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The economic value of groundwater in Obama

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ABSTRACT

Study region: Obama City has a population of 33,000 and is located in the central Wakasa district, in southwest Fukui Prefecture, Japan. Obama's groundwater resources are supported by the Kitagawa (38 km^2) and Miniamigawa (17 km^2) river basins. Groundwater is used aboveground year round for commercial and domestic purposes and during winter months to melt snow. Submarine groundwater discharge along the coast supports a nearshore fishery in the region.
Study focus: Results from a choice-based analysis suggest that residents are willing to pay on average JPY 565 per month to maintain the drinking water function and aquatic resource function of groundwater in the Fukui region. However, the static approach is not appropriate for estimating the net present value of the resource, i.e., the discounted net benefit aggregated over time. We therefore develop and propose a dynamic framework capable of assessing tradeoffs between the various water uses as scarcity increases or decreases in the future.
New hydrological insights for the region: Marginal willingness to pay for water in Obama is currently low because freshwater is abundant. We expect that future optimal water extraction patterns will depend most on trends in energy costs, climate change and demand growth.

1. Introduction

Worldwide, freshwater is important not only for direct consumption but also for its role in the production of a variety of goods and services. For example, water is used for cooling nuclear reactors and as an input for the production of energy via hydroelectric processes. Freshwater also is essential for the production of food, including crops and livestock. Recognizing these synergies and identifying tradeoffs are key components of water-energy-food (WEF) nexus research (Taniguchi et al., 2013; Loring et al., 2013; Giampietro et al., 2014). In this study, we focus on Obama City, Japan, where groundwater is used directly for domestic and commercial consumption and for melting snow. Stored groundwater also provides an indirect benefit: submarine groundwater discharge (SGD) from the aquifer supports the nearshore ecology, including a locally important fishery. Using this case study, we document some common challenges that arise when undertaking WEF research and outline an example of an integrated approach that combines multiple modes of analysis to overcome those obstacles.

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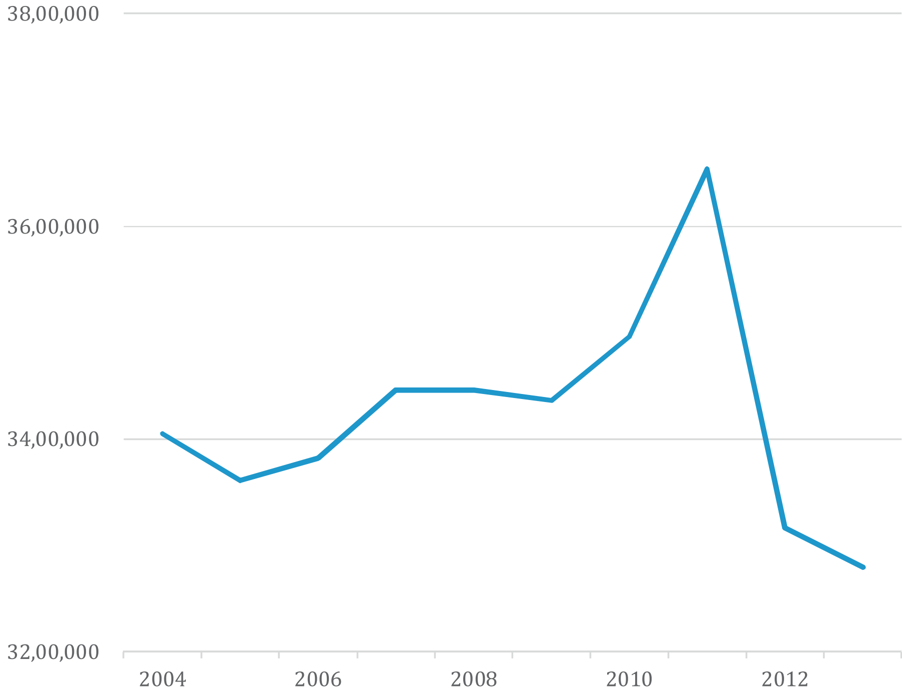

Fig. 1. Groundwater supplied in Obama (m^3/year), 2004–2013.

1.1. Groundwater use in Obama

Obama City has a population of 33,000 and is located in the central Wakasa district, in southwest Fukui Prefecture, Japan. Obama is south of Wakasa Bay, which is included in the area's "Quasi-National Park". Fishing used to be the main industry in Obama, likely due, in part, to the fact that the mixture of cold and warm currents in Wakasa Bay provides fertile fishing grounds. In ancient times, Obama became known as "Miketsukuni," supplying food to the imperial court. More recently, the city's economy has shifted largely from fishing to tourism. Nevertheless, groundwater has always been an important resource for the Obama area, for domestic, municipal, industrial, and limited agricultural use, as well as having a cultural and historical significance. During the Omizu-okuri (Water Carrying) Festival, which is held on March 2nd every year, water is drawn from the Onyu River and presented to the principal image of the temple. This annual event dates back more than 1200 years.

There are two primary river basins supporting Obama's groundwater resources. The main Kitagawa river basin has an area of 38 km^2 and a thickness of 62 m. With a porosity of 0.3 the retention ability has been estimated at 700 million m^3. The smaller Minamigawa river basin has an area of 17 km^2 and a thickness of 43 m. With a porosity of 0.3 the retention ability has been estimated at 200 million m^3. Groundwater flux for both river basins was estimated using a standard water balance analysis (D. Tahara, personal communication). For the Kitagawa and Minamigawa river basins, flux is estimated to be between 31,225–108,305 m^3/day and 16,657–17,491 m^3/day respectively.

Groundwater in Obama is used for multiple purposes. The largest use is domestic and commercial, at approximately 15,300 m^3/day. Another 4000 m^3/day is used in winter months for melting snow. Obama City is currently pumping only a fraction of their total water resource. Fig. 1 shows the total annual groundwater supplied over the last decade, which after peaking in 2011 has recently been decreasing, possibly due to population decline. Fig. 2 illustrates the local population served by this same water resource, which also experienced a peak between 2010 and 2011 but has been declining since. Fig. 3 shows the distribution of municipal tap water pumping at various locations. The seasonal spikes correspond to increases in pumping during the winter months to meet snow-melting demands.

1.2. Relationship between the groundwater resource and nearshore ecology

SGD into the bay supports the nearshore ecology because freshwater flowing into the ocean affects the temperature and salinity of coastal waters, which in turn affects the growth and health of keystone species such as algae that fish and other sea creatures depend on for survival (Taniguchi et al., 2002). Since the flow of SGD depends on the volume of stored groundwater, decisions to extract groundwater for aboveground uses indirectly affect aquatic resources that may be important to residents for cultural, subsistence, or commercial reasons.

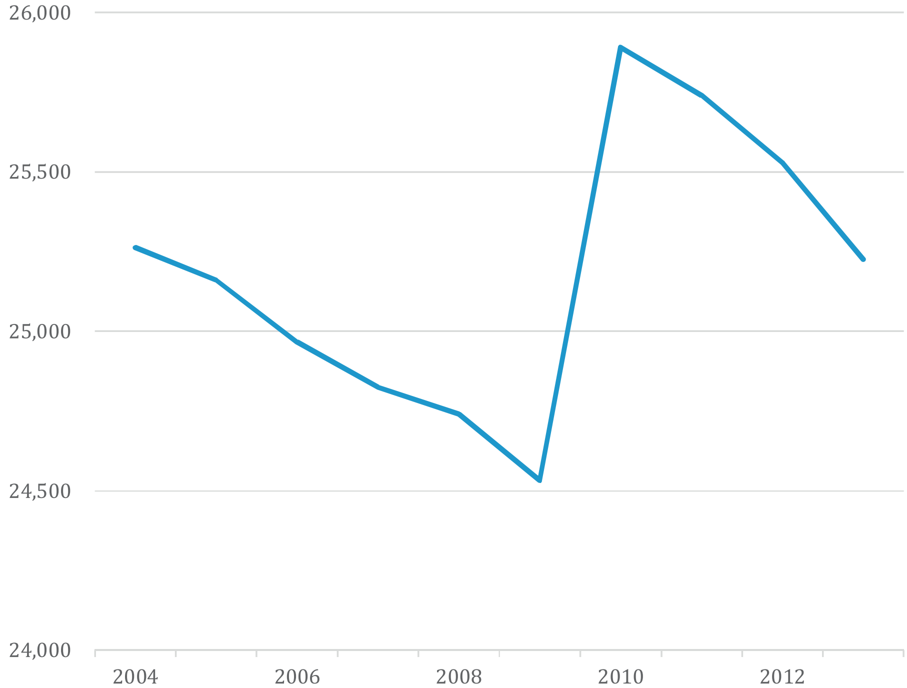

Fig. 2. Population served by the groundwater resource in Obama, 2004–2013.

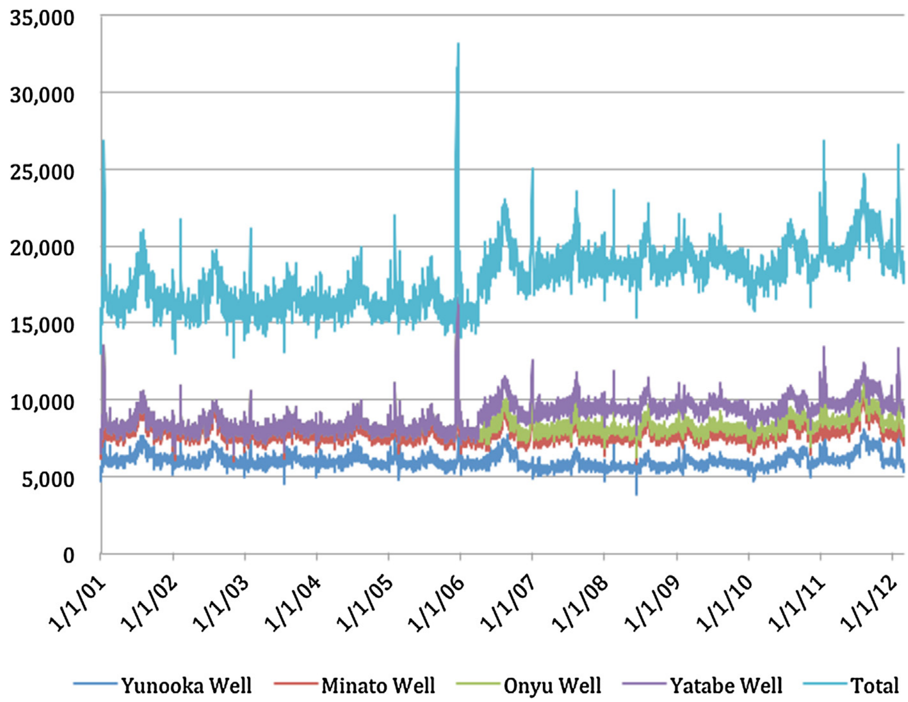

Fig. 3. Municipal groundwater pumped in Obama by well (m^3/day), 2001–2012.

In July 2014, the project research team from the Research Institute for Humanity and Nature[1] conducted a field survey at two sites in Obama with different levels of SGD. The high-SGD site (East) had more total fish and species diversity (Utsunomiya et al., submitted). The story was similar for shellfish; the high-SGD site was home to more and diverse shellfish. When data

[1] http://www.chikyu.ac.jp/rihn_e/project/R-08.html#

Table 1
Policy characteristics.

Attribute	Alternatives
Abundance of aquatic resources	Plentiful, average, scarce
Use of underground water as drinking water	No change, reduce somewhat, substantially reduce
Use of dam water as drinking water	Increase, no change
Melting snow using electricity	Increase, no change
Tax burden	JPY 1000, 2000, 3000, 4000 per person per month

Source: Research Institute for Natural Capital Co., Ltd. (2014)

collection is complete, the next step will be to estimate a relationship between groundwater levels, SGD, and fish counts. Ultimately, the objective is to develop a model that formally incorporates the tradeoffs between aboveground water-use and maintenance of SGD.

1.3. Willingness to pay for groundwater in Obama

In March 2014, the Research Institute for Natural Capital Co., Ltd. (2014) designed and conducted an online survey to assess the value of groundwater in the Reinan region of Japan's Fukui Prefecture. The survey included 23 questions that fell into one of eight categories: seafood consumption, everyday groundwater use, general knowledge of groundwater and dam construction, opinions regarding groundwater and dam construction, preferences among hypothetical water policies (choice experiment), reasons for opposing dam construction (if applicable), household characteristics, and open-ended comments related to any topics covered in the survey. The online survey was disseminated to residents in the towns of Obama, Tsuruga, Mihama, and Wakasa. The panel of participants was obtained from the online survey company Macromill, and an equal number of respondents were selected from each of three age categories: 20–39, 40–59, and 60+. In total, 184 responses were collected.

The survey results suggest that many residents are not aware of the important role that groundwater plays in supplying freshwater to the region for everyday use. For example, nearly 40% of survey participants reported having never heard that municipal water in the region comes from underground water sources, despite the fact that 70% of municipal use in Fukui Prefecture is supplied by groundwater. However, over 90% of respondents agreed that groundwater is a precious resource that should be used sustainably, and more than 70% agreed that the status of groundwater in the region should be scientifically monitored. Thus, while participants were in agreement that groundwater resources are valuable, they may not fully understand the extent to which groundwater is already being used in Fukui. A perception of groundwater abundance, whether an accurate reflection of reality or not, likely leads to a lower perceived value of the resource.

Survey participants were asked to select from alternative hypothetical future groundwater policies the option they agreed with most. By varying policy attributes for each scenario (Table 1), this type of choice-based conjoint analysis provides a means for calculating the marginal willingness to pay (MWTP) for each attribute. Results from a conditional logit model (McFadden, 1973)[2] indicate that residents in the Reinan region as a whole positively value groundwater for drinking and for its role in maintaining the aquatic nearshore ecology (statistically significant at the 1% and 10% levels respectively). When converted into monetary values, residents are willing to pay on average JPY 177 and JPY 388 per month in additional taxes to support the aquifer's aquatic resource function and drinking water function respectively. A detailed discussion of all of the estimated model's results can be found in the Research Institute for Natural Capital Co., Ltd. (2014) report.

1.4. Using the survey results to inform a dynamic optimization model

The analysis described in Section 1.3 provides an estimate of residents' willingness to pay to maintain the groundwater's ability to both provide drinking water and support interrelated aquatic resources. While a useful starting point for valuing water in the region, the MWTP of JPY 565 per month is reflective of the current usage, state of the aquifer, and understanding of the resource. If groundwater becomes scarcer in the future (e.g., due to climate change, higher demand for water) the marginal opportunity cost of using the resource rather than leaving it in situ should also increase. In that case, the marginal benefit (equivalently the MWTP) for an additional unit of groundwater must rise apace if the resource is being managed optimally. In summary, if the water resource is expected to become scarcer in the future, the MWTP for that resource will not remain constant.

Another limitation of the choice-based approach is that it, by definition, is based on stated preferences. That is, respondents are asked to choose from a number of alternatives, without any consequences for that choice. If, for example, a respondent believes that protecting the groundwater resource is what he/she should choose, a policy option may be selected to reflect that preference even if he/she really would not be willing to pay the proposed fee included with that option. Therefore,

[2] The conditional logit model or conditional logistic regression is used to address discrete choice problems wherein the choice among alternatives is a function of the characteristics of the alternatives. In this case, MWTP is estimated by examining how respondents' choices among hypothetical groundwater policies (alternatives) vary, given that each hypothetical policy has different attributes (characteristics).

revealed preference methods, wherein preferences are inferred based on actual choices in a market, are often preferred when feasible. In the case of Obama, if residents paid a unit price to a public utility for groundwater, a demand curve could be inferred from price-quantity data. Since that is not the case, however, the MWTP survey may be the next best alternative.

In Section 2, we discuss how an economic optimization model could be designed to include the (currently missing) temporal dimension in the analysis. The survey results would still be necessary to establish a contemporaneous MWTP curve, which would then serve as an input to the benefit portion of the dynamic optimization problem's objective function. Although the focus is on one particular case study, WEF nexus problems are often just as or even more complex, thus requiring creative approaches involving multiple analytical tools.

2. Methods

Because groundwater resources are typically recharged and pumped over relatively long time horizons, efficient management requires the inclusion of a temporal dimension. Optimal temporal allocation of water has been studied for many decades (Burt, 1967; Brown and Deacon, 1972).[3] More recently, standard hydrologic-economic models have been extended to allow for stock-dependent extraction costs and discharge (Krulce et al., 1997), spatially heterogeneous users (Pitafi and Roumasset, 2009; Brozovic et al., 2010), and stock-to-stock externalities (Pongkijvorasin et al., 2010). The current study is closest in nature to the Pongkijvorasin et al. (2010) study, which developed a framework to determine optimal groundwater withdrawals when a minimum growth constraint is imposed on a nearshore keystone species that depends on SGD. In the remainder of Section 2, we develop a framework to optimize groundwater withdrawals across two aboveground uses, while accounting for the relationship between groundwater stock and the nearshore ecology as it relates to a fishery.

2.1. The dynamic optimization framework

To understand the tradeoffs involved in allocating groundwater to different uses in Obama, we develop a dynamic economic-hydrological-ecological framework. The head level (h), or the distance between mean sea level and the top of the groundwater lens, is approximately proportional to the volume of freshwater stored in a coastal aquifer, provided that the transition zone at the freshwater–saltwater interface is very small. The head level increases or decreases over time depending on the relative sizes of inputs and outputs to the hydrological system. Assuming no return flow from overland use of water for irrigation and snow melting, we can assume that groundwater recharge (R) is exogenous, and is determined entirely by precipitation. Outflows from the system include extraction for domestic/commercial use (q_D), extraction for melting snow (q_S) and SGD(h), which is an increasing function of h, i.e. SGD' (h) > 0. In summary, the head level evolves over time according to the following state equation:

$$\dot{h} = R - (q_D + q_S) - \mathrm{SGD}(h) \quad (1)$$

Note that in order for the system to be in a steady state, inflows and outflows must be equal such that $\dot{h} = 0$.

As previously discussed, the water resource is linked to the nearshore ecology via SGD. Fish productivity in the nearshore environment depends on SGD because algae, a primary source of food for the fish, tend to thrive in environments with higher SGD (lower temperature and salinity). Consequently, fish growth (G) is modeled as a function of both the current stock or population of fish (X) and the head level. Analogous to Eq. (1) for the aquifer, the population of fish in the fishery evolves over time according to its own state equation:

$$\dot{X} = G(X, \mathrm{SGD}(h)) - q_X(E, X) \quad (2)$$

The fishery is in a steady state only if growth is exactly offset by fish harvest (q_X). The harvest in a given period depends on both the current stock of fish and the fishing effort exerted (E).

The benefits from domestic/commercial water consumption (b_D), measured for example as consumer surplus or the area under the marginal benefit (MWTP) curve, depend on q_D. The benefits from melting snow (b_S), determined for example by the avoided cost of alternative snow melting methods, depend on q_S. The benefits from fishing (b_X) depend directly on q_X and indirectly on SGD, since fish growth is a function of both the stock and SGD. The method of quantifying fishery benefits will depend on the type of fishing; for example, revenue received may be appropriate for a commercial fisherman, whereas the replacement cost of the catch would be more relevant for a subsistence fisherman. The total benefit to Obama residents in each period is equal to the sum of benefits obtained from the groundwater resource and fishery:

$$B = b_D(q_D) + b_S(q_S) + b_X(q_X) \quad (3)$$

Regardless of end use, the marginal cost of pumping groundwater to the surface (c_W) is a decreasing function of h, i.e. c_W' (h) < 0; as groundwater is depleted, the head level falls and water must be lifted further to reach the surface.

[3] In those studies and the current study, (economically) "optimal" refers to the trajectory or time path of allocations that maximizes the net present value of the water resource.

The marginal cost of fishing effort is c_E. Although the marginal cost of effort is constant, recall that harvest is stock dependent; for a given level of effort, catch is lower when the stock is depleted because search time increases. The total cost to Obama residents in each period is equal to the sum of costs related to use of the groundwater and fishery resource:

$$C = c_W(h)q_D + c_W(h)q_S + c_E E \tag{4}$$

Given per-period social benefits (Eq. (3)) and social costs (Eq. (4)), the economically optimal allocation of resources is determined by maximizing the net present value (NPV) of the groundwater and fishery resources jointly, i.e.

$$\max_{q_D, q_S, E} \int_{t=0}^{\infty} e^{-rt}[B - C]\,dt \tag{5}$$

subject to the state Eqs. (1) and (2) and a positive discount rate, r. If there is more than one aquifer, each will have its own state Eq. (1).

2.2. Data requirements

Operationalizing the framework developed in Section 2.1 will require a large amount of socioeconomic and scientific data, even after allowing for many simplifying assumptions. To begin, hydrological data (e.g., aquifer porosity, dimensions, current head level, etc.) will be needed to construct a relationship between the head and stored groundwater volume. Data on the inputs (recharge) and outputs (SGD, extraction) to the groundwater system will also be necessary to describe the evolution of the head level over time. Because the groundwater resource is linked via SGD to a fishery used by Obama residents, information about the fish stock and growth will be required to quantify the additional water benefits to the fishery. Table 2 summarizes the data requirements. In some instances, the data is not yet available.

Once the hydrological-ecological framework is established, the remaining challenge is to integrate economic benefits and costs generated by various uses of each resource. Estimating the benefits of groundwater used for domestic/commercial purposes requires data on the total quantity consumed, willingness to pay for drinking water, and projected demand growth. Although data is available for sewage fees and quantities, Obama residents do not pay directly for pumped groundwater, making it difficult to estimate a price-quantity relationship. This is where the MWTP survey results can help. An estimate of the MWTP to maintain the drinking water function of the aquifer provides an approximation of the marginal benefit (MB) corresponding to the current rate of extraction. That is, it can be interpreted as a single point on the demand curve for water. If we further assume that the elasticity of demand is constant, then that point can be used to parameterize a demand function of the form $D(p) = Ap^{-\eta}$, where A is the unknown coefficient to be determined and η is the elasticity of demand.

Estimating the benefits of groundwater for snow-melting requires data on the total quantity of water currently being used to melt snow and the costs of alternative methods (e.g., plowing or heating); a dollar value would be assigned to the avoided cost of using potentially costlier alternatives. Lastly, estimating the benefits of commercial fishing requires information on the quantity of fish harvested and the market price of fish. For subsistence fishing, benefits could instead be estimated as the avoided cost of replacing the catch (e.g., the cost of buying the fish at the market).

Estimating the marginal opportunity cost of water for drinking will require data on groundwater pumping costs, which likely depend largely on energy costs in the region. Each fish caught and consumed is associated with a marginal cost of effort, which may be measured as hours fished per week (or some other period of time). Calculating the marginal cost of effort will require information on the opportunity cost of that time, i.e. a wage rate. Costs, benefits, and data requirements are summarized in Fig. 4.

3. Results

The maximization problem (5) can be solved using optimal control, and the corresponding current value Hamiltonian is

$$H = B - C + \lambda[R - SGD(h) - (q_D + q_S)] + \mu[G(X, SGD(h)) - q_X(E, X)] \tag{6}$$

The maximum principle requires that the following conditions hold

$$b'_D(q_D) - c_W(h) - \lambda \le 0 \tag{7}$$

$$b'_S(q_S) - c_W(h) - \lambda \le 0 \tag{8}$$

Together, conditions (7) and (8) imply that if water is being used for both aboveground purposes, then it must be that their marginal benefits are equal to each other and also equal to the sum of the marginal extraction cost and the shadow price or marginal user cost of water; the sum of marginal costs is sometimes referred to as the marginal opportunity cost (MOC). Equivalently, if the MB of a given aboveground use is ever less than the MOC, it should not be used in that period. Otherwise, water could be reallocated from the low MB use to the high MB use to increase benefits without increasing costs. This type of standard arbitrage condition is present whenever considering competing needs for a single extracted resource.

Fig. 4. Costs, benefits and data requirements for economic optimization modeling.

The tradeoff between groundwater use and SGD maintenance is less straightforward because SGD is a function of the stock of groundwater rather than extraction. We can gain some insight by examining an additional necessary condition for Eq. (6):

$$\dot{\lambda} - r\lambda = c'_W(h)[q_D + q_S] + \lambda \mathrm{SGD'}(h) - \mu \left(\partial G/\partial \mathrm{SGD}\right) \mathrm{SGD'}(h) \tag{9}$$

Combining conditions (7)–(9) yields the following:

$$p_i = c_W(h) + \frac{\dot{p}_i - c'_W(h)[R - \mathrm{SGD}(h)] + \left(\partial G/\partial SGD\right) \mathrm{SGD'}(h)}{r + \mathrm{SGD'}(h)}, i = \mathrm{D, S} \tag{10}$$

where p_i, which is equal to the marginal benefit of use i along the optimal path, represents the price that would induce optimal extraction. Typically, when there is no effect on the nearshore ecology, the third part of the second term on the right hand side of Eq. (10) disappears, and a lower head level implies a higher price for either of the aboveground uses; as water become scarcer, optimal extraction is reduced. When SGD has a positive effect on the fishery, however, the MOC is optimally higher for any given head level precisely because that head level provides an additional benefit. The larger the SGD effect, the more conservative optimal water extraction will be.

4. Discussion

Although we do not yet have sufficient data to implement the full optimization model, we can make some inferences based on available information. At the current level of use, groundwater is relatively abundant, and the potential reduction in SGD is not yet a concern. However, future increases in demand for water (e.g., as the tourism industry grows) and threats to the groundwater resource itself (e.g., sea level rise due to climate change) may put upward pressure on resource scarcity, and consequently may lower the optimal groundwater extraction trajectory. At the same time, changes in energy prices may become more relevant as scarcity increases because both groundwater extraction and alternative snow-melting technologies depend on energy. If energy prices rise faster than technological innovation, for example, the net effect may be an increase in pumping for snow-melting (if alternatives are very energy intensive) and a decrease in pumping for domestic use. Whether

Table 2
Parameters and values.

Description	Units	Value
Kitagawa		
Porosity	–	0.3
Area	km^2	38
Thickness	m	62
Retention ability	m^3	700,000,000
Groundwater flow	m^3/day	31,225–108,305
SGD	m^3/day	TBD
Initial head level	m	TBD
Total unit cost of supplying water	¥/m^3	136.31
Energy cost per unit water supplied	¥/m^3	9.81
Domestic/commercial use	m^3/day	15,300
Snow-melting use[a]	m^3/day	4000
Minamigawa		
Porosity	–	0.3
Area	km^2	17
Thickness	m	43
Retention ability	m^3	200,000,000
Groundwater flow	m^3/day	16,657–17,491
SGD	m^3/day	TBD
Initial head level	m	TBD
Total unit cost of supplying water	¥/m^3	136.31
Energy cost per unit water supplied	¥/m^3	9.81
Domestic/commercial use	m^3/day	15,300
Snow-melting usea[a]	m^3/day	4000
Obama City		
Projected population/demand growth	–	TBD
WTP for water	¥/m^3	TBD
Cost of alternatives for snow melting	¥/year	TBD
Aquatic Resource		
Current fish stock	fish	TBD
SGD-fish growth parameter	%/m^3/day	TBD
Fish harvest	fish/year	TBD
Market price of fish	¥/fish	TBD
Fishing effort	Hours	TBD
Fishing wage	¥/h	TBD

[a] Only during winter months (Dec–Feb).

SGD increases or decreases will depend on how the gains from pumping for snow-melting compare to the potential fishery benefits of maintaining SGD.

5. Conclusion

As is the case in many regions around the world, groundwater is an important resource in Obama. It is used aboveground year round for commercial and domestic purposes and is also used to melt snow during winter months. Even the groundwater that discharges into the ocean along the coast is valuable, inasmuch as it regulates temperature and salinity, both of which are important for the survival of algae and other sources of food that nearshore fish depend upon. A preliminary survey of the community suggests that residents value both the groundwater and aquatic resources in the region but also that many do not realize the extent to which they depend on groundwater for everyday living. We develop a framework to characterize the tradeoffs involved in using groundwater for different purposes and identify the necessary data to calculate relevant benefits and costs.

Because groundwater is relatively abundant and residents are currently only using a fraction of annual groundwater flow in the region, we expect that the results will hinge strongly on assumptions about future demand growth, climate change and energy costs. Identifying and understanding the tradeoffs is the first step in developing efficient groundwater management policy. The developed integrated dynamic optimization approach incorporates those tradeoffs when determining the allocation of the water resource to maximize value to society in aggregate. Although necessarily more complex, models that include a temporal component are often desirable when addressing long term resource allocation problems. Nevertheless, static approaches such as choice-based analysis are often useful for establishing a baseline for the dynamic model. Thus, synergistic interdisciplinary integration of research approaches may prove to be particularly effective when tackling WEF nexus issues.

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Conflict of interest

Authors declare there is no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.10.002.

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