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Nash bargaining in a general equilibrium framework: The case of a shared surface water supply ☆

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ABSTRACT

We extend the axiomatic Nash bargaining approach to the context of interregional water sharing in order to assess the approach's normative implications in a general equilibrium (GE) framework. The GE model is applied to a water development project proposed for the Wasatch Front and Cache Valley regions of Utah — the Bear River Development Project (BRDP). We demonstrate conceptually how an allocation rule and attendant net regional welfare measures are endogenously determined as equilibrium solutions to the bargaining problem. Numerical analysis, based upon a simulation model calibrated to current data, reveals that Nash bargaining is generally infeasible as a solution mechanism for sharing surplus water supplies generated through the implementation of the BRDP, with or without potential ex post side-payments made between Cache Valley and the Wasatch Front. Only in the special case of (1) larger future regional population sizes, (2) a hypothetical, joint per-capita cost-share arrangement where total project (i.e. fixed) costs are shared equally across the two regions, (3) hypothetically larger water augmentation rates, and (4) the ignoring of potential environmental costs, is the Nash bargaining solution viable. Otherwise, for all other scenarios where the analysis is based upon current or future population sizes, joint- or region-specific cost-share arrangements, lower or higher water augmentation rates, and internalized or externalized environmental costs, the Nash bargaining solution is found to be unattainable as a potential mechanism to share surplus water supplies produced by the BRDP.

1. Introduction

The management of interregional, or transboundary, surface water supplies is a key marker of human history [1,2]. Historically, the extent to which contiguous regions have successfully shared common water supplies has impacted whether they have prospered or declined. As early as 2500 BC, the Sumarian city-states Umma and Lagash were engaged in intermittent wars over irrigation supplies and cropland boundaries; wars lasting for 150 years. Commonly held water in this instance served as a disunifying force. In contrast, completion of the prodigious Grand Canal in the 7th century AD created the world's largest inland waterway transportation network, which unified China into a nation-state with a strong, centralized government presiding over an expansive array of productive resources [1].[1]

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[1] Solomon [1] chronicles the histories of several of the world's great canals, e.g., the opening of New York's Erie Canal in 1825, Egypt's Suez Canal in 1869, and the Panama Canal in 1914, describing in each case how international commerce was consequently extended. Similar stories are told of the world's major dams, e.g., Arizona and Nevada's Boulder Dam (later renamed Hoover Dam), India's Bhakra Dam, Egypt's Aswan Dam, China's Three Gorges Dam, Turkey's

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Over the past half century, in the face of global climate change and persistent population growth, the question of how to efficiently and equitably manage shared water supplies has taken on added urgency in several regions of the world; regions where impending shortages in supply portend conflict in the absence of cooperative agreements (c.f., [1,4–7]). The desert nations of the Arabian Peninsula, Libya, along with Israel and Jordan, for example, could no longer support food self-sufficiency with internal water resources as early as 70 years ago [1,6]. Facing less-severe, but no less challenging water allocation issues, 10 Nile basin countries, including Egypt, Ethiopia, Sudan, and Uganda have developed a Cooperative Framework Agreement (CFA) as part of the Nile Basin Initiative (NBI) with the aim of better managing the Nile River and its riparian zones. By most accounts, the NBI process has proven to be tenuous at best, at worst disruptive (c.f., [8,9]).

In the midst of interregional conflicts such as these, regions with competing jurisdictions over existing or potentially new surface water supplies have fostered effective, formal cooperative arrangements through compacts and water markets, with the common aim of more efficiently and equitably managing their water supplies. For example, relatively well-functioning markets have been established in the western U.S. and southeastern Australia; markets facilitating both intra-agricultural and agricultural-urban trades via temporary lease agreements or purchase of actual water rights [10].[2]

Australia's Murray-Darling Basin (MDB) is site of the world's most advanced water trading program; a program engaging not only irrigators, municipalities, and industries, but also non-landholding environmental stakeholders and financial investors in the trading of "unbundled" temporary and permanent water rights [13]. The program has ended irrigation subsidies and requires farmers to pay for the maintenance of dams and canals. After a little more than a decade, cellphone-enabled water trading among farmers and between farmers, city authorities, and environmental stakeholders has skyrocketed, with roughly 80% of the basin's irrigators by now having participated in at least one trade [13]. The MDB program even allows farmers whose irrigation systems have created soil salinity problems to purchase "transpiration credits" from forest owners whose trees remove salinity through their root systems [1].[3]

In the Western US, water trading has evolved more stubbornly than it has in the MDB. For the region as a whole (including the states of Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Texas, Utah, Wyoming and Washington) slightly over 700 short-term leases and roughly 1500 sales occurred over the twenty-year period from 1987–2007. Over half of the lease arrangements and three-quarters of the sales were either agricultural-to-agricultural or agricultural-to-urban [12]. Since then, trading volume has gradually increased, particularly in the drier southwestern states.

For example, in Arizona, where over 30% of surface water withdrawals are drawn from the over-allocated Colorado River, the diversion of water supplies to rural communities in the face of limited supply has become of paramount importance for state water managers [17].[4] From 2009 to 2018, nearly 151,000 acre-feet of water was traded annually, which comprises approximately 4% of the state's annual consumptive use. As [17] report, Arizona has witnessed a near seven-fold increase in total volume traded since 2009, with a clear trend upwards since 2012 and a large spike in 2018 coinciding with "exceptional drought" conditions. In terms of types of water trades consummated, 92% were in the form of leases, while only a small volume (~8%) were tallied as permanent sales.

Although water markets have been slow to evolve on a broader scale in the western US, evidence from the operation of these existing markets suggests that gains associated with more efficient allocation of surface water resources can in fact materialize through trading [12,18–23].[5] Trades are stimulated by large-enough differentials in water values between current water owners and potential buyers. In the western US for example, the majority of trades have been from (subsidized) agricultural sellers to (unsubsidized) urban buyers who are grappling with projected increases in water demand. As previously mentioned, the impetus for developing surface water markets generally arises for one of two purposes: (1) as a tool for reallocation of common water supplies between agricultural uses (including both water rights and irrigation services), and (2) as a means of expanding a growing urban area's access to safe water supplies [32]. The setting for this paper aligns with the second purpose.

In this paper, we extend the axiomatic Nash bargaining approach to the context of interregional water sharing in order to assess the approach's normative implications in a general equilibrium (GE) framework.[6] We apply the GE model to a water development project proposed for the Wasatch Front and Cache Valley regions of Utah – the Bear River Development Project (BRDP) – and

Ataturk Dam, and Brazil and Paraquay's Itaipu Dam, where instead of international commerce, more tightly controlled apportionment of water primarily for agricultural and municipal/industrial uses within and, in some cases between regions, was the targeted outcome. See [3] for a critique of [1].

2 Not to say that these regions have historically eschewed conflict and allocative inefficiency. For instance, in the early 1900's Los Angeles municipal water authorities ruthlessly gained control of the Owens River, constructing a 250-mile aqueduct that carries water from the river valley to the city. Owens Valley farmers responded by dynamiting sections of the aqueduct and standing off against armed city agents between 1924 and 1927 [1,11]. Further south in California, irrigators in the Imperial Valley water district consume 70% of the state's 4.4 million acre-foot allocation of Colorado River water at a steeply subsidized cost, resulting in profligate farming practices and the planting of water-thirsty crops [1]. Allocative inefficiencies such as these persist in regions across the US as a result of excessive price subsidization [12].

3 The MDB program has nevertheless attracted criticism. See [14,15] and [16].

4 Relative to US averages, the southwestern states of Arizona, California, and Texas confront higher annual population growth (2.45% vs. 1.15% between 1920 and 2018), higher temperature (61.1 °F vs. 52.5 °F), and less precipitation (20.68 in vs. 30.48 in) [17].

5 See [24,25], and [26] for insightful explanations of the theoretical prerogative of water trading. See [27–29], and [30] for discussions on the role of regulators in the establishment and maintenance of water trading programs. Michelsen and Young [31] propose a unique approach targeting intermittent drought. Under this approach temporary transfers of irrigation water provide secure water supplies to non-agricultural users during drought periods. The exercise of an option transfers water to higher valued uses only when needed, while preserving water for agricultural use during normal water supply conditions.

6 As Binmore et al. (1986) show, the axiomatic theory of cooperative bargaining initially proposed by Nash [33] has a tight relationship with the non-cooperative, sequential strategic approach to bargaining also proposed by Nash [33] and later developed by Rubinstein [34]. Cooperative bargaining relies solely upon the information in the pair of utility functions representing the welfare of the bargainers, and the bargainers' respective "disagreement points", or

conceptually demonstrate how an allocation rule and attendant net regional welfare measures are endogenously determined as equilibrium solutions to the bargaining problem. Numerical analysis, based upon a simulation model calibrated to current data, reveals that Nash bargaining is generally infeasible as a solution mechanism for sharing surplus water supplies generated through the implementation of the BRDP, with and without potential ex post side-payments made between Cache Valley and the Wasatch Front. Only in the special case of (1) larger future regional population sizes, (2) a hypothetical, joint per-capita cost-share arrangement where total project (i.e., fixed) costs are shared equally across the two regions, (3) hypothetically larger water augmentation rates, and (4) the ignoring of potential environmental costs, is the Nash bargaining solution viable. Otherwise, for all other scenarios where the analysis is based upon current or future population sizes, joint- or region-specific cost-share arrangements, lower or higher water augmentation rates, and internalized or externalized environmental costs, the Nash bargaining solution is found to be unattainable as a potential mechanism to share surplus water supplies produced by the BRDP.

Our conceptual model and calibrated numerical analysis deepens the pool of studies that apply axiomatic bargaining solutions to existing resource-sharing problems. Our particular contribution to this literature centers on the method we develop to derive more of a general-equilibrium allocation rule and associated regional net welfare measures as endogenous outcomes of a cooperative bargaining framework.[7] Our application of this method to the BRDP draws salience from Utah's Recommended Water Strategy [38]. As [38] points out, Utah's agricultural systems use over 80% of water consumed statewide. These systems are spread across the state, in urban areas where they compete for available water supplies, and rural areas where agriculture is likely to remain the predominant sector. Accommodating the state's projected population growth will require continued reductions in per-capita water usage, as well as implementation of additional water projects to optimize use of limited supplies. Among the URWS's key recommendations is to augment water efficiency and conservation improvements with shifts in water supplies within and between sectors of the economy, while mitigating any associated impacts in the basins of origin. Ultimately, achieving both aggregative and allocative efficiency statewide will require changes in statutes that allow leasing of agricultural water rights, as well as development of additional water resources, such as via the BRDP [38].

The next section provides a brief review of the Nash bargaining literature. Section 3 describes our study area and the BRDP. Section 4 develops a conceptual model of the Nash bargaining problem in a general equilibrium framework. Section 5 presents the results of our numerical analysis. Section 6 concludes.

2. Review of the Nash bargaining literature

A number of applications of axiomatic bargaining solutions in support of interregional water-sharing or international environmental agreements (IEAs) can be found in the literature. Four of these studies are most pertinent to ours: [39–41], and [42]. Zhu et al. [39] derive the Nash bargaining solution for a hypothetical, transboundary water-sharing arrangement along the Mekong River between upstream China and the downstream Mekong River Committee (MRC), consisting of the Southeast Asian nations of Thailand, Laos, Cambodia, and Vietnam. In their framework, an international transfer of funds from an institution external to China and the MRC can be incorporated in the solution to provide stronger incentives for joint management of the river. Wet and dry seasons are distinguished, and in each region water users are aggregated into three representative sectors: industry and households, hydropower generators, and agriculture irrigators. Asymmetric weights are assigned to the Nash bargaining function, reflecting China's relative bargaining strength. In general, Zhu et al. [39] find relatively large welfare gains for both regions associated the Nash bargaining solution, the size and distribution of which depend upon the regions' relative bargaining powers and the extent of international transfers. Dam capacity in both regions increases in the bargaining outcome, however fixed capital costs associated with these increases in capacity are unaccounted for.

Han et al. [40] apply the Nash bargaining solution to the Hanjiang River Basin, China's largest and most developed tributary of the Yangtze River Basin in the southern region of the country. The authors solve a bi-level optimization model, where a Nash bargaining solution is determined among representative agents located in five distinct zones of the basin. The solution is constrained by both a water-resource constraint and a reservation–benefit constraint. The reservation–benefit constraint ensures that no representative agent obtains less benefit from the Nash bargaining allocation than the average benefit obtained from a first-best allocation made by a basin-wide manager. Within this framework, Han et al. [40] find that all but one representative agent (the most upstream agent) would willingly participate in the Nash bargaining scheme.

In a model where two producing countries (North and South) with differentiated abatement technologies competitively produce a homogeneous good for sale to consumers in a non-producing third country, Cai and Li [41] find that in a Nash bargaining solution the North transfers a positive side-payment to the South and the South reduces its emission level below its status quo level

reservation utility levels below which the bargainers will not voluntarily participate in the bargaining scheme. Nash [33] identifies seven desirability axioms that are satisfied by a unique cooperative outcome, four of which are generally considered key among them: (1) Pareto efficiency, (2) symmetry in the bargainers' respective utility levels net of their disagreement points, (3) invariance to affine transformations of bargainers' utility functions, and (4) independence of irrelevant alternatives. Subsequent studies of the Nash bargaining problem have suggested families of cooperative solutions satisfying more generalized versions of Nash's original axioms [35] and more limited sets of axioms [36,37].

[7] This method is different than [2] partial-equilibrium, flexible water allocation rule, which determines efficient allocations based upon alternative, exogenously determined river flows, i.e., a rule specifying an efficient schedule of river water allocations between upstream and downstream users. Our model considers an alternative setting, where regions essentially control their own region-specific water supplies e.g., their own reservoirs filled predominantly by rivers flowing strictly within their respective boundaries, but their geographic proximity nonetheless permits the establishment of a trading arrangement between the two, subject to conveyance costs.

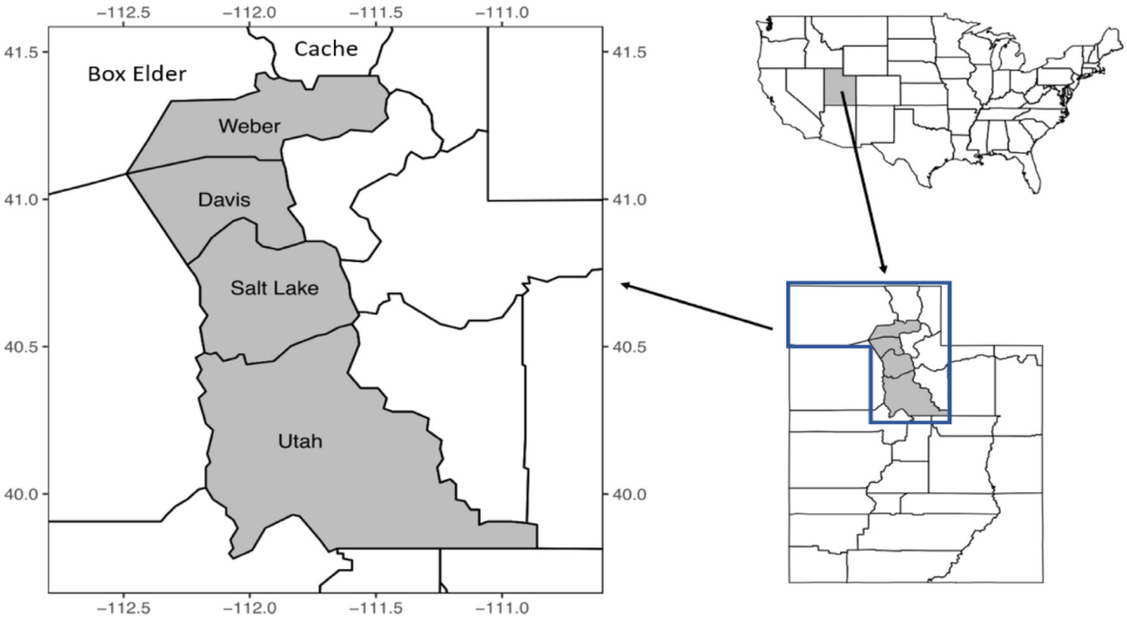

Fig. 1. The Wasatch Front and Cache Valley, Utah.

when either the South's valuation of the side-payment or the North's marginal damage from the externality is sufficiently high, i.e., when the regions are "strongly asymmetric". This result also holds when, rather than consumers in a third country purchasing the homogeneous good from the North and South, consumers in the South instead choose both domestically produced and imported amounts of the good. The authors conclude that strong asymmetry among regions can produce self-enforcing agreements.

Dijkstra and Nentjes [42] compare the Nash bargaining and Exchange-Matching-Lindahl (EML) solutions, where under the EML each agent specifies her demand for and supply of the public good according to her personal exchange rate.[8] With linear or quadratic benefits and quadratic costs, EML and the Nash bargaining solutions are equivalent in the presence of two agents. With more than two agents, high-benefit/low-cost agents are better off under EML than Nash bargaining.

Taken together, the results from these studies suggest that side-payments made between agents participating in a Nash bargaining scheme (or transfers from third-party organizations) may be necessary to ensure the voluntary participation of all agents. As [42] show, side payments may be necessary for the Nash bargaining scheme to coincide with an (unconstrained) Pareto efficient solution. Further, the extent of asymmetry in the benefits obtained by the agents is likely to impact their willingness to participate. These findings serve as points of reference for our ensuing analysis concerning the self-enforcing properties of the Nash bargaining solution.

3. The study area

Our study area encompasses two regions located in northern Utah — the Wasatch Front and Cache Valley (Fig. 1). Located in the north-central part of the state, comprised of Weber, Davis, Salt Lake, Utah, and Box Elder Counties, the Wasatch Front is Utah's largest metropolitan region. Roughly 80% of Utah's population resides in this region, which is home to the state's capital, Salt Lake City, and accounts for approximately 90% of the state's gross state product [43]. The Wasatch Front stretches along, and is hemmed in by, the Wasatch Mountains to the east and Great Salt Lake to the west. Because of these geographical barriers, much of the land along the Wasatch Front has been developed.

The Wasatch Front has experienced considerable growth since the 1950s — its population increasing by over 300% to its current 2.5 million residents, with projections of the population reaching six million residents by 2065 [44]. Much of the remaining undeveloped land is rapidly being developed, forcing local governments and regional authorities to contend with problems of urban sprawl and related transportation issues. According to Perlich et al.'s [44] projections, just under 30% of Utah's population will reside in Utah County by 2065, as will 40% of new residents to the state during this 50-year time span. Just over 20% of new residents will reside in Salt Lake County, currently the Wasatch Front's most populous county. Forty and roughly 25% of those employed in the state are projected to be working in Salt Lake and Utah Counties, respectively, by 2065. Davis County is projected to experience the state's third highest employment growth rate during this same time frame.

[8] The personal exchange rate for a given agent is based upon how much society as a whole agrees to contribute for each unit of that agent's contribution. The agent states how much he will contribute to the public good at this exchange rate. In equilibrium, the exchange rates are such that each agent demands the same amount of the public good, and this amount is the aggregate contribution across all agents.

Cache Valley's population is also growing rapidly. Population is expected to roughly double in size from 135,000 currently to 230,000 by 2050. In comparison to most other regions in Utah, the valley is relatively rich in water – JUB Engineers [45] reports a roughly 30,000 acre-feet total supply surplus annually for the valley. In terms of the valley's developed water supplies, roughly 80% is consumed by irrigated cropland, the remaining 20% devoted to municipal and industrial uses [45]. The valley is also distinguished by its rich agricultural heritage. According to recent USDA estimates, Cache Valley's average sales per farm is roughly three times as large as Davis, Salt Lake, and Weber Counties', and roughly 1.5 times as large as Utah County's [46]. Cache Valley is estimated to have slightly more than 37% of its land area in farms, while the average for the Wasatch Front counties is just over 22% [46].

In 1991, the Utah State Legislature passed the Bear River Development Act (henceforth the Act) which directed the Utah Division of Water Resources (UDWR) to develop up to 220,000 acre feet of the Bear River's surface waters and its tributaries as part of the BRDP. Of this amount, 160,000 acre-feet would be allocated to the Wasatch Front and the remaining 60,000 acre-feet allocated to Cache Valley [47]. As Fig. 2 shows, the main stem of the Bear River flows through Cache Valley to the Cutler Reservoir. From there, the river flows unimpeded south through Box Elder County to the Bear River Bird Refuge near man-made Willard Bay [47].

As indicated in Fig. 2, the project entails constructing a raw water pipeline from Cutler Dam in Cache Valley to a proposed pumping station located at the site of a potential reservoir in Fielding and the Junction Vault. From there the water is piped to the proposed West Haven treatment plant in Weber County, and subsequently routed through the Weber Basin and Jordan Valley Water Conservancy Districts along the Wasatch Front. An additional raw water pipeline is proposed from Whites Reservoir located in Box Elder County to the reservoir in Fielding and the Junction Vault. The water from Whites Reservoir represents a transfer of water within the Wasatch Front, from Box Elder County in the northern region of the Front to the more populous Weber, Davis, Salt Lake, and Utah Counties in the southern region.

To help visualize more generally the type of water-sharing arrangement captured by our conceptual and numerical models developed in Sections 4 and 5, consider Fig. 3. Panel A depicts the existing water topography between two regions prior to the implementation of a water development project such as the BRDP. In our case, we can think of Region 1 as representing the Wasatch Front and Region 2 as Cache Valley. Region 1 is larger in size (denoted by its larger non-water resource base, $L1$, relative to region 2's $L2$) and is less agricultural (denote by the region's lighter shade of green). Although the two region's available water supplies ($W1$ and $W2$) are roughly equal in size, Region 1's is smaller relative to both its non-water resource base and population size. Region 2's water supply is replenished by a larger river, r_A (e.g., the Bear River in Fig. 2), and its tributary r_B. A slightly weaker-flowing river, r_C (e.g., continuation of the Bear River in Fig. 2) flows between the two regions. And Region 1's available water supply is replenished by moderate and weaker flowing rivers r_D and r_E, respectively.

Panel B in Fig. 3 depicts the interregional water topography after the water development project is completed. We see that river r_C's flow between the two regions is enhanced, reflecting the greater amount of water now transferred from Region 2 to Region 1, e.g., via the raw water pipeline extending from Cutler Dam in Cache County to the West Haven treatment plant in Weber County in Fig. 2. In addition, an additional water source is developed in Region 1, e.g., the Whites Reservoir in Fig. 2. The water from this new source is piped south within Region 1 via river r_F. As a result of the water transfers within Region 1, and between Regions 1 and 2, Region 1's main available water supply is now larger.

UDWR's [47] cost estimates for the BRDP range from approximately \$1.5 billion to \$2.8 billion. The Act requires the state of Utah to fund the planning, studies, design and construction, and environmental mitigation costs associated with the project. The Act also requires that the funding will be repaid by the regions within a period not to exceed 50 years, at a 4% interest rate set by the Utah Board of Water Resources. Assuming a total cost estimate of \$1.7 billion (which includes reservoir and pipeline construction, and other facilities to deliver the raw water from storage and diversions to regional delivery points), UDWR [47] reports annual repayments of just under \$22 million for Cache Valley, and slightly more than \$58 million for the Wasatch Front. We utilize these cost estimates in our numerical analysis in Section 5.[9]

4. The conceptual model

We begin by setting notation in the context of a baseline (autarkic) model of two contiguous regions. Region 1 represents Cache Valley and region 2 the Wasatch Front. We then specify the Nash bargaining model and distinguish its key differences with the baseline model.

4.1. Baseline model

Assume region $i = 1, 2$ produces good $j = A, C$ using inputs $k = W, N$ according to production function,

$$q_{ij} = f_{ij}\left(z_{ijk}; \beta_{ijk}\right), \tag{1}$$

where input vector $z_{ijk} = \left(z_{iAW}, z_{iAN}, z_{iCW}, z_{iCN}\right) > 0$, and parameter vector $\beta_{ijk} = \left(\beta_{iAW}, \beta_{iAN}, \beta_{iCW}, \beta_{iCN}\right) > 0$ is defined such that function $f_{ij}(\cdot)$ exhibits constant returns-to-scale in vector z_{ijk}. Outputs A and C denote composite agricultural and all other

[9] Additional costs will be incurred by the regions to deliver and treat water from the BRDP, e.g., treatment, operation, and maintenance costs; costs that are not covered by the overall funding provided by the state. Further, potential environmental costs affiliated with the BRDP are unaccounted for.

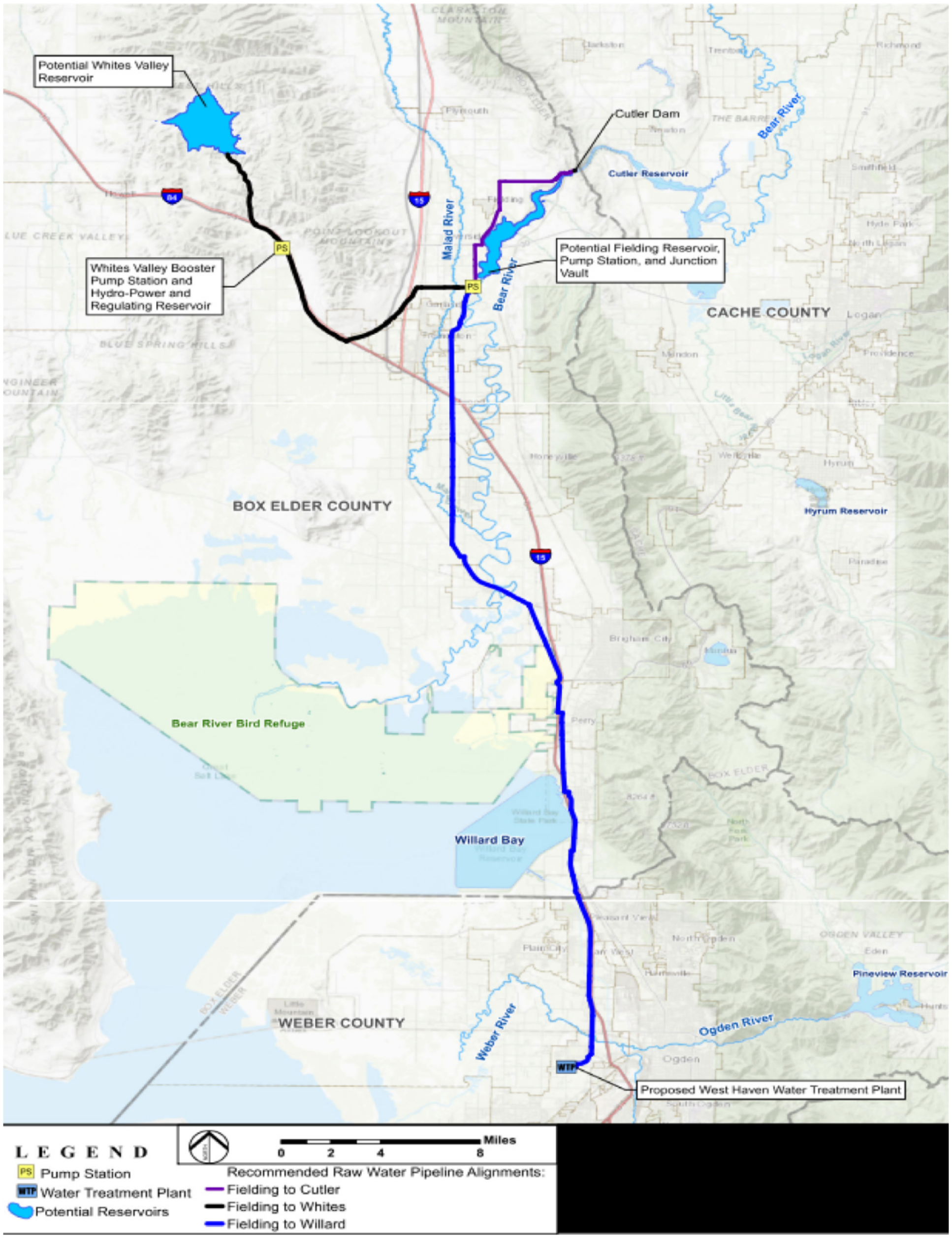

Fig. 2. The Bear River Development Project.

non-agricultural goods, respectively, and inputs W and N represent respective amounts of water and a composite of all other inputs, e.g., capital, labor, and land used to produce q_{ij}.[10]

Total cost associated with the production of good j in region i using inputs k is defined as,

$$c_{ij} = \sum_k w_{ik} z_{ijk}, \quad i = 1, 2, \quad j = A, C, \quad k = W, N, \tag{2}$$

[10] We distinguish the water input from a composite of non-water inputs in order to maintain our focus on the sharing of water between the two regions in the ensuing numerical analysis in Section 5. Similarly, we distinguish the agricultural good from a composite of non-agricultural goods to reflect Cache Valley's relatively large agricultural sector, and to simplify our ensuing analysis.

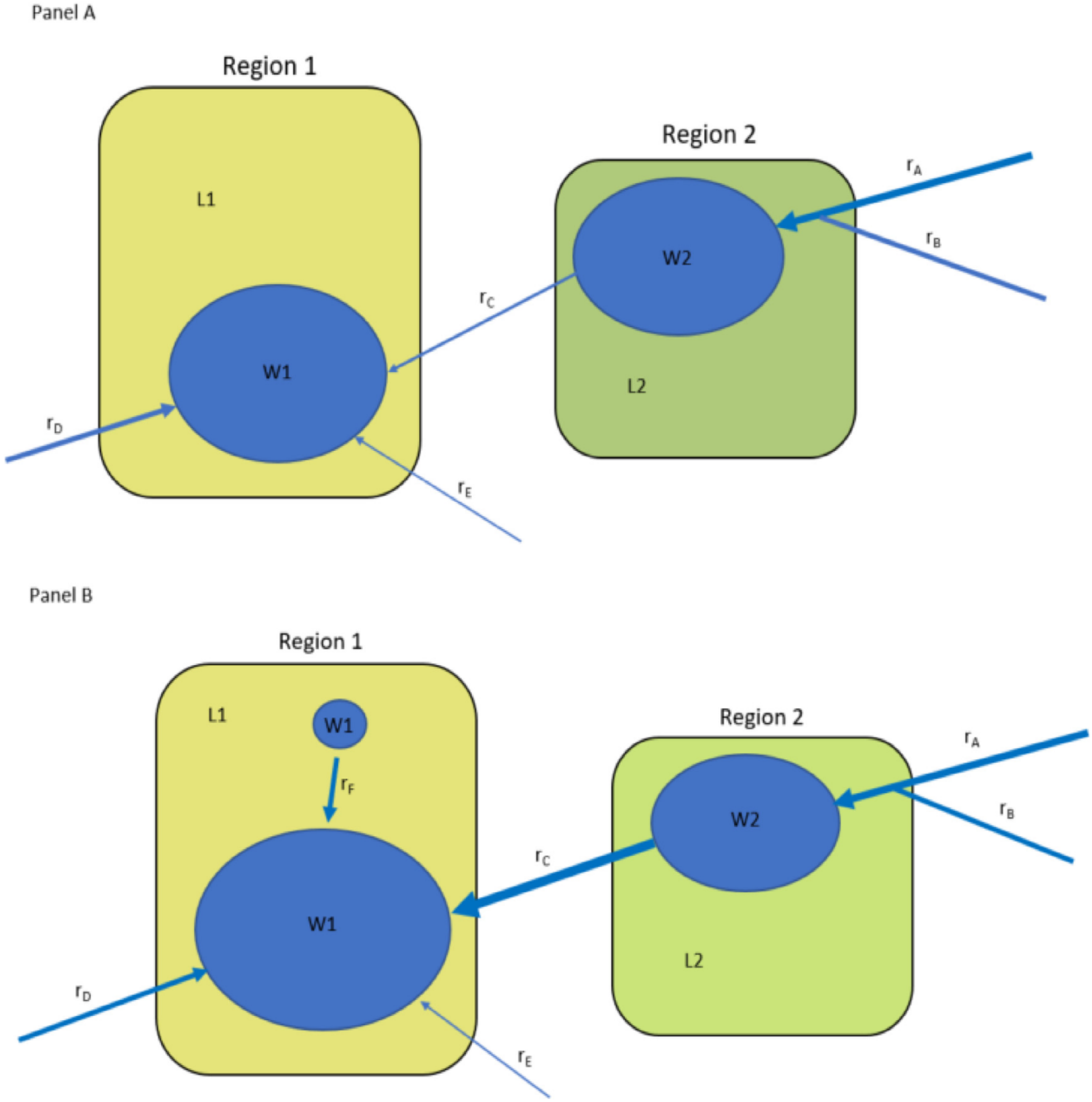

Fig. 3. General water-sharing schematic.

where $w_{ik} > 0$ denotes region i's input prices (assumed common across sectors A and C in each region).[11] Regional endowments of inputs W_i and N_i, are defined as,[12]

$$\bar{W}_i = \sum_j z_{ijW}, \quad i = 1, 2, \quad j = A, C, \tag{3}$$

$$\bar{N}_i = \sum_j z_{ijN}, \quad i = 1, 2, \quad j = A, C. \tag{4}$$

Per-capita welfare in region i is represented by utility function,

$$u_i = u_i\left(x_i; \alpha_i\right), \quad i = 1, 2, \tag{5}$$

[11] Fixed costs are normalized to zero here in order to facilitate the role they play in Section 5 in determining the social net benefits associated with implementing the BRDP.

[12] We follow the computational general equilibrium (CGE) literature by endowing the regions themselves, rather than the regions' consumers, with resource levels $\bar{W}_i$ and $\bar{N}_i$ [48].

where $x_i = \left(x_{iA}, x_{iC}\right) > 0$ represents region i's per-capita consumption vector, and parameter vector $\alpha_i = \left(\alpha_{iA}, \alpha_{iC}\right) > 0$. Region i's associated per-capita consumption constraint is defined as,

$$M_i = \sum_{ij} p_{ij} x_{ij}, \quad i = 1, 2, \quad j = A, C, \tag{6}$$

where $p_{ij} > 0$ denotes per-unit prices of goods $j = A, C$ produced in region i, and M_i represents region i's per-capita wealth level.

In the baseline equilibrium (as in the Nash bargaining model described in Section 4.2), region i independently and simultaneously solves its cost-minimization and per-capita utility maximization problems. For cost minimization, input vector z_{ijk} is chosen to minimize Eq. (2) subject to Eqs. (1), (3), and (4) with region i taking input prices w_{ik} as given. Conceptually, the first-order conditions for this problem solve for vector z_{ij}, and constraints (3) and (4) solve for input prices w_{ik}. The production function's curvature conditions in tandem with binding regional resource constraints ensures a unique, interior solution to region i's cost-minimization problem. For utility maximization, consumption vector x_i is chosen to maximize Eq. (5) subject to (6), with region i taking prices p_{ij} and per-capita wealth level M_i as given. The utility function's curvature conditions in tandem with a linear consumption constraint likewise ensure a unique interior solution to region i's utility maximization problem.

Two sets of market-clearing conditions close the model,

$$\frac{q_{ij}}{n_i} = x_{ij}, \quad i = 1, 2, \quad j = A, C, \tag{7}$$

$$\frac{R_i}{n_i} = M_i, \quad i = 1, 2, \tag{8}$$

where $R_i = \sum_j p_{ij} q_{ij}$ and n_i denotes region i's population size. Eq. (7) states that in equilibrium regional supplies of goods A and C equate with their corresponding consumption demands (on a per-capita basis), which in turn effectively determine equilibrium prices p_{ij}. Conditions (8) indicate that regional wealth is equal to regional gross domestic product (GDP), i.e., the sum of regional revenue levels from the production of goods A and C (again, on a per-capita basis).[13] The baseline equilibrium is ultimately characterized by the regions' respective input-demand, output-supply, output-demand, indirect-utility, and cost functions, as well as their respective regional GDPs: $z^0_{ijk} = z_{ijk}\left(\Omega^0_i, p^0_{ij}, w^0_{ik}\right)$, $q^0_{ij} = q_{ij}\left(\Omega^0_i, p^0_{ij}, w^0_{ik}\right)$, $x^0_{ij} = x_{ij}\left(\Omega^0_i, p^0_{ij}, w^0_{ik}\right)$, $u^0_i = u_i\left(\Omega^0_i, p^0_{ij}, w^0_{ik}\right)$, $c^0_{ij} = c_{ij}\left(\Omega^0_i, p^0_{ij}, w^0_{ik}\right)$, and $R^0_i = \sum_j p^0_{ij} q^0_{ij}$, where parameter vector $\Omega^0_i = \left(\alpha_i, \beta_{ijk}, \bar{W}_i, \bar{N}_i, n_i\right)$, and, as mentioned previously, equilibrium prices p^0_{ij} and w^0_{ik} are determined endogenously via Eqs. (3), (4), and (7), $i = 1, 2, j = A, C, k = W, N$ (the 0 superscript denotes baseline-equilibrium values).

Admittedly, designating the baseline equilibrium as the status quo is an abstraction from any bilateral economic relationship. At any given point in time, regions are involved in multiregional economic relationships. Thus, by abstracting to a bilateral relationship we either ignore or exogenize any impacts on that relationship emanating from pre-existing, "internal" trade between the two regions, as well as "external" trade between each region and its other trading partners. Currently, the Wasatch Front and Cache Valley do not internally trade their respective water supplies (the focal point of this study). Further, as we discuss in Section 5, the data used to calibrate our numerical model are denominated in dollars, which enables us to normalize all prices in the model to one, thus mitigating potential bias associated with the prices' respective equilibrium values. Nevertheless, to the extent that the Wasatch Front and Cache Valley engage in trade relationships with other regions statewide, nationwide, and globally, both our baseline equilibrium and Nash bargaining solution likely underestimate the regions' respective wealth levels.

4.2. Nash bargaining solution

Unlike the [47] engineered regional water allocations resulting from the BRDP, the Nash bargaining solution (henceforth NBS) explicitly satisfies [33] original desirability properties of Pareto optimality, symmetry, invariance, and independence of irrelevant alternatives, indeed, the NBS uniquely satisfies these properties [49]. As such, the solution is both normative and positive. Further, the NBS enables us to endogenously determine compensating-variation welfare measures for each region associated with the water-sharing arrangement. Although demonstrative in nature, the NBS serves as a starting point for obtaining estimates of these measures endogenously via numerical optimization.[14]

To begin, the regional costs specified in Eqs. (2) are now independently minimized subject to (4), and a new interregional version of constraint (3),

$$\bar{W} = (1 + r_1)\bar{W}_1 + (1 + r_2)\bar{W}_2 = \sum_i \sum_j z_{ijW}, \quad i = 1, 2, \quad j = A, C. \tag{9}$$

Constraint (9) accounts for the fact that regional water supplies, $z_{ijW}, i = 1, 2, j = A, C$, are tradable in the NBS, i.e., that the two regions now share a common supply of available water, priced at a common rate of w_W (as they would via a project such as the BRDP). Further, available water supplies in regions 1 and 2, respectively, are augmented by growth factors $r_1 > r_2 > 0$, mimicking

[13] Following [48], our general-equilibrium model abstracts from the household sector's resource allocation decisions (i.e., allocation of z_{ijk}). Thus, regional revenues accruing to the household sector in the form of wealth is consistent with non-negative profits obtained at the industry level. If its resource allocation decision had instead been explicitly modeled, then household sector wealth would accrue in the form of industry costs, c_{ij}, plus profits.

[14] Of course, benefit transfers from previous studies that have estimated water values in agriculture use, municipal/industrial use, and for environmental purposes represent the most expedient method of affixing welfare measures to the specific amounts of water supply generated by the BRDP (c.f., [50]).

the respective increases in Cache Valley's and the Wasatch Front's available water supplies as a result of the BRDP, in particular that Cache Valley's percentage increase exceeds the Wasatch Front's. For example, in accordance with [47,51] and [52], the BRDP is expected to result in roughly 20% and 10% increases in Cache Valley's and the Wasatch Front's available water supplies, respectively, implying $r_1 = 0.2$ and $r_2 = 0.1$.

A pair of per-capita regional utility values $\left(u_1^*, u_2^*\right)$ denotes the NBS. These are solution values for the interregional maximization problem,

$$\underset{\{x_1,x_2\}}{Max} \quad \left[u_1\left(x_1;\alpha_1\right) - u_1^0\right]\left[u_2\left(x_2;\alpha_2\right) - u_2^0\right], \tag{10}$$

subject to

$$\left(u_1^*, u_2^*\right) \geq \left(u_1^0, u_2^0\right), \tag{11}$$

and constraints (6). Eq. (11) constrains the NBS to deliver each region no less per-capita welfare than they would otherwise obtain in the baseline equilibrium (i.e., the status quo). As depicted in (10), where each region's utility function is unweighted, we effectively assign a non-discriminatory, egalitarian welfare function across the two regions. Egalitarianism in this sense is epitomized by the resulting NBS allocation, $\left(u_1^*, u_2^*\right)$ satisfying $u_1^* - u_1^0 = u_2^* - u_2^0$, i.e., each region retains an equal share of the payoff gain. Since we have no a priori reason to favor one region's per-capita welfare level over the other in the NBS (as reflected in [47] and [38]), the standard, unweighted bargaining function is deemed most appropriate for this normative exercise.[15]

Market-clearing conditions (7) continue to hold in the NBS for each region's composite good C. However, to account for the possibility of trade in "embodied water", i.e., the good produced in Cache Valley that uses water relatively intensively (composite agricultural good A), conditions (7) corresponding to good A are now rewritten as,

$$\sum_i q_{iA} = \sum_i n_i x_{iA}, \quad i = 1, 2. \tag{12}$$

Similar to the interregional water constraint specified in (9), market-clearing condition (12) accounts for the fact that agricultural composite good A is tradable in the NBS at a common equilibrium price, p_A.

Market-clearing conditions (8) continue to hold in the NBS, albeit in modified forms,

$$M_1 = \frac{R_1}{n_1} + \frac{w_W\left[(1+r_1)\bar{W}_1 - \sum_j z_{1jW}\right]}{n_1}, \quad j = A, C, \tag{13}$$

$$M_2 = \frac{R_2}{n_2} + \frac{w_W\left[(1+r_2)\bar{W}_2 - \sum_j z_{2jW}\right]}{n_2} \quad j = A, C. \tag{14}$$

Eqs. (13) and (14) adjust the regions' respective per-capita wealth levels to account for the value of water transferred between the regions. Given that region 1 is initially relatively well-endowed with an available water supply and its supply is augmented by a relatively large growth factor, i.e., $r_1 > r_2 > 0$, we expect $\frac{w_W\left[(1+r_1)\bar{W}_1 - \sum_j z_{1jW}\right]}{n_1} > 0$ in (13) and $\frac{w_W\left[(1+r_2)\bar{W}_2 - \sum_j z_{2jW}\right]}{n_2} < 0$ in (14), i.e., that Cache Valley will export its excess water to the Wasatch Front in the NBS equilibrium.

Similar to the baseline equilibrium, the NBS is ultimately characterized by the regions' respective input-demand, output-supply, output-demand, indirect-utility, and cost functions, as well as regional GDPs: $z_{ijk}^* = z_{ijk}\left(\Omega_i^*, p_{iC}^*, p_A^*, w_{iN}^*, w_W^*\right)$, $q_{ij}^* = q_{ij}\left(\Omega_i^*, p_{iC}^*, p_A^*, w_{iN}^*, w_W^*\right)$, $x_{ij}^* = x_{ij}\left(\Omega_i^*, p_{iC}^*, p_A^*, w_{iN}^*, w_W^*\right)$, $u_i^* = u_i\left(\Omega_i^*, p_{iC}^*, p_A^*, w_{iN}^*, w_W^*\right)$, $c_{ij}^* = c_{ij}\left(\Omega_i^*, p_{iC}^*, p_A^*, w_{iN}^*, w_W^*\right)$, and $R_i^* = \sum_j p_{ij}^* q_{ij}^*$, where now parameter vector $\Omega_i^* = \left(\alpha_i, \beta_{ijk}, \bar{W}_i, \bar{N}_i, n_i, r_i\right)$ and equilibrium prices $\left(p_{iC}^*, p_A^*, w_{iN}^*, w_W^*\right)$ are determined endogenously, $i = 1, 2, j = A, C, k = W, N$ (the $*$ superscript denoting their NBS values). Based upon these results, we can define per-capita regional welfare measures (compensating variations) and net benefits associated with the regions having chosen to participate in the NBS as a means of allocating water shares arising from the BRDP. Region i's per-capita compensating variation (CV_i) solves,

$$u_i\left(\Omega_i^* \mid R_i^* - CV_i\right) = u_i^0 = u_i\left(\Omega_i^0 \mid R_i^0\right) \quad i = 1, 2. \tag{15}$$

Eq. (15) indicate that CV_i is the dollar amount that – when subtracted from region i's per-capita GDP obtained in the NBS (R_i^*) – reduces the region's NBS per-capita utility to its corresponding baseline utility level (u_i^0). As such, CV_i represents region i's per-capita willingness-to-pay to participate in the NBS, and thereby obtain the solution's water allocation. Letting $Cost_i$ represent region i's per-capita share of the fixed capital costs associated with participating in the BRDP (these costs are explained in more detail in Section 5), the region's net benefit (NB_i) from choosing to participate in the NBS is defined as,

$$NB_i = CV_i - Cost_i \quad i = 1, 2. \tag{16}$$

The ultimate goal of our numerical analysis presented below is to derive NB_i estimates for Cache Valley and the Wasatch Front.

5. Numerical analysis

We begin this section by specifying the respective functional forms chosen for $f_{ij}\left(z_{ijk};\beta_{ijk}\right), i = 1, 2, j = A, C, k = W, N$ and $u_i\left(x_i;\alpha_i\right), i = 1, 2$, in Eqs. (1) and (5). Next, we discuss the model's calibration to available data for the Wasatch Front and Cache Valley, followed by a presentation of the model's numerical results. We finish this section with a sensitivity analysis of the results.[16]

[15] See [34] for a generalization of the standard Nash bargaining function.

[16] Our numerical analyses are performed using GAMS v. 33.2.0 r4f23b21 WEX-WEI x86 64bit/MS Windows.

Table 1
Data for model calibration[a].

Variable	Description	Cache valley	Wasatch front[b]
z_{iAW}	Water used in agricultural production ($1,000/yr).	6,564	5,617
z_{iCW}	Water used in production of composite good ($1,000/yr).	14,675	31,573
z_{iAN}	Composite input used in agric. production ($1,000/yr).	40,912	32,567
z_{iCN}	Composite input used in prod. of comp. good ($1,000/yr).	4,857,265	28,141,600
$\bar{W}_i$	Total water resource ($1,000/yr).	21,239	37,189
$\bar{N}_i$	Total composite resource ($1,000/yr).	4,898,176	28,174,166
q_{iA}	Aggregate supply of agricultural good ($1,000/yr).	47,475	38,184
q_{iC}	Aggregate supply of composite good ($1,000/yr).	4,871,939	28,173,200
n_i	Regional population size (# of individuals).	133,741	501,661

[a]Data values are scaled for inclusion in respective regional social accounting matrices following [48].
[b]Average county-level value (averaged over the five counties comprising the Wasatch Front).

5.1. Model specification

We specify the regional production function for q_{ij} in Eq. (1) as Cobb–Douglas,

$$q_{ij} = \gamma_{ij} \prod_k z_{ijk}^{\beta_{ijk}}, \quad i = 1,2, \quad j = A,C, \quad k = W,N, \tag{17}$$

where parameters γ_{ij} capture the effects of neutral technological change in sectors $j = A,C$ in region i, and marginal productivity parameters satisfy $\beta_{ijW}+\beta_{ijN} = 1, i = 1,2, j = A,C$. We also specify region i's per-capita utility function u_i in Eq. (5) as Cobb–Douglas,

$$u_i = \delta_i \prod_j x_{ij}^{\alpha_{ij}}, \quad i = 1,2, \quad j = A,C. \tag{18}$$

where parameters δ_i capture the regional effects of neutral welfare change associated with a bundle of consumption goods $j = A,C$. Consistent with our scale assumption for production, and to help ensure a sparse parameter set for calibration purposes, we also assume that $\alpha_{iA} + \alpha_{iC} = 1, i = 1,2$.[17]

5.2. Model calibration

Model calibration is based upon data obtained from four separate sources. Water supply and use data are taken from [51] and [52], and the remaining county-level economic and production data is obtained from [56]. Regional population data is taken from [57]. Column 3 of Table 1 compiles the corresponding data for Cache Valley, and Column 4 the data for the Wasatch Front (reported here at the per-county level, i.e., averaged over the five counties comprising the Wasatch Front region).[18] As noted in the table, for simulation purposes the data in Table 1 is compiled in a social accounting matrix (SAM) and then scaled according to the procedure recommended in [48]. From Table 1 we see that the average Wasatch Front county is indeed relatively well-endowed with the composite resource, which in turn is allocated primarily to the production of its composite good. As a result, for our baseline equilibrium the quantity of the composite good produced in the Wasatch Front is considerably larger than that produced in Cache Valley. Further, the population size of the average Wasatch Front county is roughly three times larger than Cache Valley's.

Based upon Eqs. (1)–(8) from Section 4.1, with (17) and (18) from Section 5.1 substituted for (1) and (5), respectively, and the first-order conditions for the cost-minimization and utility-maximization problems described in Section 3, calibration of the baseline equilibrium results in the parameter values reported in Table 2. We normalized the price of the composite good to one in each region and observed the remaining prices each solve endogenously to one. Hence, in line with [48], all prices in our baseline equilibrium are normalized to one (i.e., $p_{ij} = w_{ijk} = 1, i = 1,2, j = A,C, k = W,N$). This normalization comports with our numerical analysis, since our input and production data in Table 1 are denominated in dollars. For future reference, note that since the calibration exercise is based upon data contained in Table 1, and this data defines our baseline equilibrium, Table 1 represents both the data for calibration and the baseline equilibrium.

From Table 2 we see that Cache Valley and the average county in the Wasatch Front share similar values for the neutral technology shift parameters (γ_{ij}, $i = 1,2, j = A,C$) and substitution parameters in production (β_{ijk}, $i = 1,2, j = A,C, k = W,N$). Cache Valley's neutral preference shift parameter ($\delta_1 = 0.5$) exceeds the average Wasatch Front county's ($\delta_2 = 0.1$), as does Cache Valley's preference substitution parameter for the agricultural good ($\alpha_{1A} = 0.01$ versus $\alpha_{2A} = 0.001$). Also contained in Table 2 are the parameter values for r_1 and r_2, respectively, the assumed augmentation rates of available water supplies in Cache Valley and the Wasatch Front's average county resulting from implementation of the BRDP [47,51,52].

[17] Our functional forms and parameter restrictions reflect both the simplicity and substitutability typically built into computable general equilibrium (CGE) models, particularly CGE models aggregated at national or regional levels [48]. These models are in turn calibrated to highly aggregated data, which often warrant sparse parameter sets (cf., [53–55]).

[18] We conducted our analysis using average county values for the Wasatch Front in order to enhance comparability with the (single county level) Cache Valley.

Table 2
Parameter values.

Parameter	Description	Cache valley	Wasatch front[a]
γ_{iA}	Neutral technology shift parameter in agriculture.	1.49	1.52
γ_{iC}	Neutral technology shift parameter in comp. good.	1.02	1.01
β_{iAW}	Substitution parameter for water in agric. production.	0.14	0.15
β_{iAN}	Substitution parameter for comp. input in agric. prod.	0.86	0.85
β_{iCW}	Substitution parameter for water in comp. good prod.	0.003	0.001
β_{iCN}	Substitution param. for comp. input in comp. good prod.	0.997	0.999
δ_i	Neutral preference shift parameter	0.5	0.1
α_{iA}	Preference substitution parameter for agricultural good.	0.01	0.001
α_{iC}	Preference substitution parameter for composite good.	0.99	0.999
r_i	Water augmentation rates (r_1 and r_2).	0.2	0.1

[a]Average county-level value (averaged over the five counties comprising the Wasatch Front).

Table 3
NBS results.

Variable	Description	Cache valley	Wasatch front[a]
z^*_{iAW}	Water used in agricultural production ($1,000/yr).	7,329	6,621
z^*_{iCW}	Water used in production of composite good ($1,000/yr).	16,629	35,817
z^*_{iAN}	Composite input used in agric. production ($1,000/yr).	40,316	33,835
z^*_{iCN}	Composite input used in prod. of comp. good ($1,000/yr).	4,857,861	28,140,330
q^*_{iA}	Aggregate supply of agricultural good ($1,000/yr).	47,599	40,414
q^*_{iC}	Aggregate supply of composite good ($1,000/yr).	4,874,370	28,175,910
x^*_{iA}	Per-capita consumption of agricultural good ($/person/year).	366.17	77.82
x^*_{iC}	Per-capita consumption of composite good ($/person/year).	36,446	56,165
R^*_i	Regional Gross Domestic Product (GDP)($1,000/yr).	4,920,992	28,215,550
$\bar{W}$	Total water resource[b,c] ($1,000/yr).	66,395	
W^T_i	Value of water traded ($1,000/yr).	1,345	−1,345
CV_i	Per-capita compensating variation ($/person/yr).	19.22	9.78
$Cost_i$	Per-capita fixed capital cost share ($/person/yr).	164.50	23.12
P^*_A	Per-unit adjustment factor for value of agricultural good.[c]	0.98	
w^*_{iN}	Per-unit adjustment factor for value of composite input.	1.00	1.00
w^*_W	Per-unit adjustment factor for value water input.[c]	0.88	

[a]Average county-level value (averaged over the five counties comprising the Wasatch Front).
[b]Total water resource available to Cache Valley and the average Wasatch Front County.
[c]This value is common across both the Cache Valley and the average Wasatch Front County.

5.3. Numerical results

Table 3 contains our numerical results for the NBS, for the case of $r_1 = 0.2$ and $r_2 = 0.1$. In addition to the relevant NBS values for the same variables presented Table 1, i.e., z^*_{ijk} and q^*_{ij}, $i = 1, 2, j = A, C, k = W, N$, Table 3 includes the values for $\bar{W} = \sum_i (1 + r_i)\bar{W}_i$, $W^T_i = \left(1 + r_i\right) \bar{W}_i - \sum_j z^*_{ijW}$, and CV_i, $i = 1, 2, j = A, C$. Recall that $\bar{W}$ represents the common supply of available water as a result of the BRDP's implementation (left-hand side of constraint (9)). Variable $W^T_i > 0(< 0)$ represents the value of region i's water exported(imported), and CV_i denotes region i's per-capita compensating-variation measure (as defined in Eq. (15)). Also included in Table 3 are the NBS values for per-capita consumption levels x^*_{ij}, regional GDP levels R^*_i, and prices p^*_A, w^*_{iN}, w^*_W, $i = 1, 2, j = A, C$. We note that because all variables are denominated in dollars, these prices should be interpreted as 'value-adjustment factors' rather than per-unit prices per se.[19] Lastly, Table 3 includes per-capita annual repayments on the fixed costs associated with participating in the BRDP, $Cost_i, i = 1, 2$, based upon [47] projections for Cache Valley and the Wasatch Front. Although [47] allocates specific repayment cost shares to three of the Wasatch Front's water conservancy districts – the Jordan Valley, Weber Basin, and Bear River Water Conservancy Districts – and thus attributes these cost shares to respective Wasatch Front counties, we aggregate the cost shares across all Wasatch Front counties and divide by the Front's total population to derive its per-capita regional cost share.

To begin, we compare our NBS results for z^*_{ijk} and q^*_{ij} with what are effectively the benchmark equilibrium values z^0_{ijk} and q^0_{ij} $i = 1, 2, j = A, C, k = W, N$ from Table 1 (recall that the data in Table 1 mimic the benchmark equilibrium by design of the calibration exercise). We see that, as expected, the value of water consumption under the NBS for production of both the agricultural and composite goods increases by larger percentages in the typical Wasatch Front county than in Cache Valley. This outcome is consistent with the pattern of trade in water depicted by the values for $W^T_i, i = 1, 2$ in Table 3 – over $1.3 million worth of water

[19] The composite good's value adjustment factor in each region, $p_{iC}, i = 1, 2$, continues to be normalized to one in the NBS.

is traded annually in the NBS between Cache Valley and the average Wasatch Front County as a result of the BRDP. Relatively minor changes occur in both regions with respect to the value of the composite input used in the production of the agricultural and composite goods. Interestingly, relatively larger increases in the value of agricultural(composite-good) production occur in the Wasatch Front(Cache Valley).

Most importantly for our purposes are the results for CV_i and $Cost_i$, $i = 1, 2$ contained in Table 3. Clearly, the net benefits for each region from participating in the NBS as a means of distributing resources resulting from implementation of the BRDP are negative. Appealing to Eq. (16), we find that Cache Valley's per-capita net benefit is roughly -\$145 per person (\$19.22 - \$164.50), and the typical Wasatch Front county's is approximately -\$13 per person (\$9.78 - \$23.12). These results suggest that if Cache Valley and the Wasatch Front were to consider participating in an NBS agreement as a means of dividing the expected net surplus resulting from the BRDP's expected water augmentation rates and cost-share arrangement, neither region would voluntarily agree to participate. Rather than sharing a net surplus, the regions would be forced to share a net deficit.

5.4. Sensitivity analysis

We test the sensitivity of our NBS results from Section 5.3 in two different settings – one assuming current regional population sizes (see Table 1), the other assuming projected population sizes in 2045 [58].[20] In both settings we consider each of the following three effects. First, we measure the sensitivity of regional i's net benefit (NB_i) to successive increases in [47] projected water augmentation rates from their baseline levels of $r_1 = 0.2$ and $r_2 = 0.1$ (see Table 2). We assume successive increases in these rates by a factor of 0.05, e.g., from $\left(r_1 = 0.2, r_2 = 0.1\right)$ to $\left(r_1 = 0.25, r_2 = 0.15\right)$ to $\left(r_1 = 0.3, r_2 = 0.2\right)$, etc. Given the baseline results of $NB_i < 0, i = 1, 2$ from Section 5.3, our goal here is to measure the extent to which the BRDP would hypothetically need to costlessly augment the regions' available water supplies in order for the baseline results to be reversed, i.e., for $NB_i > 0, i = 1, 2$.

Second, we measure the sensitivity of Section 5.3's baseline results to economy-wide aggregation of the BRDP's annual repayment costs, rather than region-wide cost shares. Recall from Section 5.3 that $Cost_i, i = 1, 2$ is region i's per-capita cost share under the BRDP agreement. Here, we consider a hypothetical, joint per-capita cost-share arrangement (henceforth denoted as $Cost$), whereby the project's total annual repayment cost of \$80 million is divided equally among Cache Valley's and the Wasatch Front's aggregated population sizes of 2,642,046 (current aggregate population size) and 3,750,696 (projected aggregate population size by 2045), respectively. And third, based upon [59] average estimate that resource and environmental costs account for 62% of the typical water-development project's total accounting cost, we measure the sensitivity of our NBS results to the inclusion of these external costs.

Fig. 4 depicts our results for the sensitivity of regional i's net benefit (NB_i) to successive costless increases in [47] projected water augmentation rates from their baseline levels of $r_1 = 0.2$ and $r_2 = 0.1$ assuming current regional population sizes. The figure's horizontal axis charts the successive increases in $\left(r_1, r_2\right)$, denoted as $\left(r_{Cache}, r_{WF}\right)$, respectively, and its vertical axis measures corresponding per-capita, regional compensating variation levels relative to both regional and economy-wide annual repayment costs – each measured in \$/person/year. Cache Valley's per-capita compensating variation curve(denoted $CV(Cache)$) and annual repayment cost curve (denoted $Cost(Cache)$) are depicted in the color gray, and the average Wasatch Front county's compensating variation curve (denoted $CV(WF)$) and annual repayment cost curve (denoted $Cost(WF)$) are depicted in blue. The hypothetical aggregate cost-share curve (denoted $Cost$) is depicted in the color red.[21]

From Fig. 4 we see that when facing their respective region-specific, per-capita cost shares, i.e., $Cost(Cache)$ and $Cost(WF)$, Cache Valley's per-capita net benefit is negative at all water augmentation rates, and the Wasatch Front's per-capita net benefit becomes positive at point B, corresponding roughly to ($r_{Cache} = 1.425$, $r_{WF} = 1.325$). Referring to the corresponding data table in Appendix A, we see that the Wasatch Front's per-capita net benefit equals \$1.40 and Cache Valley's equals -\$113.55 at ($r_{Cache} = 1.45$, $r_{WF} = 1.35$), the closest discrete augmentation rate combination associated with positive net benefits in the Wasatch Front. Hence, without a side-payment made from the Wasatch Front to Cache Valley, the NBS is unattainable, even at noticeably larger (albeit hypothetical) water augmentation rates. To see this, we multiply the Wasatch Front's per-capita net benefit of \$1.40 by the region's total population size of 2,508,305 (referring to Table 1 this is equal to the per-county population size of 501,661 multiplied by the five counties comprising the Wasatch Front), which equals \$3,511,627. We then divide this amount by Cache Valley's population size of 133,741, which equals \$26.26. Since this potential per-capita side-payment from the Wasatch Front is well below Cache Valley's negative per-capita net benefit of \$113.55, we conclude that even with a potential side-payment from the Wasatch Front to Cache Valley, the NBS is not viable.

To the contrary, when facing the hypothetical joint per-capita cost-share arrangement represented by the hashed horizontal red line at $Cost = 30.28$ in Fig. 4, Cache Valley's per-capita net benefit becomes positive at point A, corresponding roughly to ($r_{Cache} = 1.275$, $r_{WF} = 1.175$). However, now the Wasatch Front's per-capita net benefit is negative at all water augmentation rates. Using the same method as was used above to show that no side-payment from the Wasatch Front to Cache Valley can support the NBS under the BRDP's proposed regional cost shares, we find that Cache Valley's maximum per-capita side payment of \$0.13 is well beneath the Wasatch Front's negative per-capita net benefit of \$14.25, indicating that the NBS is unsupportable under hypothetical joint cost sharing as well.[22]

[20] The year 2045 represents the midpoint of [47] 50-year planning horizon.

[21] The corresponding data table for both Figs. 4 and 5 is contained in Appendix A.

[22] The NBS is unattainable under joint cost-sharing even at the highest water augmentation-rate combination of ($r_{Cache} = 1.5$, $r_{WF} = 1.4$), since the highest per-capita side-payment Cache Valley is capable of making at this rate combination is \$1.40, which is still beneath the Wasatch Front's negative per-capita net benefit of \$3.13.

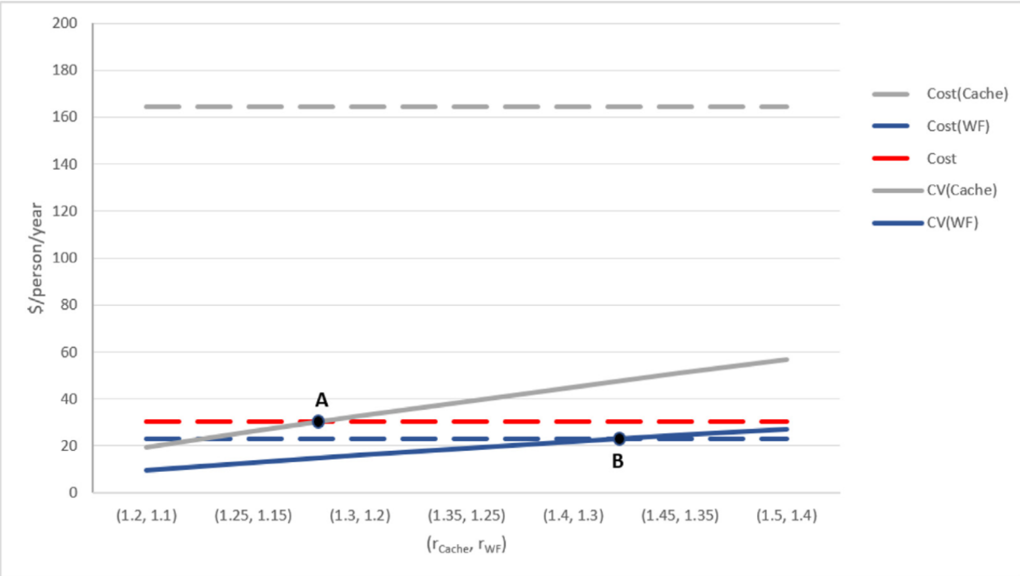

Fig. 4. Regional net benefits with increasing water augmentation rates and current populations. ($Cost(Cache)$ and $Cost(WF)$ represent the BRDP's regional cost shares, and $CV(Cache)$ and $CV(WF)$ are corresponding compensating variation values. $Cost$ represents the hypothetical joint cost share.)

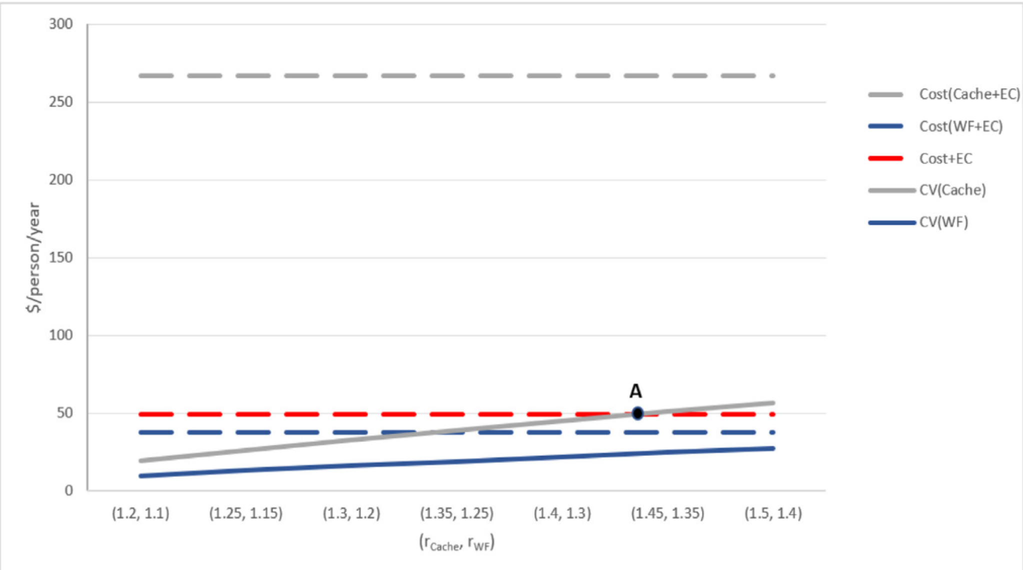

Fig. 5. Regional net benefits with increasing water augmentation rates, current populations, and internalized environmental costs. ($Cost(Cache + EC)$ and $Cost(WF + EC)$ represent the BRDP's regional cost shares with internalized environmental costs, and $CV(Cache)$ and $CV(WF)$ are corresponding compensating variation values. $Cost + EC$ represents the hypothetical joint cost share with internalized cost shares.)

Fig. 5 depicts our results again for the sensitivity of region i's net benefit (NB_i) to successive increases in [47] projected water augmentation rates assuming current regional population sizes, but this time in the presence of now-internalized environmental costs (ECs). From the figure we see that when ECs are internalized, neither region attains positive per-capita net benefits at any water augmentation-rate combination. When facing the hypothetical joint per-capita cost-share arrangement represented by the hashed horizontal red line at $Cost = 49.05$, Cache Valley's per-capita net benefit becomes positive at point A, corresponding roughly to ($r_{Cache} = 1.43$, $r_{WF} = 1.33$). Clearly, even with a potential side-payment from Cache Valley to the Wasatch Front at any possible water augmentation-rate combination the NBS is not viable.

Lastly, we present numerical results for the future-population setting. For reference purposes, we begin by comparing current and future population estimates in Table 4. We see that populations in all counties are expected to increase quite significantly, with the greatest percentage increase expected for the Wasatch Front's Utah County.

Table 4
Current and projected population sizes for cache valley and the Wasatch Front.

County	Current population size[a]	Projected population size[b]
Cache Valley	133,741	195,325
Wasatch Front		
Salt Lake County	1,164,859	1,470,574
Utah County	670,844	1,192,304
Weber County	255,468	344,025
Davis County	359,925	474,028
Box Elder County	57,207	74,440
Total (Wasatch Front)	2,508,305	3,555,371

[a]Number of individuals, as reported in [57].
[b]Number of individuals, as reported in [58] for 2045.

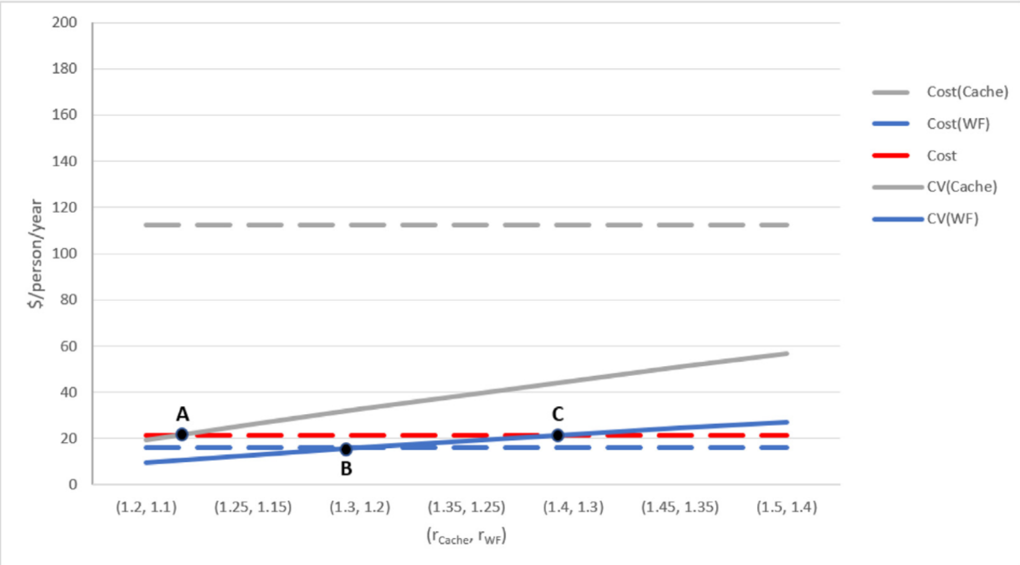

Fig. 6. Regional net benefits with increasing water augmentation rates and projected populations. ($Cost(Cache)$ and $Cost(WF)$ represent the BRDP's regional cost shares, and $CV(Cache)$ and $CV(WF)$ are corresponding compensating variation values. $Cost$ represents the hypothetical joint cost share.)

Fig. 6 depicts our associated sensitivity results for the future-population setting without internalized ECs (the corresponding data table for both Figs. 6 and 7 is contained in Appendix B).[23] In comparison with the results presented in Fig. 4, we again see that – when facing their respective region-specific per-capita cost shares ($Cost(Cache)$ and $Cost(WF)$) – Cache Valley's per-capita net benefit is negative at all water augmentation rates r_{Cache} and r_{WF}. The Wasatch Front's per-capita net benefit becomes positive at point B, corresponding roughly to ($r_{Cache} = 1.3$, $r_{WF} = 1.2$). Clearly, with or without a side-payment from the Wasatch Front to Cache Valley, the NBS is unattainable.

However, when facing the hypothetical joint per-capita cost-share arrangement represented by the hashed horizontal red line at $Cost = 21.33$, Cache Valley's per-capita net benefit becomes positive at point A, corresponding roughly to ($r_{Cache} = 1.225$, $r_{WF} = 1.125$), and the Wasatch Front's per-capita net benefit becomes positive at point C, corresponding roughly to ($r_{Cache} = 1.4$, $r_{WF} = 1.3$). From Appendix B data table we see that between these two water augmentation-rate combinations Cache Valley is unable to afford the necessary side-payment to entice the Wasatch Front to participate in the NBS. Thus, the NBS is unattainable unless augmentation rates reach the ($r_{Cache} = 1.4$, $r_{WF} = 1.3$) levels, where the Wasatch Front's per-capita net benefit also becomes positive. At this water augmentation-rate combination the NBS is viable without the need for side-payments.

Fig. 7 depicts our final set of results, in this case for internalized ECs in the presence of future population levels. Similar to our previous results, the NBS is unattainable with or without side-payments and whether annual repayment cost shares are region-specific, as stipulated in [47], or hypothetically administered according to a joint per-capita cost-share arrangement.

In the case of region-specific cost shares, the point at which the Wasatch Front's net benefit becomes positive (point B) does not generate a large enough net benefit to fund a side-payment to Cache Valley that would garner its participation in the NBS. Similarly, in the case of a joint cost-share arrangement, the point at which Cache Valley's net benefit becomes positive (point A) does not generate a large enough net benefit to fund a side-payment to the Wasatch Front.

[23] For this analysis we assume that the BRDP's annual repayment costs as well as regional per-capita compensating variations $CV_i, i = 1, 2$, remain constant in the face of growing regional population sizes. In general, we would expect per-capita compensating variations to change in response to changes in production and input-use levels as the regions's respective economies grow.

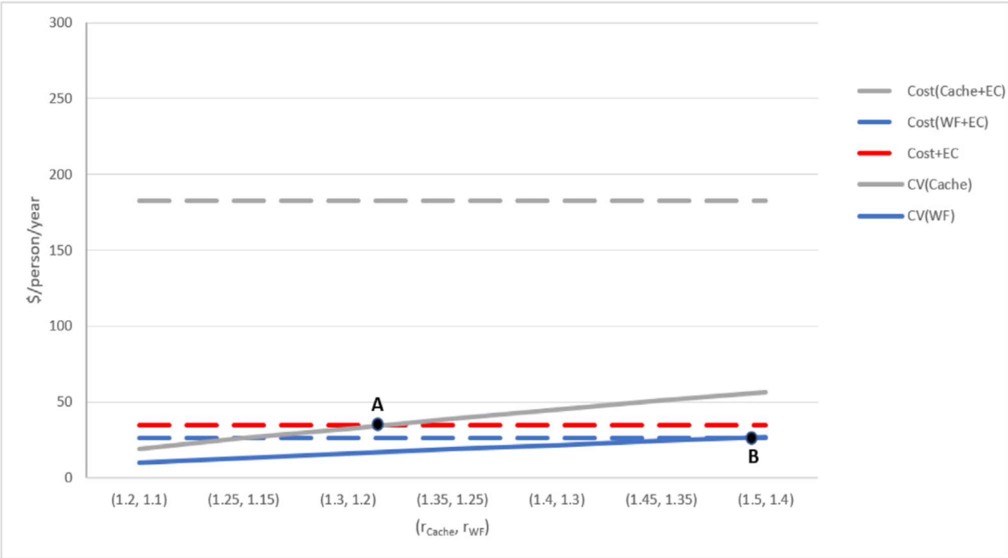

Fig. 7. Regional net benefits with increasing water augmentation rates, projected populations, and internalized environmental costs. ($Cost(Cache + EC)$ and $Cost(WF + EC)$ represent the BRDP's regional cost shares with internalized environmental costs, and $CV(Cache)$ and $CV(WF)$ are corresponding compensating variation values. $Cost + EC$ represents the hypothetical joint cost share with internalized cost shares.)

6. Summary and conclusions

In this paper, we have extended the axiomatic Nash bargaining approach to the context of interregional water sharing in order to assess the approach's normative implications in a general equilibrium framework. As [33] showed, the NBS uniquely satisfies four properties desired in any sharing agreement: Pareto efficiency, symmetry in the bargainers' respective utility levels net of their disagreement points, invariance to affine transformations of bargainers' utility functions, and independence of irrelevant alternatives. We have applied our conceptual general-equilibrium model to a water development and sharing project proposed for the Wasatch Front and Cache Valley regions of Utah – the Bear River Development Project (BRDP) – and demonstrated how an allocation rule and attendant net regional welfare measures are endogenously determined as equilibrium solutions to the bargaining problem. Numerical analysis, based upon a simulation model calibrated to current data, reveals that Nash bargaining is generally infeasible as a solution mechanism for sharing surplus surface-water supplies generated through the implementation of the BRDP, with or without potential ex post side-payments made between Cache Valley and the Wasatch Front. Only in the special case of (1) larger future regional population sizes, (2) a hypothetical, joint per-capita cost-share arrangement where total project costs are shared equally across the two regions, (3) hypothetically larger water augmentation rates, and (4) ignoring potential environmental costs, is the Nash bargaining solution viable. Otherwise, for all other scenarios, the NBS is found to be unattainable as a potential mechanism to share surplus water supplies produced by the BRDP.

It is interesting to note that our admittedly pessimistic findings for the BRDP align with those reached for another major water development and sharing agreement proposed for the southern part of Utah, the Lake Powell Pipeline (LPP) project. In the case of the LPP, evidence suggests that Washington County (which would receive approximately 95% of the project's water supply) will incur debt, and thereby be forced to increase water rates and/or increase impact fees, at levels deemed financially unsustainable [60–62]. For example, [62] estimate annual per-capita repayment costs for Washington County residents of $369 – $761, which dwarf those estimated by UDWR [47] for the BRDP examined in this study. Although [62] and [60] focus exclusively on the cost side of the ledger, the LPP's relatively large per-capita repayment costs points to a likely inviability under a Nash bargaining framework, at least to the extent to which the compensating variation measures calculated in this study for Cache Valley and the Wasatch Front apply to residents of Washington County.

The major limitation of our numerical analysis is its reliance on highly aggregated data across industries and sectors of the economies that drive the main uses of water in the two regions. Our current level of aggregation – to the agricultural and composite-good sector levels – dispels more disaggregated information about the regional economies that could at the very least refine our numerical results. As such, our numerical results are perhaps, at this stage, more demonstrative than actionable from a policymaking perspective. Nevertheless, the results are suggestive of issues that should be addressed as a project such as the BRDP moves closer to implementation. Questions concerning the cost-share arrangement, water augmentation rates, and the extent to which environmental costs are explicitly accounted for need to be answered. Should total project costs be shared equally across the two regions, or assigned regionally, as they are currently specified in the BRDP? To what extent can the project's water augmentation rates be increased in order to ensure an economically viable interregional water-sharing agreement? To what extent should potential environmental costs be incorporated in the analysis upfront?

While our analysis has not explicitly incorporated potential effects from climate change, the framework for our analysis suggests that as river flow diminishes in response to reduced snowpack and higher year-round temperatures in both the Wasatch Front and Cache Valley (as indicated by US Environmental Protection Agency (USEPA) [63]), the viability of Nash bargaining as a mechanism to share surplus water supplies produced by the BRDP will hinge on two opposing influences. On the supply side, reduced water availability will tend to diminish potential economic surpluses resulting from the NBS. However, on the demand side it could be that, sans aggressive water conservation efforts enacted by regional regulatory authorities, household willingness-to-pay for water supplied via the BRDP will increase enough to offset the anticipated supply-side effect, particularly among Wasatch Front households. The results from this study suggest the offset would need to be considerable.

A transcendent question is whether surplus-sharing mechanisms such as the Nash bargaining solution have a place in the public decision-making rubric. Can mechanisms like this be operationalized to inform actual interregional surplus-sharing decisions? We believe the answer is yes. This paper demonstrates how the mechanism can potentially be utilized to generate endogenous measures of net regional welfare, which in turn provides a basis upon which to determine the economic viability of water-sharing arrangements.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Data tables for Figs. 4 and 5

(r_{Cache}, r_{WF})	$Cost(Cache)$	$Cost(WF)$	$Cost$	$Cost(Cache+EC)$	$Cost(WF+EC)$	$Cost+EC$	$CV(Cache)$	$CV(WF)$
(1.2, 1.1)	164.50	23.12	30.28	266.49	37.46	49.05	19.22	9.78
(1.25, 1.15)	164.50	23.12	30.28	266.49	37.46	49.05	26.10	12.97
(1.3, 1.2)	164.50	23.12	30.28	266.49	37.46	49.05	32.69	16.03
(1.35, 1.25)	164.50	23.12	30.28	266.49	37.46	49.05	39.01	18.97
(1.4, 1.3)	164.50	23.12	30.28	266.49	37.46	49.05	45.09	21.80
(1.45, 1.35)	164.50	23.12	30.28	266.49	37.46	49.05	50.95	24.52
(1.5, 1.4)	164.50	23.12	30.28	266.49	37.46	49.05	56.60	27.15

$Cost(Cache)$ and $Cost(WF)$ represent the BRDP's regional cost shares, and $CV(Cache)$ and $CV(WF)$ are corresponding compensating variation values. $Cost$ represents the hypothetical joint cost share. $Cost(Cache + EC)$ and $Cost(WF + EC)$ represent the BRDP's regional cost shares with internalized environmental costs.

(r_{Cache}, r_{WF})	$NB(Cache)$ Associated with:				$NB(WF)$ Associated with:			
	$Cost(Cache)$	$Cost$	$Cost(Cache+EC)$	$Cost+EC$	$Cost(WF)$	$Cost$	$Cost(WF+EC)$	$Cost+EC$
(1.2, 1.1)	−145.28	−11.06	−247.27	−29.83	−13.34	−20.50	−27.68	−39.27
(1.25, 1.15)	−138.40	−4.18	−240.39	−22.95	−10.15	−17.31	−24.49	−36.08
(1.3, 1.2)	−131.81	2.41	−233.80	−16.36	−7.09	−14.25	−21.43	−33.02
(1.35, 1.25)	−125.49	8.73	−227.48	−10.04	−4.15	−11.31	−18.49	−30.08
(1.4, 1.3)	−119.41	14.81	−221.40	−3.96	−1.32	−8.48	−15.66	−27.25
(1.45, 1.35)	−113.55	20.67	−215.54	1.90	1.40	−5.76	−12.94	−24.53
(1.5, 1.4)	−107.90	26.32	−209.89	7.55	4.03	−3.13	−10.31	−21.90

Appendix B. Data tables for Figs. 6 and 7

(r_{Cache}, r_{WF})	$Cost(Cache)$	$Cost(WF)$	$Cost$	$Cost(Cache+EC)$	$Cost(WF+EC)$	$Cost+EC$	$CV(Cache)$	$CV(WF)$
(1.2, 1.1)	112.63	16.31	21.33	182.47	26.43	34.55	19.22	9.78
(1.25, 1.15)	112.63	16.31	21.33	182.47	26.43	34.55	26.10	12.97
(1.3, 1.2)	112.63	16.31	21.33	182.47	26.43	34.55	32.69	16.03
(1.35, 1.25)	112.63	16.31	21.33	182.47	26.43	34.55	39.01	18.97
(1.4, 1.3)	112.63	16.31	21.33	182.47	26.43	34.55	45.09	21.80
(1.45, 1.35)	112.63	16.31	21.33	182.47	26.43	34.55	50.95	24.52
(1.5, 1.4)	112.63	16.31	21.33	182.47	26.43	34.55	56.60	27.15

$Cost(Cache)$ and $Cost(WF)$ represent the BRDP's regional cost shares, and $CV(Cache)$ and $CV(WF)$ are corresponding compensating variation values. $Cost$ represents the hypothetical joint cost share. $Cost(Cache + EC)$ and $Cost(WF + EC)$ represent the BRDP's regional cost shares with internalized environmental costs.

(r_{Cache}, r_{WF})	$NB(Cache)$ Associated with:				$NB(WF)$ Associated with:			
	$Cost(Cache)$	$Cost$	$Cost(Cache+EC)$	$Cost+EC$	$Cost(WF)$	$Cost$	$Cost(WF+EC)$	$Cost+EC$
(1.2, 1.1)	−93.41	−2.11	−163.25	−15.33	−6.53	−11.55	−16.65	−24.77
(1.25, 1.15)	−86.53	4.77	−156.37	−8.45	−3.34	−8.36	−13.46	−21.58
(1.3, 1.2)	−79.94	11.36	−149.78	−1.86	−0.28	−5.30	−10.40	−18.52
(1.35, 1.25)	−73.62	17.68	−143.46	4.46	2.66	−2.36	−7.46	−15.58
(1.4, 1.3)	−67.54	23.76	−137.38	10.54	5.49	0.47	−4.63	−12.75
(1.45, 1.35)	−61.68	29.62	−131.52	16.40	8.21	3.19	−1.91	−10.03
(1.5, 1.4)	−56.03	35.27	−125.87	22.05	10.84	5.82	0.72	−7.40

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