and crop failures due to climate change. Therefore, the focus on food and water policies by residents in the CRB might reflect this knowledge. Although studies show that fish populations have recently declined due to multiple long-term factors, including dam barriers and loss of habitat, the negative effects of sporadic natural hazards are much smaller than human effects on the fish population. Also, declines in fish populations are not encountered by most people in their daily lives, so it might not be a general concern. Following this logic, Fig. 7 shows that environmental issues in the CRB usually rank as a lower priority for residents.

Fig. 7 shows higher resident support for policies to enhance environmental reliability than policies to enhance energy reliability. In the CRB, hydroelectric energy generation by multiple dams causes several environmental issues. Research showed that fish populations have dropped from 130,000 to less than 10,000 in a span of 70 years in a tributary of the CRB, Snake River basin (Helmer 2018). Existing dams threaten future fish population growth, and they can potentially increase the risk of extinction (Helmer 2018). This evidence may be why people pay more attention to environmental reliability than power reliability. Regarding resilience and vulnerability, we observed a similar pattern of ranking the four sectors across all demographic groups. People usually ranked water as the highest priority, followed by food and then by energy and the environment, with only a few exceptions. For example, Canadians ranked environmental resilience higher than energy resilience; people who were aware of the CRT ranked food resilience higher than water resilience; and people located in the US upstream ranked energy resilience as the second-highest priority.

Two things are worth emphasizing in this study. First, rankings for resilience and vulnerability were similar across all demographic groups; this may be because resilience and vulnerability are closely linked to natural hazards. Therefore, even though we used plain language questions in the survey, it is possible that the respondents do not truly understand the difference, which results in a similar

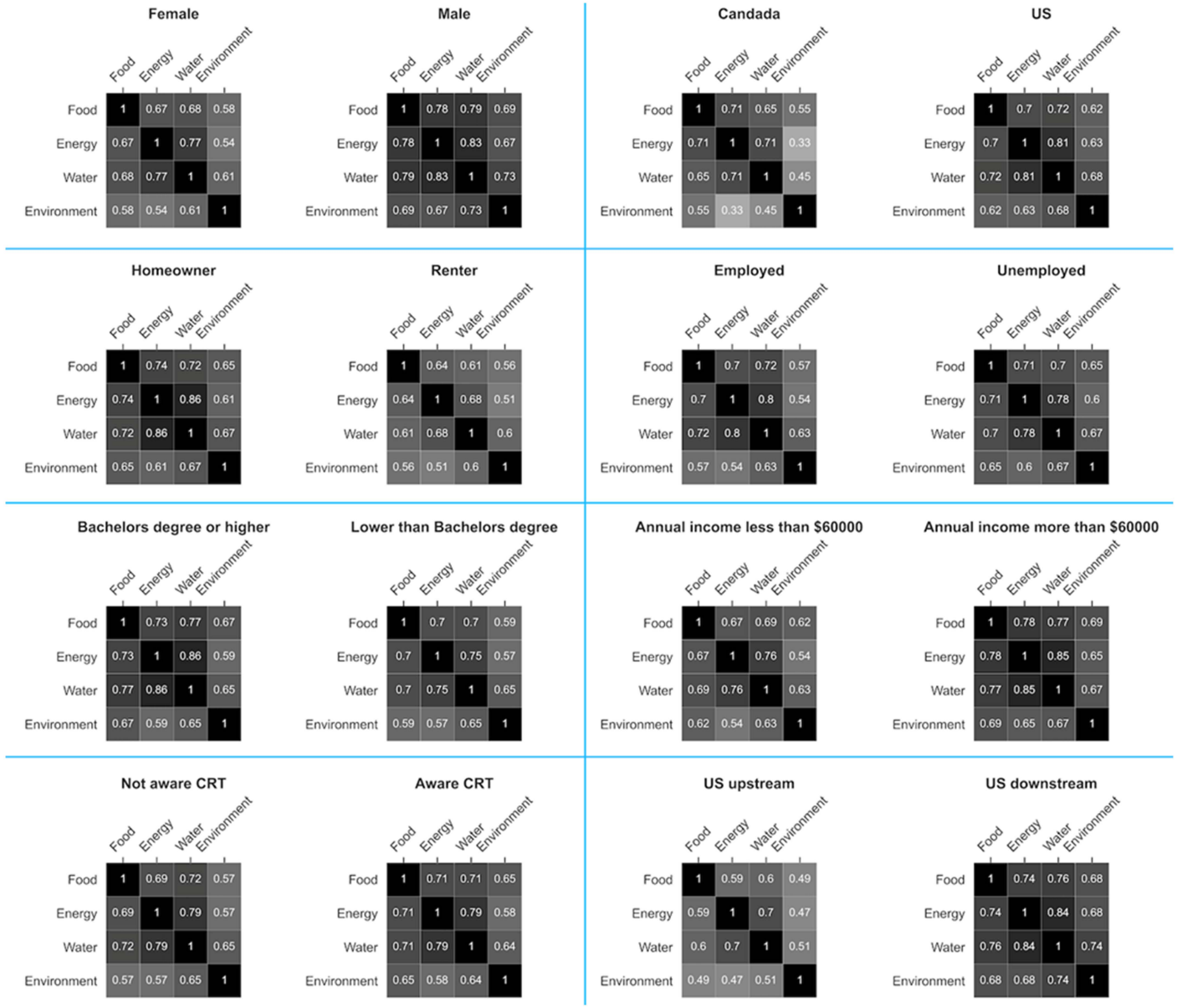

Fig. 6. Correlation analysis of FEWE sector by different sociodemographic statuses. Darker shading indicates two sectors have a higher positive correlation.

ranking. Second, natural hazards, such as floods or storms, can result in the loss of life and destruction of property and infrastructure. These impacts are easily recognized and frequently reported in the media. Food and water are two essential resources for people's life after natural hazard impacts, so it is not surprising that they were given the highest rankings. While natural hazards may have indirect effects on people via direct effects on the ecosystem or environment, indirect effects are not highly recognized because they are less visible and more challenging to evaluate (Talbot et al. 2018). Therefore, prioritizing the energy sector's resilience and vulnerability over that of the environmental sector is a consensus among residents.

These survey results are helpful for bridging gaps between policies and public opinion. Norton (2002) emphasizes that public involvement and social learning in the adaptive management process are critical for policy implementation. Policymakers should incorporate public input from local groups and residents, taking their hopes, concerns, and values as a starting point in the search for management goals. Furthermore, our survey results reflect local resident concerns, which can potentially be considered in CRT negotiations. For example, residents show stronger support for policies related to food and water. This may inform the negotiating positions of the US and Canada. They can consider water requirements for agriculture use or irrigation in the treaty negotiations. Canada has suggested that the US receives other benefits from the treaty that are not accounted for in the current agreement, such as benefits to US irrigation, navigation, and fisheries (British Columbia 2019).

Integration of Institutional and Residential Aspects

We will try to synthesize lessons learned from both the workshop and survey results in this section. First, the lack of interagency coordination highlighted in the workshop could result in lower public trust in the government. This impact will be most obvious during a natural disaster. For example, when a snowstorm simultaneously interrupts power and water supplies, different agencies will try to restore their supply using their own resources. These inefficient

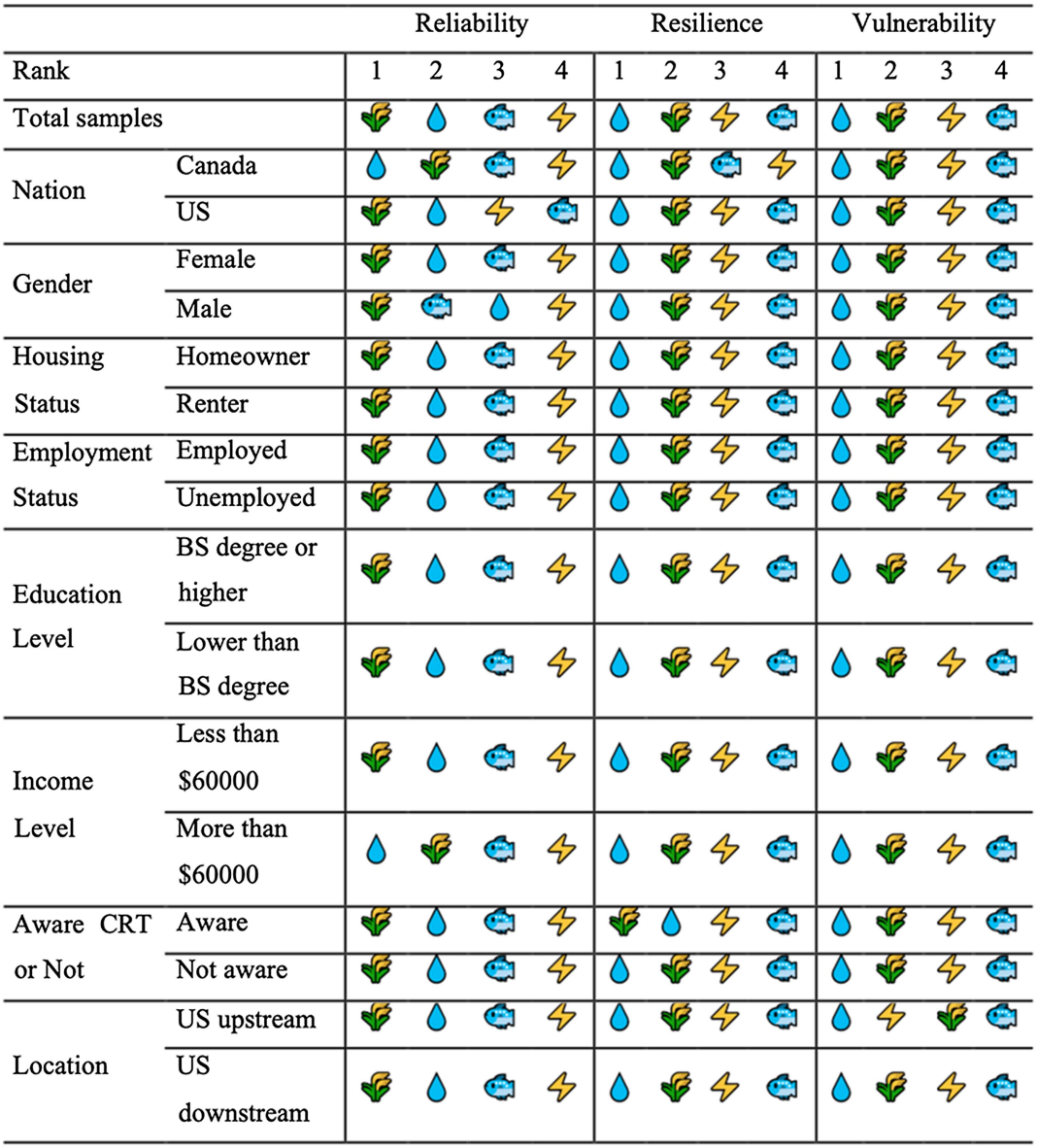

Fig. 7. Priorities of metrics for each group: corn represents food sector; lightning bolt represents energy sector; water droplet represents water sector; and fish represents environment sector.

and uncoordinated decisions might result in a delay in the recovery process, reducing resident confidence in the government. Second, the importance of communicating with residents was emphasized in the workshop. We observed that some progress was made during the CRT renegotiation. Solicitation of public opinions began in the US in 2018, with the hosting of several town hall meetings and online/in-person public forums (US Department of State 2021). Also, websites were set up by the Bonneville Power Administration that enables the general public to provide feedback (Bonneville Power Administration 2021). All of these activities are evidence of government agencies hearing the voices of local residents to obtain unique information on local conditions and improve the quality of decision-making (Yearly et al. 2003; Newig 2007; Berry et al. 2019). To some extent, these attempts will bridge the gap between the institutional and residential aspects and reduce public resistance in implementing FEWE policies (Kythreotis et al. 2019). Finally, surveys and interviews are potential methods to translate qualitative data from the workshop, such as cultural values and religious beliefs, into semiquantitative data that can be input into a model. For example, we can conduct an interview with elders from different tribes and ask them a question such as the following: compared to what you saw when you were a child, how do you feel the fish population has changed? Then, a similar Likert scale from 7 (dramatically increased) to 1 (dramatically decreased) can be used, and these interview results could serve as a reference for fish population change in follow-up model building.

Discussion

Comparing CRB Results with Those from Other Transboundary River Basins

These results on the human dimension of the FEWE nexus in the CRB provide promising opportunities for comparison with similar results for other transboundary river basins. Khan et al. (2017) applied a similar role-playing game in three transboundary basins: the Indus, Mekong, and Niger. They collected results on the institutional

aspect. In the Indus, their results showed that stakeholders would generally invest in the energy sector upstream and the food and environment sectors downstream. In the Mekong, the energy sector received greater investment upstream, and the environment sector received investment in both the upstream and downstream. In the Niger, stakeholders were more likely to invest in the food and water sectors across the basin and the energy sector upstream.

Comparing the results from these four transboundary river basins, there were similarities between the CRB, Indus, and Mekong. The environmental sector attracted more attention downstream in all of these basins, likely because most fishery habitats are located in the middle and lower basins, such as Tonle Sap Lake (largest freshwater lake in Southeast Asia) in the Mekong and the Indus River Delta (critical habitats of Indus River dolphins) in the Indus. However, over the last few decades, dams along these rivers have contributed to the destruction of fish habitats and population reductions. A decline of more than 50% in the total population of Indus River dolphins has resulted from individuals being trapped in parts of the river due to dam construction (Thomas 2015). Similarly, dam construction has caused a great loss of fisheries in the lower Mekong basin: approximate reductions of 280,000 and 180,000 tons of fish capture have been observed in Cambodia and Vietnam since 2015 (Yoshida et al. 2020).

There are also clear differences between the CRB and the other three transboundary basins. Relative to the CRB, stakeholders in the Indus, Mekong, and Niger basins would like to increase investment in the energy sector upstream, especially in hydropower. This is expected because many developing countries in these three basins still suffer from energy shortages. For example, the Diamer–Bhasha dam on the Indus River could potentially provide 4,500 MW of electricity for the national grid. This could serve 80 million people in Pakistan who currently lack reliable electricity (Ansari 2009). These shortages make hydropower an attractive, clean energy source. In addition, dams also provide water storage, irrigation, and flood control. Therefore, it is not surprising that the energy sector attracts a significant amount of investment in the upstream areas of the Mekong, Niger, and Indus basins.

Limitation and Future Work

We highlight several limitations of our study and potential future works in this section. To make the definitions of reliability, resilience, and vulnerability accessible to residents, some hypothetical policies related to corresponding FEWE definitions were used in the survey as scenario questions. Answers to those questions could be biased by the hypothetical policies in the study. To overcome this limitation, future studies can use a pilot test with open-ended questions to identify resident perspectives on policies related to FEWE reliability, resilience, and vulnerability. Then, closed-ended questions can be developed to include the most suitable policies. Second, because we conducted the survey online, we restricted our survey participants to those who have Internet access, which could lead to sampling bias like self-selection bias and nonresponse bias. Even though we did not have restrictions on gender, most respondents were women, which may indicate that women are more likely to take part in an academic study. In this case, gender may not be accurately represented, and we should be cautious when reviewing the results. To reduce sampling bias, future studies can use print questionnaires that are mailed to residents. The combination of both electronic and print methods can help us ensure better sample coverage and reduce these biases.

Finally, combining the workshop and survey results will enable us to develop a new model following the concept of participatory modeling, which is listed as one of the great challenges of coupled human-natural system modeling by Elsawah et al. (2020). We plan to develop an agent-based model (ABM) (Yang et al. 2009; Hyun et al. 2019) that defines local water users as well as policymakers in the basin as *agents*. Connecting with the existing models mentioned in the "Result" section, this ABM will have a food module (irrigation), an energy module (GENESYS), and a water/environment module (MOSART). Agents will make their decisions based on specific rules derived from the workshop and survey results. For example, we will prioritize water use for different water-use agents based on the ranking results in the survey. We can also simulate various learning and adaptive processes to update agent decisions and mimic the adaptive management highlighted in the workshop. By integrating institutional and resident aspects in an ABM framework, we can demonstrate a possible path to implement efficient FEWE nexus policies with institutional cooperation and public support. This procedure can provide a complete picture of the human dimension of the FEWE nexus and compliment studies that focus on the physical and technological dimensions. This ABM framework is potentially transferrable to other transboundary river basins in the world that face similar challenges in the FEWE nexus, such as the Indus River in South Asia (Yang et al. 2016a), the Mekong River in Southeast Asia (Keskinen et al. 2015; Keskinen and Varis 2016; Yu et al. 2019), and the Niger River in West Africa (Khan et al. 2017; Yang et al. 2018a).

Conclusion

The human dimension of the FEWE nexus has generally been ignored in previous technical or physical studies. This paper explores the human dimension of the FEWE nexus in transboundary river basins from both institutional and residential aspects, using the CRB as an example. Stakeholders in the workshop (institutional aspect) offered their perspectives on different aspects of sustainability in the FEWE nexus. Workshop participants agreed that common metrics facilitate meaningful cross-sector comparisons among FEWE sectors. Participants also identified institutional barriers and indicated that adaptive management and interagency cooperation were key components of future FEWE nexus management. Finally, open communication channels between government agencies and residents were also emphasized in the workshop. We also conducted a survey (residential aspect) to investigate the perspectives of residents in the CRB about FEWE sustainability. Our results showed that sociodemographic status affects the level of support for sustainability in a specific sector. For example, females and renters showed stronger support for sustainability in all FEWE sectors. Residents had different preferences for sustainability in all FEWE sectors, and policies related to the food and water sectors received more attention from residents.

Combining the knowledge from both the workshop and survey can provide a complete picture of the human dimension of the FEWE nexus and enable us to develop a new model using the concept of participatory modeling. This new model can potentially compliment studies that focus on the physical and technological dimensions and highlight the institutional and residential aspects of the FEWE nexus.

Data Availability Statement

Following the Institutional Review Board's procedure, the raw data of the workshop (recording and meeting minutes) and the survey (actual responses) are not publicly available due to the privacy of participants. The survey questions and high-level statistics are

given in the Supplemental Materials, and no other data was used in this paper.

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Supplemental Materials

Survey questions are available online in the ASCE Library (www.ascelibrary.org).

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