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ORIGINAL PAPER

Who pays for water scarcity? Evaluating the welfare implications of water infrastructure investments for cities

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Abstract

Continued provision of low-cost municipal and industrial water is anticipated to be a challenge for cities in the coming decades. To address this, many are considering large-scale infrastructure projects to expand their water supply. In this article, we develop a general equilibrium model to evaluate the economy-wide distributional impacts of water infrastructure projects. The model framework includes a regulated water utility with a cost-recovery mandate and captures the trade-off between the immediate costs of financing infrastructure projects and the long-term costs that water scarcity imposes on the regional economy. We apply the model to an on-going water infrastructure project in Las Vegas, Nevada.

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1 Introduction

Provision of low-cost water for municipal and industrial (M&I) use is an important policy objective for cities worldwide, influencing patterns of residential development, business location and investment decisions, and household welfare (Klaiber et al. 2017; Fan et al. 2018). Continued provision of low-cost M&I water in coming decades is anticipated to be a challenge for many cities in the USA due to increasing demand and changing supplies (Watson and Davies 2011). To address this, many cities are considering—or have begun working on—large-scale infrastructure projects to expand or maintain their water portfolios. While infrastructure projects can bring large benefits to regional economies over time by increasing water availability and, thereby, reducing the costs of water scarcity, they are also expensive to construct, often involved significant sunk costs, and have permanent operating and maintenance costs.[1] The net benefit of a water infrastructure project depends on the magnitude and timing of these benefits and costs.

Evaluating water infrastructure projects requires an economy-wide model that can assess both the direct and indirect impacts of water scarcity on households and firms. In this article, we develop a general equilibrium (GE) model that captures the economy-wide impacts of water scarcity in an urban setting where M&I water is provided by a municipal water utility that operates as a regulated monopoly with a cost-recovery (i.e., zero-profit) mandate. Water utilities' cost-recovery mandates prohibit them from charging rate payers for the opportunity cost of scarce water, so that the value of scarce water appears in the price of other assets in the economy. Previous GE models have not considered the role that the regulated monopoly status of most water utilities plays in determining the economic impacts of water scarcity in cities, and, as such, cannot provide realistic representation of the economic impacts infrastructure projects that increase water availability (e.g., Dixon 1990; Berck et al. 1991; Goodman 2000; Watson and Davies 2011; Rose et al. 2011).[2]

That the water utility's cost-recovery mandate prohibits it from earning economic rents from customers on the water rights in its portfolio has two implications for our analysis. First, this assumption implies that the water utility makes production and pricing decisions assuming that the untreated (raw) water that it holds perennial rights over has no opportunity cost so that the marginal cost associated with its supply is determined solely by the cost of non-water inputs. While this assumption accords with the decision-making of most regulated public

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[1] An important motivation for previous general equilibrium models of public infrastructure projects is that these projects often have limited alternative uses and therefore involve sunk costs, so that ex ante analysis is particularly necessary to ensure that expected benefits exceed these costs (Rioja 1999; Seung and Kraybill 2001; Haughwout 2002; Rioja 2003; Giesecke et al. 2008; Brueckner and Picard 2015).

[2] Previous studies using GE models to analyze the role of water in the economy have been conducted at a variety of geographic scales, including international (Berrittella et al. 2007; Calzadilla et al. 2011), national (Diao and Roe 2003; Hassan and Thurlow 2011), interregional (Berck et al. 1991; Goodman 2000; Gomez et al. 2004; Watson and Davies 2011), single-region rural (Seung et al. 1998, 2000), and single-region urban (Dixon 1990; Rose and Liao 2005; Rose et al. 2011).

utilities, previous studies have generally assumed that utilities face a constant, nonzero marginal cost for all raw water regardless of ownership (e.g., Dixon 1990) and have implicitly assumed that water utilities can lease water to other sectors in the economy to maximize the economic rent on the water assets in their portfolio (e.g., Goodman 2000; Watson and Davies 2011), which runs counter to their cost-recovery mandate.

Second, the assumption that the regulated water utility is prohibited from earning economic rents on its water rights holdings implies that water scarcity rents are not capitalized in the water sector. We assume in our model that scarce water limits residential housing growth so that the water scarcity rent is capitalized in the housing market. The assumption that scarce water limits residential housing growth reflects the practice that developers must obtain water rights and donate them to water utilities (or cash in lieu of) in order to undertake new construction.[3] Under this system, an increase in the cost of acquiring water rights due to water scarcity will limit new construction and, thereby, increase the value of existing real estate.

Our empirical case evaluates the Southern Nevada Water Authority (SNWA)'s Groundwater Development Project (GWD), which will build a pipeline to transport groundwater from rural east-central Nevada 300 miles south to the Las Vegas–Henderson–Paradise metropolitan statistical area (henceforth Las Vegas). The groundwater to be accessed by the GWD is the only significant new water source available to meet projected increases in water demand in Las Vegas due to population growth (Southern Nevada Water Authority 2017).[4] Despite this, it remains an open question whether the GWD benefits are commensurate with its significant construction and operating costs. The analysis assumes that the GWD is financed by customers in Las Vegas through higher water rates.[5]

We parameterize our empirical model using microbilling data on household and firm water consumption in Las Vegas. The microbilling data allow us to accurately portray water use and payments to the municipal water sector from households and industrial sectors, and give us confidence in our predictions of

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[3] Water utilities typically act as wholesalers of water rights, buying and selling water rights on an ongoing basis to provide liquidity to the water rights market and to reduce transaction costs for developers. In Las Vegas, the SNWA's water rights are managed by an independent nonprofit corporation (Southern Nevada Water Authority 2018). Profits from water rights sales do not appear on SNWA's balance sheet, which suggests that this nonprofit corporation does not seek to exploit arbitrage opportunities in the water rights market.

[4] Existing infrastructure is based on delivery of Nevada's share of Lower Colorado River Compact water. Other compact members (California, Arizona, and Mexico) are unlikely to be in a position to permanently transfer portions of their annual allotments to Nevada given that water demand is projected to exceed supply for the Colorado River Basin as a whole by a median 3.2 million acre-feet annually by 2060 (U.S. Bureau of Reclamation 2012). Further, Las Vegas has nearly exhausted its ability to transfer water from nearby agriculture to M&I use.

[5] While our assumption that GWD is financed by customers through higher water rates accords with reality in Las Vegas and other cities serviced by a regulated water utility, previous GE models have assumed that water infrastructure investments are financed by exogenous government surplus or outside investors (e.g., Seung and Kraybill 2001; Rioja 2003; Strzepek et al. 2008; Bom and Ligthart 2014).

the distributional impacts of the GWD. The majority of regional GE models in the US use *IMPLAN* data to calibrate production and utility functions (e.g., Goodman 2000; Rose and Liao 2005; Watson and Davies 2011). It is not possible, however, to isolate payments for M&I water from the *IMPLAN*-provided sectors.[6]

Our empirical results consider the welfare impacts of the Las Vegas GWD infrastructure against a baseline case of where scarce water limits residential housing supply. Our choice to evaluate the GWD against a no-policy baseline is a reflection of the limited policy options available to Las Vegas to manage water demand.[7] We report results for 2030 and 2050 and find that the additional water supplied by the GWD project is not needed in 2030, but the increased price of municipal water for households and firms as required to service the debt reduces welfare. In contrast, we find that the water infrastructure project improves welfare in 2050, when the additional water from the pipeline project prevents the system from becoming supply-constrained and allows Las Vegas to avoid higher home prices driven by water scarcity. The results suggest that the intertemporal trade-offs are significant, with substantial welfare losses from the project in 2030 (annual losses of \$200–\$2200 per household, depending on household income group) but substantial benefits in 2050 (annual benefits of \$400–\$2900).

This article only considers the costs and benefits of the GWD in Las Vegas. The paper does not consider whether the net benefits (if any) of the GWD for Las Vegas are sufficient to compensate for the potential environmental costs of groundwater pumping in the three rural counties in Nevada—Lincoln, White Pine, and Nye—where the water for the GWD is sourced. A full benefit–cost analysis of the GWD should consider these environmental costs, as well as the economic benefits for rural counties associated with constructing and maintaining the GWD infrastructure.

The remainder of this article is structured as follows. Section 2 describes the literature that has used general equilibrium modeling to assess the impacts of infrastructure. Section 3 develops an analytical GE model to illustrate our approach in modeling the regulated water utility and water infrastructure project. Section 4 describes our empirical GE model of the Las Vegas economy and parameterization. Section 5 presents results on welfare and other impacts of the GWD for Las Vegas in 2030 and 2050. Section 6 concludes.

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[6] In *IMPLAN*, municipal water appears in two sectors: private water utility sector (sector 51) and public utilities (sector 526). After reconstructing the water sector for Las Vegas using both sectors 51 and 526, we find the off-the-shelf data from *IMPLAN* understates the size of the municipal water sector by a factor of more than two and also inaccurately represents the relative water-intensities of industrial sectors.

[7] Las Vegas currently recycles almost 100% of indoor water and has already implemented one of the most aggressive voluntary conservation programs in the USA, suggesting likely decreasing returns from future conservation efforts. Between 2002 and 2016, the region reduced its net gallons per capita per day by 38% (Southern Nevada Water Authority 2017). Further, there is almost no scope for expanding Las Vegas' M&I water portfolio by transferring water out of nearby agriculture or by developing alternative water resources such as rainwater recycling (Southern Nevada Water Authority 2017).

2 Review of the literature on general equilibrium modeling of infrastructure

There are many examples of GE models used to evaluate the economy-wide impacts of public infrastructure (Rioja 1999; Seung and Kraybill 2001; Haughwout 2002; Rioja 2003; Giesecke et al. 2008). The existing literature includes many examples of GE models that have been used to examine the economic consequences of alternative water projects, allocations, or prices, as well as the effects of increasing scarcity. See Calzadilla et al. (2017) for a recent survey of the literature on water-related GE models.

Berck et al. (1991) develop one of the first GE models to include water use. They measure a shadow price for water that would be diverted from agricultural production and evaluate this shadow price in the context of water prices in nearby urban areas. In their application, urban water users could easily afford to compensate rural farmers for the marginal value product of the water taken out of irrigated agriculture.

Seung et al. (2000) examine the impacts of water transfers from agriculture to recreational uses without explicitly modeling water as a factor of production. More recent GE models have incorporated water as a separate input to sectoral production (Goodman 2000, Gomez et al. 2004) to address economy-wide impacts of water allocation at scales ranging from watershed to national, and even international (Berrittella et al. 2007). GE models that explicitly account for the role of water can also illustrate potential impacts of climate change (Calzadilla et al. 2011).

Goodman (2000) uses a GE model to demonstrate the economic impacts of water trades in the Arkansas River Basin in southeastern Colorado, finding that water trading that compensates agricultural water users can improve welfare for both agricultural and M&I users. Watson and Davies (2011) develop an 18 sector GE model to analyze the implications of future increases (25–30 years in the future) in urban water demand with and without water rights markets. Rose et al. (2011) used a GE model to examine the short-term economic effects of water supply disruptions due to an earthquake in Los Angeles, California, and Portland, Oregon, respectively. Other recent examples of water-related GE models that consider M&I water use include Hassan and Thurlow (2011), Luckmann et al. (2014), Zhong et al. (2015), Faust et al. (2015), Fang et al. (2016), and Chemingui and Thabet (2016). In all cases, these models follow Dixon (1990) in assuming a nonzero opportunity cost for water supplied by a utility.

We build on this literature to develop a GE model of water use that accounts for the regulated monopoly status of most water providers. In this context, cost-recovery means that utilities cannot charge for the opportunity cost of scarce water. We also use microbilling data to accurately account for the consumption of water in households and in each of the productive sectors of the economy.

3 A general equilibrium model with a regulated water utility

This section develops a three-sector GE model of a closed-economy to illustrate the model innovations related to the regulated water utility. We use the model to explore the impact of a water infrastructure project on regional welfare. In the next section, we generalize the three-sector model developed here to an applied GE model with fourteen industrial sectors, nine household groups, nine wage groups for labor, four government sectors, six housing types, and trade with the outside world in order to analyze the impacts of the GWD for Las Vegas.

3.1 Production

There are three sectors in the economy: industry (m), housing services (s), and a regulated water utility (u). Each sector produces $Y_i, i = m, s, u$, according to a constant returns-to-scale production technology with Leontief intermediate inputs

$$Y_i = \min\left\{A_i L_i^{\alpha_i} K_i^{1-\alpha_i}, \left(\theta_{j,i}\right)^{-1} Y_{j,i}, \left(\theta_{l,i}\right)^{-1} Y_{l,i}\right\}, \quad j, l \neq i, \tag{1}$$

where L_i and K_i are labor and capital used in sector i, A_i is total factor productivity in sector i, $\alpha_i\left(1-\alpha_i\right)$ is the elasticity of output with respect to labor (capital) in sector i, and

$$Y_{j,i} = \theta_{j,i} Y_i, \quad i \neq j, \tag{2}$$

is the quantity of good j used as an intermediate input in sector i. Cost minimization implies

$$wL_i = \alpha_i p_i Y_i \text{ and } rK_i = \left(1-\alpha_i\right) p_i Y_i, \tag{3}$$

$$\mathrm{MC}_i = \left[A_i\left(\alpha_i\right)^{\alpha_i}\left(1-\alpha_i\right)^{1-\alpha_i}\right]^{-1} w^{\alpha_i} r^{1-\alpha_i} + \theta_{j,i} p_j + \theta_{l,i} p_l, \tag{4}$$

where p_i is the output price for sector i, w and r are the prices for labor and capital, and MC_i is the marginal cost of production in sector i. We assume that industrial and water utility outputs are used as intermediate inputs, but that housing services are not (i.e., $\theta_{s,m} = \theta_{s,u} = 0$).

3.2 Municipal water sector

Three key assumptions underlie how we model the municipal water sector. First, we assume that a regulated water utility operates under a cost-recovery mandate requiring that its equilibrium profit equals zero and that it not earn economic rents on water rights held in its portfolio. This implies that the water utility makes production decisions assuming a zero marginal cost for untreated (raw) water. We further assume that raw water enters the water utility's production function as a Leontief intermediate input,

$$Y_{rw,u} = \theta_{rw,u} Y_u, \quad 0 < \theta_{rw,u} \leq 1, \tag{5}$$

where $\theta_{rw,u} < 1$ in the case where the utility employs water recycling so that it provides a greater volume of treated water than its raw water input.[8] The assumption that raw water is a Leontief intermediate input with zero marginal cost implies including raw water in (1) for the water utility would not impact the cost-minimizing input demands in (2) and (3).

Second, we assume that to produce and deliver municipal water to a region of population L requires sector-specific capital, such as pumping stations, water treatment facilities, and pipelines. This sector-specific capital is not a complement or substitute with other factors of production and, as such, does not appear in (1). The utility is permitted to earn revenue in excess of variable cost in order to service debt acquired to finance investments in sector-specific capital.[9]

Third, the utility faces a water supply constraint:

$$\left(\theta_{rw,u}\right)^{-1}\bar{Y}_{rw,u} = \bar{Y}_u \geq Y_u, \tag{6}$$

where $\bar{Y}_{rw,u} > 0$ is the volume of raw water available to be treated by the utility given water rights held in its portfolio. We assume that when water supply constraint (6) binds, water availability limits the supply of housing services so that water demand and supply are in equilibrium. This mechanism implies that water scarcity rents are captured in the housing sector, represented by marginal rent, λ_s.

The water utility's cost-recovery mandate together with the assumption of perfect competition in m- and s-sectors imply that, in equilibrium,

$$\begin{aligned} \pi_m &= \left(p_m - MC_m\right)Y_m = 0, \\ \pi_s &= \left(p_s - MC_s - \lambda_s\right)Y_s = 0, \\ \pi_u &= \left(p_u - MC_u\right)Y_u - S_u = 0, \end{aligned} \tag{7}$$

where $\lambda_s = p_s - MC_s \geq 0$ are water scarcity rents capitalized in the housing sector and $S_u \geq 0$ are debt payments for sector-specific capital in the u-sector. We assume that S_u is paid to creditors outside of the region.[10] λ_s is determined by the complementary-slackness condition

$$\bar{Y}_u - Y_u \geq 0 \perp \lambda_s \geq 0. \tag{8}$$

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[8] While several previous studies have assumed that raw water is substitutable with other inputs in the production of treated water (Goodman 2000; Diao and Roe 2003; Rose and Liao 2005; Watson and Davies 2011), we believe that the Leontief assumption with a provision for water recycling is a more accurate description of production by a water utility.

[9] Our assumption of sector-specific capital implies that the regulated utility's production and pricing decisions are influenced by the debt it assumes to finance sector-specific capital rather than by the rental rate of capital in the broader economy. In contrast, previous studies have assumed one type of physical capital that can be used by all sectors in the economy with equilibrium-determined prices (e.g., Goodman 2000; Rose and Liao 2005; Watson and Davies 2011).

[10] The applied GE model assumes, as we do here, that the debt payments for water infrastructure are paid to creditors outside of Clark county. This assumption is in keeping with our approach of underestimating the welfare benefits of GWD.

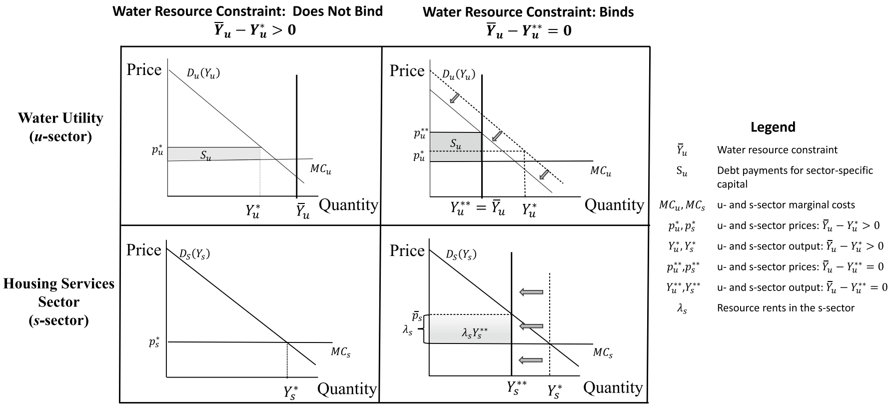

Fig. 1 Model equilibria with water supply constraint. Equilibria for the water utility (*u*-sector) and housing services sector (*s*-sector) when the water supply constraint is slack and when it binds. See text for further detail

Figure 1 illustrates the equilibria in the *u*- and *s*-sectors when (1) the water resource constraint does not bind ($\bar{Y}_u > Y_u$) and there are no water scarcity rents in the economy and when (2) the water resource constraint binds ($\bar{Y}_u = Y_u$) and water scarcity limits the supply of housing so that the water scarcity rents accrue in the *s*-sector.[11]

3.3 Households

The representative household is assumed to maximize utility according to:

$$\max_{Y_{m,h}, Y_{s,h}} \quad U\left(Y_{m,h}, Y_{s,h}\right) = Y_{m,h}^{\beta} Y_{s,h}^{1-\beta}$$

$$\text{s.t.} \quad p_m Y_{m,h} + p_s Y_{s,h} \leq wL + rK + \lambda_s Y_s = I,$$

where $Y_{i,h}$ is the quantity of output from sector i, $i = m, s$, consumed by the household and $\beta(1-\beta)$ is the expenditure share on good $Y_{m,h}\left(Y_{s,h}\right)$. The representative household consumes treated water indirectly through their consumption of *m*- and *s*-sector outputs. The representative household earns income, I, from supplying its labor endowment, L, and capital endowment, K, and from resource rents in s-sector, $\lambda_s Y_s \geq 0$. Utility-maximizing demand functions and indirect utility function are:

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[11] While our assumption that water scarcity rents are capitalized in the housing sector is realistic for Las Vegas, this assumption may not be appropriate in jurisdictions where the water utility does not operate under a cost-recovery mandate. Without a cost-recovery mandate, a utility would be free to set water prices to maximize profit given the constraint that water demand and supply are balanced and, hence, capture water scarcity rents. We do not consider this counterfactual scenario in this article because there is no evidence that an institutional change that would allow utilities in Las Vegas to set water prices above long-run average cost is being contemplated.

$$Y_{m,h} = \frac{\beta}{p_m} I, Y_{s,h} = \frac{1-\beta}{p_s} I, \quad \text{and} \quad v\big(p_m, p_s, I\big) = \left(\frac{\beta}{p_m}\right)^{\beta} \left(\frac{1-\beta}{p_s}\right)^{1-\beta} I. \tag{9}$$

3.4 Model closure and equilibrium

Equilibrium is defined by the three market-clearing conditions for *m*-, *s*-, and *u*-sector outputs

$$Y_m = Y_{m,h} + Y_{m,s} + Y_{m,u}, \quad Y_s = Y_{s,h}, \quad \text{and} \quad Y_u = Y_{u,m} + Y_{u,s}, \tag{10}$$

the two-factor market-clearing conditions,

$$L = L_m + L_s + L_u \quad \text{and} \quad K = K_m + K_s + K_u, \tag{11}$$

the six cost minimization conditions for labor and capital from (3), the three zero-profit conditions from (7), the five conditions for intermediate input demands from (2) and (5), the two household demand functions from (9), and the complementary-slackness condition from (8). The equilibrium solves for 22 endogenous variables: output $\big(p_m, p_s, p_u\big)$ and factor prices (w, r), factor demands for labor $\big(L_m, L_s, L_u\big)$, capital $\big(K_m, K_s, K_u\big)$, and intermediate inputs $\big(Y_{m,s}, Y_{m,u}, Y_{u,m}, Y_{u,s}, Y_{rw,u}\big)$, final output $\big(Y_m, Y_s, Y_u\big)$, household consumption $\big(Y_{m,h}, Y_{s,h}\big)$, and resource rents to scarce water (λ_s).

3.5 Welfare impacts of a water infrastructure project

We use compensating variation (CV) to measure the welfare impact infrastructure investment, where CV for a new water infrastructure project is defined as

$$v\big(p_{m,0}, p_{s,0}, I_0 + \mathrm{CV}\big) = v\big(p_{m,1}, p_{s,1}, I_1\big), \tag{12}$$

where 0 denotes values without the new infrastructure and 1 denote values with the new infrastructure. Using (9), we can express CV as

$$\mathrm{CV} = \big(w_1 L + r_1 K + \lambda_{s,1} Y_{s,1}\big) \left(\frac{p_{m,0}}{p_{m,1}}\right)^{\beta} \left(\frac{p_{s,0}}{p_{s,1}}\right)^{1-\beta} - \big(w_0 L + r_0 K + \lambda_{s,0} Y_{s,0}\big). \tag{13}$$

This expression for CV allows us to investigate the welfare implications of a water infrastructure project that increases the amount of raw water available to the water utility ($\bar{Y}_{u,1} > \bar{Y}_{u,0}$). There are two relevant cases. First, when the system is not supply-constrained without the new infrastructure ($Y^*_{u,0} < \bar{Y}_{u,0}$ and $\lambda^*_{s,0} = 0$), the water utility will be forced to raise its price ($p^*_{u,1} > p^*_{u,0}$) in order to service the additional debt from the new infrastructure ($S_{u,1} > S_{u,0}$). The increase p_u will increase production costs, and, as a result, output prices, in the *m*- and *s*-sectors ($p^*_{m,1} > p^*_{m,0}$ and

$p^*_{s,1} > p^*_{s,0}$), and reduce payments to factors of production ($w^*_1 < w^*_0$ and $r^*_1 < r^*_0$) so that, from (11), the new infrastructure will unambiguously reduce regional welfare.[12]

Second, when the system is supply-constrained without new infrastructure ($Y^*_{u,0} = \bar{Y}_{u,0}$ and $\lambda^*_{s,0} > 0$), the sign of CV is ambiguous. The new infrastructure will reduce the cost of housing services ($p^*_{s,1} < p^*_{s,0}$), which will increase welfare. The increase in the supply of housing services ($Y^*_{s,1} > Y^*_{s,0}$), however, will also increase demand for (and, hence, price of) m-sector output ($p^*_{m,1} > p^*_{m,0}$), which will reduce welfare. This reduction will be offset by an increase in payments to factors of production ($w^*_1 > w^*_0$ and $r^*_1 > r^*_0$), which will increase welfare. Further, the impact of new infrastructure on price of treated water is ambiguous ($p^*_{u,1} \lesseqgtr p^*_{u,0}$) and depends on the increase in debt in the u-sector ($S_{u,1} > S_{u,0}$) and the change in water demand. Given this ambiguity, evaluating the welfare impacts of a specific water infrastructure project requires an applied GE model.

The analytical GE model developed in this section demonstrates that while new water infrastructure has the potential to improve regional welfare when the system would be supply-constrained in the absence of the new infrastructure, the welfare impacts are ambiguous. Therefore, we parameterize a more general version of the analytical GE model in the next section in order to analyze when (if ever) the GWD will improve welfare in Las Vegas and how potential welfare gains or losses depend on future population growth and water availability.

4 Applied general equilibrium model for Las Vegas

The previous section demonstrated that welfare implications of a water infrastructure project are theoretically ambiguous, and that the timing of any potential welfare gain depends on when (if ever) the system becomes supply–constrained in the absence the new infrastructure. In this section, we extend the analytical GE model from the previous section to build an applied GE model capable of analyzing the welfare impacts of the GWD for Las Vegas. The applied GE model developed in this section includes fourteen industrial sectors, nine household groups, nine wage groups for labor, four government sectors, six housing types based on home value, and trade with the outside world. Following Berck et al. (1996) and Cutler and Davies (2007), each industrial sector, including housing services, has a constant elasticity of substitution value-added production function (allowing us to generalize from the Cobb–Douglas production function described above) with three types of primary factor inputs—labor, capital, and land—and Leontief intermediate inputs.

Other than housing services and treated water, industrial sectors in the model are tradable sectors, with outputs consumed in the region (either directly by consumers or as an intermediate input) and exported to the rest of the world according to a constant elasticity of transformation function. Housing services and treated

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[12] The welfare implications for this first case also apply to the case when the system is supply-constrained without new infrastructure but the additional debt causes the utility to reduce water supply, i.e., $Y^*_{u,1} < Y^*_{u,o} = \bar{Y}_{u,0}$.

water produced in Las Vegas can only be consumed in Las Vegas. Treated water is consumed by industrial and housing service sectors as an intermediate input, while housing services can only be consumed by households in Las Vegas.

Households are divided into nine income groups, each modeled with a representative household that receives factor income from labor wages, capital and land rents, and social security transfers from the federal government. After paying income and property taxes, each representative household allocates disposable income to private consumption, housing, savings, and income transfers to other regions. Representative household's demand functions are derived by maximizing a Cobb–Douglas utility function subject to post-tax income. We assume that there are six categories of housing services based on housing type (single family or multi-family), home value, and lot size, and that for each household group (based on income), total housing services expenditure is distributed across the six categories in a fixed proportion in all simulation runs. Following Partridge and Rickman (2010), we do not require that regional capital investment and savings balance.

The model includes federal, state, and two levels of local government (administration and public safety). The federal government collects income taxes from households, and social security payments from employees and employers. The state government receives sales taxes from all industrial sectors, as well as gaming and related taxes. (There is no state income tax in Nevada.) The local government receives property taxes from the industrial and housing services sectors, county-level sales taxes, hotel taxes, and a variety of other taxes from industrial sectors. Government sectors employ factors and purchase Leontief intermediate inputs. We assume that local governments have balanced budgets, but that federal and state governments are allowed to transfer tax revenue to and from the region.

Labor is supplied by households. Numbers of households are determined by exogenous population trends and endogenous net migration that occurs as households respond to changes in local earnings opportunities. Capital supply is investment plus initial capital stock minus depreciation. Capital and land supplies evolve over time following equations A30 and A33 in "Appendix A".

Model closure includes commodity and factor market-clearing conditions. Foreign ownership of capital and land, net exports, and federal and state government regional transfers are not constrained but are calibrated in the model. The structure of our empirical general equilibrium model is summarized in Table 1, with the detailed mathematical construction of the model in "Appendix A".

4.1 Data and parameterization

Data are organized in a Social Accounting Matrix (SAM), building on the method developed by Schwarm and Cutler (2003) and Hannum et al. (2017), and augmented with detailed data supplied by the Las Vegas Valley Water District (LVVWD). A SAM is a comprehensive data framework representing regional economic accounts (Lofgren et al. 2002) that allows specification of exogenous parameters for a GE model. The benchmark year of our data is 2013.

Table 1 Structure of the model and data

Account				Data sources
Productive sectors				
Sector				Data sources
(1) Agriculture	(8) Service			*IMPLAN* Clark County regional Input–Output Table
(2) Mining and extraction	(9) Hospital and health			
(3) Utilities excluding water utility	(10) Accommodation			
(4) Construction	(11) Gambling (excluding casino resorts)			
(5) Manufacture	(12) Food, drinking, and restaurant			
(6) Warehousing and transportation	(13) Casino resorts			
(7) Retail				
(14) Water utility	NAICS code 221310			LVVWD
Housing service sectors				
	Housing types	Size	Housing values	
$HS1$	Single-family housing	Lot size < 1 acre	$HS1 \leq \$20,000$	PUMS and assessor data
$HS2$			$\$20,000 < HS2 \leq \$50,000$	
$HS3$			$HS3 > \$50,000$	
$HS4$		Lot size > 1 acre	$HS4 \leq \$20,000$	
$HS5$			$HS5 > \$20,000$	
$HS6$	Multi-family housing			
Factor				
Labor	Labor demand and supply are obtained from PUMS data. Labor is divided into nine groups by wages or salary income past 12 months			DETR data PUMS data
Capital and land	Capital and land values are the land improvement and land value assessed by the county office			Assessor data
Government sectors				
Federal government	Federal government in Clark County			PUMS and *IMPLAN*
State government	State government in Clark County			

Table 1 (continued)

Account			Data sources
Local government—administration			CAFR
Local government—safe			
Tax sectors			
Sale tax (to state)	Excise and other taxes (to county)		Nevada Department of Taxation Clark county CAFR
Sale tax (to county)	Property tax (to county)		
Room tax (to county)			
Gaming tax (to state)	Live tax(to state)		NV Gaming Control Board
Household groups			
(*Household income includes: wage, interest income, all other income, public assistance, retirement income, self-employment income, supplementary security income, and, social security income*)			
$HH1 < \$10{,}000$	$\$25{,}000 \le HH4 < \$35{,}000$	$\$75{,}000 \le HH7 < \$100{,}000$	PUMS DATA (Household data)
$\$10{,}000 \le HH2 < \$15{,}000$	$\$35{,}000 \le HH5 < \$50{,}000$	$\$100{,}000 \le HH8 < \$150{,}000$	
$\$15{,}000 \le HH3 < \$25{,}000$	$\$50{,}000 \le HH6 < \$75{,}000$	$HH9 \ge \$150{,}000$	

IMPLAN Clark County regional Input–Output Table were validated by Center for Economic Development, University of Nevada, Reno

The employment is validated by PUMS and DETR data

Local government sectors related to courts, police, legal counsel and prosecution, correction institutions, parole offices, fire protection, and other justice and safety sectors. The definition can found in the NAICS code ranging from 922110 to 922190

Data for revenues and expenditures by industry come from the *IMPLAN* Input–Output Table. Employment and wage data are from the 2013 5-year American Community Survey Public Use Microdata Sample (PUMS) household records in the US census. We also use the PUMS data to determine the fixed proportion that total housing services expenditure is distributed across the six housing services categories for each of the nine household groups. Capital and land inputs for productive sector and housing service sectors are from Nevada's Clark County assessor's office and the Nevada Department of Employment, Training and Rehabilitation (DETR).[13]

The challenge for constructing the water sector is that *IMPLAN* does not explicitly report water utility data.[14] To create the water sector, we use microbilling records from the LVVWD, the largest water utility agency in Las Vegas. We approximate the water use for each industrial sector by merging three datasets: LVVWD water billing records, Clark County Tax Assessor data, and DETR data. From this, we obtain water use and a North American Industry Classification System (NAICS) code per parcel. For residential data, we merge LVVWD data with the assessor data to get water use by housing service category. Since the LVVWD service area accounts for approximately 70% of total water consumption in Clark County, we scale-up our water use by industry and households to match total water consumption for Clark County, as provided by the Southern Nevada Water Authority.

In Las Vegas, treated water is not sold outside the region or imported from other regions, and therefore, we impose that imports and exports of the water utility are zero. Our constructed water utility sector yields a positive surplus in our SAM. We interpret the surplus as the annualized cost of financing water-specific capital and infrastructure.[15]

The model's elasticities are selected from previous literature (see "Appendix B"). The remaining exogenous parameters are calculated from the SAM. All prices are set to the unity in the model calibration. Solving the model with base parameters reproduces the 2013 data described in the SAM.

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[13] DETR data identify each firm by six-digit NAICS code. We merge county tax assessor commercial parcel data with DETR employment data using street addresses and geographic information system information to generate money and physical flows of land and capital for each productive sector in Las Vegas. Similarly, we aggregate county tax assessor residential parcel data into six groups based on property value and lot size, and distribute six housing service sectors across the nine household groups using PUMS household records. Assessed value is converted to annualized rental flows using a midterm discount rate of 11%.

[14] One potential method to construct the water sector would be to separate the water utility from IMPLAN's "other local government enterprises" sector based on employment numbers. However, our initial work revealed that this method using IMPLAN data would not work for Las Vegas because approximated total revenue for the water utility would be less than half of the total revenue calculated using LVVWD billing data.

[15] Starting in 2013, a water infrastructure charge has been included with all SNWA customer water bills to fund necessary improvements to facilities at Lake Mead, the reservoir by which Nevada receives its share of Colorado River water. Our method of using tax assessor records does not capture the capital cost of this infrastructure, since it is on federal land. Thus, we use the surplus to represent the current sector-specific infrastructure costs.

4.2 Impact of the GWD on water supply

The largest water resource for the Southern Nevada Water Authority is the Colorado River apportionment, established under the 1922 Colorado River Compact and the Boulder Canyon Project Act. Southern Nevada's total entitlement of the Colorado River is 272,205 acre-feet per year (AFY) (consumptive use). Return-flow credits from water recycling have allowed this total to be extended to 476,359 AFY (diversion equivalent) of water used by households and firms in Las Vegas. We simulate the Las Vegas economy in 2030 and in 2050 under expected shortage conditions for the Colorado River, as predicted in SNWA's 2017 Resource Plan (Southern Nevada Water Authority 2017).[16] Total water supplies in 2030 and 2050 under these projected long-term shortage conditions are 510 thousand AFY. In addition, we also include average customer (industrial and residential) conservation projections of 2.9% by 2030 and 7.3% by 2050 (Southern Nevada Water Authority 2017).

We developed our model to analyze the Las Vegas economy under average annual supply conditions. We focus on average annual supply conditions for two reasons. First, SNWA has undertaken several initiatives to ensure a stable water supply for M&I use in Las Vegas even in the face of multi-year below-average supply conditions. These initiatives include creating 400,000 AF of 'Intentionally Created Surplus' in Lake Mead, 'banking' 806,000 AF of Colorado River water in California and Arizona, and the storage of approximately 337,000 AF in the Las Vegas Valley aquifer (Southern Nevada Water Authority 2017). Given Las Vegas' ability to smooth their water supply over time, average annual supply is a credible representation of M&I water availability despite the inter-annual fluctuations in new water entering the system. Second, our focus on average annual supply conditions is consistent with the basic assumptions underlying our GE framework. The GE framework assumes that firms and households make decisions based on average prices and not on temporary fluctuations in price. Similarly, our focus on average annual supply conditions assumes that firms and households make decisions based on stable M&I prices determined by the utility's cost-recovery mandate and housing service prices that incorporate water scarcity rents based on average annual supply conditions.

To address the projected water shortage, SNWA proposed the GWD to convey groundwater from central and eastern Nevada to Las Vegas. Once completed, the GWD is estimated to have cost a total of \$15.5 billion (2011 dollars) and would transfer 83,988 AFY of raw water into Las Vegas annually.[17] SNWA estimates that

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[16] Approximately 40% of water sold in Las Vegas is recycled (Southern Nevada Water Authority 2017). Of this 40%, 90% is treated to a potable standard and returned to the Colorado River (i.e., Lake Mead) for reuse by M&I customers in Las Vegas. The remaining 10% is not treated to a potable standard and is used directly for outdoor watering, primarily on golf courses. While we do not consider non-potable recycled water as a separate category in our analysis, we do not believe that this simplification influences our conclusions given that non-potable reuse accounts for less than 4% of total water used in Las Vegas.

[17] The approval of the inter-basin transfers of groundwater for the GWD involved several lengthy hearing processes where the Nevada State Engineer's Office had to establish that the groundwater rights in all affected basins be less than or equal to the average perennial yield, which is the amount of water that can be withdrawn without exceeding the natural recharge in the basin (Welsh and Endter-Wada 2017). Given the imperative that all basins supplying water for the GWD be in hydrologic balance, it is expected that water from the GWD will be have limited inter-annual variation in supply.

the water from the project will be available by 2050, but not by 2030. The annualized cost of \$15.5 billion over 30 years is \$668 million assuming an annual interest rate on the debt of 1.5%. We assume that debt incurred by the water utility is paid by the water utility customers through higher water rates so that the water utilities zero-profit conditions from (7) binds in equilibrium. Further, we assume that debt payments for water infrastructure are paid to creditors outside of Las Vegas. The assumption that these debt payments do not represent income for any households in Las Vegas means that we are overestimating the costs of financing the GWD for Las Vegas. Similarly, we do not consider any economic impacts related to constructing the GWD, which will lower the potential benefits of the GWD for Las Vegas predicted by our model. This assumption is reasonable given that much of the GWD construction will take place outside of Clark County, so that much of the labor, capital, and materials used in construction will not come from Las Vegas.

4.3 Model simulations

Following previous studies (Watson and Davies 2011; Burnett et al. 2012), we represent the expected growth of the Las Vegas region by simulating both population and export growth. The numbers of households are determined by a combination of exogenous population growth and endogenous net migration. Net migration is determined by average wage, household disposable income, the unemployment rate, and regional consumer price index. The migration equation is described in "Appendix A". The baseline simulations assume exogenous population growth of 25% by the year 2030 and 50% by 2050 based on projections from the Center for Economic Development at University of Nevada, Las Vegas (Center for Business and Economic Research 2016).

Export growth is implemented by increasing exports of health, construction, transportation and warehousing, accommodation, and food services. Following Burnett et al. (2012), the export growth rates are calibrated to match the predicted increase in employment in the health, construction, transportation, and warehousing, accommodation, and food services sectors in 2030 and 2050 reported in the Clark County Comprehensive Planning report (Clark County 2018).[18]

We assume that total factor productivity (TFP) in the productive sectors and physical capital stock grow at 1% and 2% a year, respectively. The stock-flow relationship between investment and capital stock in our model is described in "Appendix A". The growth rates for sectoral TFP are smaller than those in many recent

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[18] For example, the Clark County Comprehensive Planning report predicts that employment in the health, construction, transportation and warehousing, accommodation, and food services sectors will increase by 60%, 45%, 40%, 25%, and 25% by 2030, and 160%, 150%, 100%, 40%, and 40% by 2050 (Clark County 2018). We cut the growth projections in the Clark County Comprehensive Planning report in half because the high employment growth rates in the report cannot be rationalized under standard assumptions about the growth rates for total factor productivity and capital stock. Further, given that higher export growth will increase the cost of water scarcity for Las Vegas, cutting these growth rates in half is consistent with our approach of selecting model parameters so as to not overstate the potential future benefits of the GWD.

studies (e.g., Fan et al. 2018). Sensitivity analyses[19] suggest that higher TFP growth increases the cost of water scarcity in Las Vegas. Therefore, our decision to use low estimates for TFP growth means that our estimates of the benefits of the GWD are conservative.

We use predicted population and export growth as our baseline scenario (henceforth *baseline*), in which water supplies do not increase so that as population grows so that water becomes scarce. We compare our baseline to the GWD scenario in which both water availability and cost increase (henceforth *GWD scenario*). If the system becomes water supply-constrained, water scarcity rents appear as equilibrium profits in the housing services sector and, as such, are net of housing and construction costs. We assume that these rents are redistributed to households in proportion to land ownership in the model. This assumption reflects the fact that land ownership includes the obligation of the water utility to provide water in perpetuity, i.e., implies ownership of water rights. As such, an increase in the value of water rights will translate into higher land values, thereby influencing the existing housing market.

We use the General Algebraic Modeling System with a nonlinear solver, *CONOPT*, to solve for the equilibrium conditions of the parameterized model. "Appendix C" presents a detailed description of the model implementation.

5 Results

This section uses results from our empirical GE model to evaluate the economy-wide impacts of the GWD for Las Vegas in 2030 and in 2050.[20] We describe impacts for regional population, employment, and production, county and state tax revenue, household housing expenditures and total disposable income, and household welfare. In addition, we consider how our conclusions about the GWD change when we adjust our assumptions about future Colorado River water supply and future population growth in Las Vegas.

5.1 Economy-wide impacts

The water resource constraint does not bind in 2030 under our baseline parameterization but binds in 2050. While the additional water provided by the GWD project is not available or needed in 2030, the annual cost of the debt incurred to finance the GWD is passed on to ratepayers through an increased price of treated water in 2030. As predicted by our analytical GE model, the increase in the price of municipal water implies that the GWD project will reduce welfare in 2030 compared to

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[19] We performed sensitivity analysis of model results assuming faster TFP growth (not reported). As expected, the sensitivity analysis indicated that faster TFP growth increases the negative impact of water scarcity in 2050 and, as a result, causes the benefit of GWD project become larger.

[20] In our baseline parameterization, "2030" or "2050" refers to when the population is increased by 25% or 50%, respectively.

Table 2 Economy-wide impact of groundwater development project

	2030 (25% population increase)			2050 (50% population increase)		
	Base scenario	GWD scenario		Base scenario	GWD scenario	
	Total	Total	% Diff.	Total	Total	% Diff.
Resource constraint bind	No	No		Yes	No	
Supply constraint (1000 AFY)	510	510		510	594	
Residential conservation equivalent	NA	NA		11.3	NA	
Infrastructure cost ($1,000,000 2013)	0	668		0	668	
Housing sector profits	NA	NA		Yes	NA	
Water use Q* (1000 AFY)	498	494	−0.88	510.0	517.1	1.39
Water price (unity price)	1.00	1.96	95.79	1.03	1.91	85.44
Population (# of *HH*)	876,458	875,320	−0.13	1,041,812	1,043,844	0.20
Total county tax	2793	2780	−0.50	3352	3370	0.52
Sale tax to state	2720	2705	−0.54	3258	3299	1.26
Total output	71,737	71,497	−0.33	79,662	80,325	0.83

Dollar figures in millions of 2013

scenarios without the GWD. Table 2 reports that the GWD nearly doubles the average price of treated water in 2030, leading to reductions in population, county and state tax revenue, and industrial revenue relative to the baseline scenario.

In 2050, on the other hand, our simulations predict that without new water resources from the GWD, the system is supply-constrained in "shortage" years for Lower Colorado River Agreement water. We use the shortage scenario as our baseline because it is viewed as the most likely scenario given US Bureau of Reclamation forecasts for water supply in the Colorado River Basin over the next 50 years. Table 2 reports that the population in 2050 is only 0.20% higher in the GWD scenario compared with the base scenario. As with population, the fiscal impacts of the GWD are modest in 2050. From Table 2, GWD scenario total county tax and state-level sale tax revenues from Clark County are increased by $18 million (0.52%) and $41 million (1.26%), respectively, compared to the base scenario, which is due to the combined effect of higher per capita incomes and a larger population in the GWD scenario.[21]

Table 3 orders sectors from least to most water-intensive and shows that in 2050, employment and output by industrial sector in the GWD scenario will be approximately 1% higher, on average, compared with the base scenario.[22] Sectoral use of capital and land follow similar patterns as employment and are not reported. All else equal, the higher price of water in the GWD scenario increases the cost of

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[21] Given the assumption that water ratepayers finance the GWD, the additional tax revenue in the GWD scenario is net of GWD costs.

[22] Water intensity here refers to share of water in total sectoral production costs.

Table 3 Sectoral employment and output

	Base scenario	GWD scenario	
	Total	Total	% Diff.
Sectoral employment			
Mining and extraction	1625	1664	2.40
Utilities excluding water utility services	4089	4133	1.08
Gambling (excluding casino resorts)	33,434	34,246	2.43
Construction	103,262	104,672	1.37
Warehousing and transportation	92,867	94,127	1.36
Manufacturing	34,561	34,932	1.07
Service	303,736	307,276	1.17
Hospital and health	150,935	152,323	0.92
Retail	149,807	151,831	1.35
Casino resorts	126,319	126,618	0.24
Accommodation	83,306	83,629	0.39
Food, drinking, and restaurant services	97,005	96,917	−0.09
Total	1,180,946	1,192,368	0.97
Sectoral output (2013 $)			
Mining and extraction	146	149	2.31
Utilities excluding water utility services	1148	1159	0.95
Gambling (excluding casino resorts)	1579	1616	2.37
Construction	8234	8337	1.26
Warehousing and transportation	7307	7387	1.10
Manufacturing	3056	3084	0.92
Service	22,032	22,246	0.97
Hospital and health	10,821	10,904	0.77
Retail	7496	7579	1.10
Casino resorts	9704	9716	0.13
Accommodation	3737	3748	0.29
Food, drinking, and restaurant services	4345	4339	−0.14
Total	79,603	80,264	0.83

Ranked in Ascending Sectors are ordered in ascending order of water intensity (e.g., from least water-intensive to most water-intensive)

We exclude agriculture from the water intensity rankings. Treated water cannot be legally used in agricultural in Las Vegas, so the agricultural sector has the lowest water intensity of all sectors the LVVWD microbilling data. Agricultural producers in Las Vegas obtain water outside the municipal water system

Total Revenue of Productive Sectors does not include the water utility sector

Dollar figures in millions of 2013

production and depresses employment, particularly in water-intensive sectors. This effect is more than offset by the overall increase in demand in the GWD scenario due to the lower cost of housing and higher disposable income. Overall, employment in less water-intensive sectors is higher in the GWD scenario than in the base scenario, while employment in more water-intensive sectors is similar across the two scenarios. These results suggest that the GWD project will impact both total employment and the distribution of employment across sectors, with the least water-intensive sectors experiencing the largest increases in employment and output. The least water-intensive sectors benefit most from the GWD because they get the boost in demand from the increased economic activity due to the GWD but pay proportionately less of the project's cost through higher water rates.

5.2 Housing and household income

Table 4 reports results for the housing services sector in 2050, showing that housing prices are significantly lower in the GWD scenario relative to the base scenario (4.7–6.4% depending on housing type) while consumption of housing services is higher in the GWD scenario. Table 5 demonstrates that the net effect of higher prices and lower consumption is that total expenditure on housing for each household group is higher in the base scenario compared with the GWD scenario. The higher housing prices in 2050 in the base scenario is a result of water scarcity rents being capitalized in the housing sector.

Table 5 reports real disposable income by household groups. Real disposable income is calculated as nominal disposal income (post-tax) for each household group divided by the consumer price index (CPI) for that group. Real disposable income is higher in 2050 in the GWD scenario compared to the base scenario for each household group, and these differences become more pronounced when income net of housing expenditures is considered. Further, when compared to the GWD scenario, the negative impacts of increased housing costs on household disposable income in the base scenario is not offset by the additional household income from equilibrium profits in the housing sector (resource rents from scarce water).

Table 4 Housing services in 2050

	Base scenario	GWD scenario	
Housing services: price (unity price)			
*HS*1	1.5	1.42	−5.33%
*HS*2	1.53	1.45	−5.23%
*HS*3	1.61	1.52	−5.59%
*HS*4	1.41	1.32	−6.38%
*HS*5	1.54	1.46	−5.19%
*HS*6	1.5	1.43	−4.67%
Housing services: consumption			
*HS*1	11,645	11,920	2.36%
*HS*2	864	883	2.29%
*HS*3	360	367	1.99%
*HS*4	116	119	2.56%
*HS*5	170	174	1.97%
*HS*6	2349	2400	2.21%

Table 5 Real income per household in 2050

	Base scenario		GWD scenario			
	Real income	Housing expenditure	Real income	% Diff.	Housing expenditure	% Diff.
*HH*1	21,958	8776	22,170	0.98	8673	− 1.17
*HH*2	20,177	8568	20,454	1.39	8504	− 0.75
*HH*3	30,527	11,809	30,846	1.05	11,664	− 1.23
*HH*4	41,782	14,937	42,307	1.29	14,781	− 1.04
*HH*5	43,555	14,816	44,116	1.30	14,656	− 1.08
*HH*6	56,592	19,637	57,510	1.63	19,488	− 0.76
*HH*7	86,470	24,039	87,842	1.59	23,808	− 0.96
*HH*8	113,680	25,786	114,970	1.17	25,363	− 1.64
*HH*9	165,601	27,101	166,516	0.55	26,413	− 2.54

Real income (in 2013 dollars) is nominal income divided by the consumer price index (CPI) for each household group

5.3 Household welfare

Table 6 reports household income and compensating variation (CV) for the GWD by household group in 2030 and 2050. CV is calculated as the change in household income in the base scenario necessary for households to achieve the same utility as in the GWD scenario, holding total savings constant. Negative values of CV correspond with higher household welfare in the base scenario; positive values correspond with higher household welfare in the GWD scenario. The model predicts significant welfare losses from the GWD in 2030, with CV to avoid increased water prices due to the GWD as ranging from approximately $240 for the least wealthy households (*HH*1) to over $2160 for the wealthiest households (*HH*9). In contrast,

Table 6 Welfare per household (2013 $)

	Compensating variation (CV) for the Groundwater Development Project (GWD)			
	2030		2050	
	CV	Relative CV (%)	CV	Relative CV (%)
*HH*1	− 238	− 1.00	446	2.03
*HH*2	− 252	− 1.13	668	3.31
*HH*3	− 399	− 1.20	784	2.57
*HH*4	− 566	− 1.24	1189	2.85
*HH*5	− 661	− 1.40	1336	3.07
*HH*6	− 957	− 1.56	2380	4.21
*HH*7	− 1310	− 1.40	2857	3.30
*HH*8	− 1545	− 1.28	2430	2.14
*HH*9	− 2157	− 1.26	654	0.39

Relative CV is as total CV divided by real income for each household group in 2050 all household groups in Las Vegas are better off with the GWD, compared with the baseline, with a positive CV for the GWD of between $440 and $2860 per year, compared to the baseline.

These results highlight the distributional and intertemporal considerations related to the GWD project, as would be the case with other large water infrastructure projects. Concerning the distribution of benefits of the GWD across income groups, the results suggest that wealthier households suffer the most (in absolute terms) from higher water prices in 2030 due to the GWD project. That wealthier households suffer most is due, in part, to the fact that household water use is modeled as a Leontief input into the production of housing services. This assumption implies households can only change their direct water consumption by reducing consumption or changing categories of the bundle of housing services. As wealthier households are concentrated in the category of housing services with the highest water use, the direct loss in disposable income associated with the water price increase is greatest for these households. Further, the general equilibrium effects work against wealthier households in 2030, where a smaller economy in the GWD scenario implies lower returns to factors of production (labor, capital, and land), of which wealthy households own a disproportionately large share.

On the other hand, the general equilibrium effects work in favor of wealthy households in 2050, where the economy is larger in the GWD scenario. The wealthiest households ($HH9$), however, gain less in the GWD scenario than all other household groups except the least wealthy ($HH1$). This is due to the fact that the wealthiest household benefit disproportionately from higher housing prices in the non-GWD scenario because of their higher ownership share.

Table 6 also reports relative CV for each household group, where relative CV is calculated as total CV divided by real disposal income for each household group. Table 6 shows that in 2030, the nine household groups have similar relative welfare losses, with negative CV for the GWD of slightly more than 1% of real income. This suggests the cost of the GWD to households in 2030 from the combination of high water prices and lower returns to factors of production increases roughly proportionately with their income. Conversely, in 2050, relative CV is highest among the upper-middle-income households (positive CV of 4.21% of real income for $HH6$ and 3.30% for $HH7$), with a precipitous drop-off for the highest income households (positive CV of 2.14% of real income for $HH6$ and 0.39% for $HH7$). This result is due to the fact that while both $HH6$/$HH7$ households and $HH8$/$HH9$ households' benefits from the lower housing costs and increased economic activity due to the GWD, the $HH8$/$HH9$ households receive greater benefit from the higher housing prices in the non-GWD scenario due to their high ownership share of land.

5.4 Colorado river water supply

The previous subsection demonstrated that while the additional water provided by the GWD eventually improves household welfare in Las Vegas, it reduces welfare in years before the GWD water is needed. This implies that net benefits of the GWD for Las Vegas depend critically on when the system becomes supply-constrained in the absence of the GWD, which depends, in turn, on our assumptions on Colorado River water supply. Table 7 reports results for 2050 for the three supply conditions for Las Vegas forecast by SNWA depending on Colorado River water supplies: 510,000 acre-feet per year (AFY) (*baseline*), 545,000 AFY (*normal supply*), and 475,000 AFY (*additional shortage*).

Table 7 reports that under normal supply conditions, the additional water from the GWD is not needed in 2050. In this case, the GWD reduces population, industrial output, and household welfare in both 2030 and 2050. On the other hand, if the system is in additional shortage conditions in 2050, Table 7 demonstrates that the positive impacts of the GWD project on population, tax revenue, and production in 2050 are substantially greater than in our baseline scenario reported in Table 2. This result illustrates the potential insurance benefit of the GWD in that it can shield Las Vegas from the negative consequences of large potential shortages in Colorado River water.

5.5 Las Vegas population

Table 8 considers how our results change when exogenous population growth is lowered from our baseline assumption of 50% growth by 2050 to either 30% or 40% growth by 2050. We focus on the implications of overstating population growth for our analysis because population, and hence, water consumption can change the necessity of the GWD in 2050 and substantially alter our conclusions about the desirability of the GWD. On the other hand, if our population growth assumptions understate future growth, our results would understate the economic case for the GWD for Las Vegas.

Table 8 shows that when population in Las Vegas is increased by 30%, the system is not supply-constrained in 2050 so that the additional water provided by the GWD is not needed and the GWD reduces population, production, county and state tax revenue, and household welfare. In contrast, when population is increased by 40%, the water supplied by the GWD is needed in 2050 in that the system is supply-constrained in the absence of the project, but that water is more expensive in the GWD scenario, as a result, water use is lower. These results highlight that the benefit of the GWD project ultimately depends on continued rapid population growth in the region.

Table 7 Colorado river water supply in 2050

	Shortage (base) (510,000 AFY)		Additional shortage (475,000 AFY)		Normal supply (545,000 AFY)	
	Base	GWD	Base	GWD	Base	GWD
Supply constraint (1000 AFY)	510	594	475	475	545	545
Water use Q* (1000 AFY)	510	517.1	475	517.1	521.05	517.1
Population (# of *HH*)	1,041,812	1,043,844	1,031,399	1,043,844	1,044,795	1,043,844
Total county tax	3352	3370	3254	3370	3383	3370
Sale tax to state	3258	3299	3090	3299	3313	3299
Total output	79,662	80,325	76,750	80,325	80,541	80,325

Total Revenue of Productive Sectors does not include the water utility sector and housing services

Dollar figures in millions of 2013

Table 8 Las vegas population by 2050

	50% pop. growth (base)		30% pop. growth		40% pop. growth	
	Base	GWD	Base	GWD	Base	GWD
Supply constraint (1000 AFY)	510	594	510	594	510	594
Water use Q* (1000 AFY)	510	517	503	499	510	508
Population (# of *HH*)	1,041,812	1,043,844	910,852	909,786	977,024	976,628
Total county tax	3352	3370	2943	2929	3154	3147
Sale tax to state	3258	3299	2888	2874	3088	3085
Total output	79,662	80,325	74,039	73,809	77,157	77,111

Total Revenue of Productive Sectors does not include the water utility sector and housing services sector

Dollar figures in millions of 2013

6 Conclusions

This paper develops a general equilibrium model framework to analyze the economic and distributional impacts of water infrastructure projects that have significant impacts on a region's water portfolio. The model captures the salient features of the decision-making of a municipal water sector that operates under a cost-recovery mandate. This model innovation can be applied to model the provision of many public services supplied by regulated natural monopolies operating under a cost-recovery mandate that constrain their ability to appropriately price scarce resources, so that the scarcity rents are capitalized in the price of other assets in the economy, causing both efficiency and distributional changes in the economy.

We calibrate the model to measure the welfare impacts of a specific water project in Las Vegas. Data are compiled from several sources, including microbilling data on household and firm water consumption, to ensure that the model provides an accurate representation of payments to the municipal water sector from industries and households.

The results demonstrate that a significant intertemporal trade-off results from the need to invest in infrastructure to support future growth. Namely, current households must bear costs before the infrastructure is needed while future generations benefit from the investment. In the case of Las Vegas, the magnitude of these trade-offs is significant because additional water supplied by the GWD may not be necessary for several decades, while the increased cost of municipal water required to service the debt related to the GWD project reduces real income and welfare in the intervening years. Our model predicts that the GWD leads to substantial welfare losses in 2030 (annual losses of \$200–\$2200 per household) and substantial benefits in 2050 (annual benefits of \$400–\$2900).

Sensitivity analysis revealed that whether the system is supply-constrained in the absence of the GWD in a given year depends critically on Colorado River water supply and population growth in Las Vegas, both of which are uncertain. As such, the time horizon for the benefits of the GWD to be realized is uncertain. While the static analysis in this paper does not allow us to analyze whether the eventual welfare gains to households from the GWD are sufficiently large to compensate for the more immediate welfare losses, it does suggest the conditions under which this intertemporal compensation criterion is likely to be met (i.e., low Colorado River water supplies, high population growth for Las Vegas). The analysis also does not allow us to address whether the eventual benefits of the GWD for Las Vegas are sufficient to compensate for the environmental impacts of groundwater pumping in the regions of rural Nevada where the groundwater is sourced.

We find that the GWD has limited impact on many of the top-line economic indicators for Las Vegas under our base assumptions. In 2030, the higher cost of municipal water in the GWD scenario slightly reduces population, industrial output, and county and state tax revenue, while these variables are slightly higher in the GWD in 2050 when the additional water allows Las Vegas to balance M&I supply and demand without restricting the growth of the housing supply or significantly increasing water rates. The relatively small impact of the GWD project on these variables is due to the fact that water is a small portion of household and firm expenditures, so that while the price of water has a significant impact on household welfare, it has a more muted impact on household migration and firm production. If the model were extended to allow per capita water use to impact migration directly through regional quality-of-life, the effect of the GWD on population and industrial production could be more significant.[23]

We also find that the GWD influences industrial composition. In 2030, the higher cost of water in the GWD scenario depresses industrial output, with the most water-intensive sectors experiencing the largest declines. In 2050, however, while the GWD increases output and employment in all sectors, the largest employment gains relative to the baseline are in the least water-intensive sectors. This counterintuitive result is related to the fact that the GWD would be funded by water rate payers. Rate payer financing implies that the least water-intensive sectors benefit from the increased economic activity due to the GWD, but pay proportionately less of its cost through their water bills. This counterintuitive result suggests that if large water and energy infrastructure projects are funded by rate payers, they may ultimately tilt cities' industrial composition toward less resource-intensive sectors.

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Appendix A: Mathematical presentation of model

See Table 9.

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[23] Previous studies have suggested that turf and trees moderate heat island effects and improve urban quality-of-life in cities in the southwest USA (e.g., Klaiber et al. 2017).

Table 9 Mathematical presentation of the model

Indices and sets			
All of the accounts in SAM (Z)	Productive sectors (IP, JP) Housing sectors (HS)	Sectors excluding water utility (INW, JNW)	INT good (I, J)
	Water utility (WU)		
	Federal, State Local (GNL)	Government (GN)	
	Factor Tax (GF)		
	Sale tax and other local tax (GS)	All government taxes (GX)	All government sectors (G)
	Income tax (GI)		
	Internal government transfer (IGT)	Internal transfer (GT)	
	Labor ($L : L1 - L9$)		
	Capital (K)	Factors (F)	Factors (F)
	Land (LA)		
	Household: ($H : HH1 - HH9$)		Household (H)
	Rest of world (ROW)		ROW

Variable	
Price-related endogenous variables	
CPI_H	Consumer price index
P_I	Aggregated price of market goods I paid by intermediate sectors, household, and governments
PD_I	Producer price (domestic price) of sector I
PVA_I	Value-added price of productive sectors I
μ	Shadow price of housing services
λ	Shadow price of water utility (water scarcity price)
RA_F	Economy-wide scalar rental rates of factors
$R_{F,I}$	Factor rental rates such as wage, land value, and capital rent
$R_{L,GN}$	Labor wage rates for government sectors

Table 9 (continued)

Variable	
Demand-related endogenous variables	
$CG_{I,G}$	Government consumption including federal, state, and local government
$CH_{I,H}$	Household consumption or consumer purchase
CN_I	Gross investment by sector of source
CX_I	Export demand
DD_I	Domestic demand
DS_I	Domestic supply
$FD_{F,I}$	Factor demand for industrial sector I
$FD_{F,GN}$	Factor demand for federal, state, and local government sectors
M_I	Import demand
V_I	Demand of intermediate Good
D_I	In domestic demand, share of good *I* produced domestically
Regional economic endogenous variables	
$GVFOR_G$	Government outflow
HH_H	Number of Households
HW_H	Number of working households
HN_H	Number of households not working
$IGT_{G,GX}$	Internal government transfer
$KPFOR_K$	Capital outflow
$KS_{K,IG}$	Capital supply
$N_{K,I}$	Gross investment by sector of destination
NKI	Net capital inflow
$LAS_{LA,G}$	Land supply for each sector
$LNFOR_{LA}$	Land outflow

Table 9 (continued)

Variable	
S_G	Government savings
S_H	Household savings
SPI	Personal income
YH_H	Household income
YF_F	Factor income including labor income YF_L, land income YF_{LA}, capital income YF_K
YG_G	Government and tax income (Y_{GN}, Y_{GX}), and an agent sector, tax pool ($Y_{taxpool}$)
YD_H	Household disposable income
YK_H	Local household capital income
YLA_H	Local household land income
HR_{HS}	Housing rent (profit) caused by the water scarcity issue
WR	Water rent by conservation rate
UTL_H	Household utility
CV_H	Compensating variation
All exogenous variables	
CCM_I	Capital investment from commodity
$NRPG_H$	Natural rate of population growth
$PIT_{GI,H}$	Per personal income tax rate
$PW0_I$	Export price = \$1
$PWM0$	Import price = \$1
$TAXES_{G,GX}$	Tax destination shares
$TP_{H.G}$	Government social security payment
$Kout_K$	Share of capital inflow–outflow
$LAout_{LA}$	Share of land inflow–outflow
$GVout_G$	Share of government inflow–outflow

Table 9 (continued)

Variable	
$HHout_H$	Income inflow–outflow per *HH*
Inv	Annualized debt of the infrastructure
$W_{s,inf}$	Water supply condition, index S refers to the supply condition, and index inf = 1 denotes the pipeline is invested, otherwise, inf = 0
Initial values for endogenous variables	
$CG0_{I,G}$	Initial value of government consumption
$CHO_{I,H}$	Consumer Consumption from baseline data (SAM)
$CN0$	Initial value of real investment by sector of source
$CPI0_H$	Initial values of $CPI = 1$
$CX0_I$	Initial value of export demand calculated from baseline data (SAM)
$D0_I$	Initial value of ratio of domestic supply to domestic demand
$DD0_I$	Initial value of domestic demand
$DS0_J$	Initial value of domestic supply
$FD0_{F,I}$	Initial value of factor demand
$GVFOR0_G$	Initial value of government outflow
$HH0_H$	Initial value of number of households
$HW0_H$	Initial value of number of working households
$KS0_{K,IG}$	Initial capital stock from baseline data (SAM)
$LAS0_{LA,I}$	Initial land stock from baseline data (SAM)
$M0_I$	Initial value of imports
$MI0_H$	Numbers of household migrate in
$MO0_H$	Numbers of household migrate out
$N0_{K,I}$	Initial value of gross investment by sector of destination
$P0_I$	Unity price = \$1

Table 9 (continued)

Variable	
$PIT0_{GI,H}$	Nominal tax per working household
$R0_{F,I}$	Factor rental rates calculated from baseline data (SAM)
$S0_H$	Household saving from baseline data (SAM)
$V0_I$	Initial value of intermediate demand
$YG0_G$	Initial value of government income
$YF0_F$	Initial value of factor income including labor income $YF0_L$, land income $YF0_{LA}$, capital income $YF0_K$
$YD0_H$	Nominal *HH* disposable income
$YH0_H$	Nominal *HH* income
$YK0_H$	Initial value of household capital income
$YLA0_H$	Initial value of household land income
$HR0_{HS}$	Initial value of housing rent (profit) caused by the water scarcity issue
$WR0$	Initial value of water rent by conservation rate
$UTL0_H$	Household utility
$CV0_H$	Compensating variation
Parameter	
Elasticity	
$\lambda_{J,I}$	Cross-price elasticity
β	Income elasticity for demand
ρ_I	CES top-level function exponent: $\rho_I = (1 - \sigma)/\sigma$
σ	Elasticity of CES top-level function
η_I^e	Elasticity for export demand
η_I^d	Domestic share price elasticity
η_I^m	Import elasticity with respect to domestic price
$\eta_{K,I}^{ix}$	Capital elasticity (land and capital elasticity)

Table 9 (continued)

Parameter	
$\eta^{l}_{LA,I}$	Land elasticity (land and capital elasticity)
η^{ra}_{H}	Labor supply elasticity with respect to average wage
η^{pt}_{H}	Household response to transfer payments
η^{pit}_{H}	Labor supply elasticity with respect to taxes
η^{yd}_{H}	Responsiveness of immigration to after tax earnings
η^{u}_{H}	Responsiveness of immigration to unemployment
η^{pit}_{H}	Household response to income tax
Computed share parameters	
$a_{H,L}$	Share of labor supply by each *HH* (each *HH* indicates divide number of *HW*)
$a_{H,LA}$	Share of land supply by each *HH*
$a_{H,K}$	Share of capital supply by each *HH*
$ad_{J,I}$	Share of domestic input–output coefficient
$\alpha_{F,I}$	Share of factors in production function
$cd_{I,H}$	Consumption elasticity for commodities in the Cobb–Douglas utility function
$ag_{I,G}$	Shares of government expenditure
$taxs_{G,GX}$	Tax to Federal, state, and local (Tax pool) government
$TaxShare_{GNL}$	Share of tax redistributing back to local government (administration and safe department)
Tax rates	
$\tau^{q}_{GS,I}$	Average sales tax rates
$\tau^{f}_{GF,F,I}$	Factor input taxes including labor, land, and capital tax
$\tau^{fl}_{G,L}$	Factor tax: labor
$\tau^{fla}_{G,LA}$	Factor tax: land
$\tau^{fk}_{G,K}$	Factor tax: capital

Table 9 (continued)

Parameter	
$\tau^{fh}_{GF,F}$	Aggregated factor taxes
$\tau^{fx}_{GF,F,I}$	Factor taxes (for counterfactual—CF scenario)
Other parameters	
γ_I	Scale parameter in production function
$Depr$	Depreciation rate of capital, and this parameter is calibrated by the ratio of investment consumption to capital supply using the baseline value (SAM)
$jobcor_{H,L}$	Correction factor between workers from households H and labors L
Model equation	
Household block	
Consumer Price Index: CPI_H	
(A1)	$CPI_H = \frac{\sum_I P_I \cdot \left(1+\sum_{GS} \tau^q_{GS,I}\right) \cdot CH_{I,H}}{\sum_I P0_I \times \left(1+\sum_{GS} \tau^q_{GS,I}\right) \cdot CH_{I,H}}$
Capital income redistributed to the local household	
(A2)	$YK_H = \sum_K \frac{(a_{H,K} \cdot HW_H)}{\sum_H (a_{H,K} \cdot HW_H)} \cdot (Y_K + KPFOR_K)$
Land income redistributed to the local household	
(A3)	$YLA_H = \sum_{LA} \frac{(a_{H,LA} \cdot HW_H)}{\sum_H (a_{H,LA} \cdot HW_H)} \cdot (Y_{LA} + LNFOR_{LA})$
Household income	
(A4)	$Y_H = \sum_L \frac{(a_{H,L} \cdot HW_H)}{\sum_H (a_{H,L} \cdot HW_H)} \cdot Y_L \cdot \left(1 - \sum_G \tau^{fl}_{G,L}\right) + YLA_H \cdot \left(1 - \sum_G \tau^{fla}_{G,LA}\right) + YK_H \cdot \left(1 - \sum_G \tau^{fk}_{G,K}\right)$
Housing rent redistributed to the local housing owner	
(A5)	$HR_{HS} = \mu \cdot DS_{HS} \cdot \left(1 + \frac{KPFOR_K + LNFOR_{LA}}{\sum_{LA} YF_{LA} + \sum_K YF_K}\right)$

Table 9 (continued)

Model equation

Water scarcity rent redistributed to the local household and business owner

(A6)
$$WR = \lambda \cdot DS_{wu} \cdot \left(1 + \frac{KPFOR_K}{\sum_K YF_K}\right)$$

Disposable income = household factor income + government transfer + housing rent redistribution + water rent redistribution + income tax + property tax + compensating variation

(A7)
$$YD_H = Y_H + HHout_H \cdot HH_H + \sum_G TP_{H,G} \cdot HH_H + \left(\sum_{HS} HR_{HS}\right) \cdot \frac{\left(YK_H + YLA_H\right)}{\sum_H \left(YK_H + YLA_H\right)} + WR \cdot \frac{\left(YK_H\right)}{\sum_H \left(YK_H\right)}$$
$$- \sum_{GI} PIT_{GI,H} \cdot Y_H - \sum_G \tau_H \cdot HH_H + CV_H$$

Household consumption for market goods and housing services (derived from Cobb–Douglas utility function)

(A8)
$$CH_{I,H} = CH0_{I,H} \cdot \left(\frac{YD_H/YD0_H}{CPI_H/CPI0_H}\right)^{\beta_{I,H}} \cdot \prod_J \left[\frac{P_J \cdot \left(1+\sum_{GS} \tau^q_{GS,J}\right)}{P0_J \cdot \left(1+\sum_{GS} \tau^q_{GS,J}\right)}\right]^{\lambda_{J,I}}$$

Household saving = Disposable income – Consumption

(A9)
$$S_H = YD_H - \sum_I P_I \cdot CH_{I,H} \cdot \left(1 + \sum_{GS} \tau^q_{GS,I}\right)$$

Cobb–Douglas utility function

(A10)
$$UTL_H = \prod_I CH_{I,H}^{cd_{I,H}}$$

Producer Equations

Value-added price for productive sectors and housing sectors excluding the water sector

(A10)
$$PVA_{INW} = PD_{INW} - \sum_J ad_{J,INW} \cdot P_J \cdot \left(1 + \sum_{GS} \tau^v_{GS,J}\right)$$

Value-added price for the water sector

(A11)
$$DS_{wu} \cdot PVA_{wu} = DS_{wu} \cdot PD_{wu} - \sum_J ad_{J,wu} \cdot P_J \cdot \left(1 + \sum_{GS} \tau^v_{GS,J}\right) \cdot DS_{wu} - Inv$$

Table 9 (continued)

Model equation	
CES value-added production function	
(A12)	$DS_I = \gamma_I \cdot \left(\sum_F \alpha_{F,I} \cdot FD_{F,I}^{-\rho_I} \right)^{-\frac{1}{\rho_I}}$
Factor demand: FOC of Unit cost production function	
(A13)	$R_{F,I} \cdot RA_F \cdot \left(1 + \sum_{GF} \tau_{GF,F,I}^{fx} \right) = \alpha_{F,I} \cdot \left(FD_{F,I} \right)^{-\rho_I - 1} \cdot PVA_I \cdot DS_I \cdot \left(\sum_F \alpha_{F,I} \cdot FD_{F,I}^{-\rho_I} \right)^{-1}$
Intermediate demand	
(A14)	$V_{INW} = \sum_J AD_{INW,J} \cdot DS_J$
Water demand	
(A15)	$V_{WU} = \sum_{HS} ad_{WU,HS} \cdot DS_{HS} + \sum_{IP} ad_{WU,IP} \cdot DS_{IP} + ad_{WU,WU} \cdot DS_{WU}$
Labor income:	
(A16)	$YF_L = \sum_{IG} R_{L,IG} \cdot RA_L \cdot FD_{L,IG}$
Land income:	
(A17)	$YF_{LA} = \sum_{IG} R_{LA,IG} \cdot RA_{LA} \cdot FD_{LA,IG}$
Capital income:	
(A18)	$YF_K = \sum_{IG} R_{K,IG} \cdot RA_K \cdot FD_{K,IG}$
Land outflow from the region	
(A19)	$LNFOR(LA) = LAout_{LA} \cdot YF_{LA}$
Capital outflow from the region	
(A20)	$KPFOR(K) = Kout_K \cdot YF_K$
Trade Equations	

Table 9 (continued)

Model equation	
Export function	
(A21)	$CX_{IP} = CX0_{IP} \cdot \left(\frac{PD_{IP}\left(1+\sum_{GS} \tau^{q}_{GS,IP}\right)}{PW0_{IP}\left(1+\sum_{GS} \tau^{q}_{GS,IP}\right)} \right)^{\eta^{e}_{IP}}$
Share of domestic consumption that is produced/supplied locally, exogenous world price	
(A22)	$D_{IP} = D0_{IP} \times \left(\frac{PD_{IP}}{PWM0} \right)^{\eta^{d}_{IP}}$
Import demand	
(A23)	$M_{IP} = \left(1 - D_{IP}\right) \cdot DD_{IP}$
Average price faced by domestic consumption, world price is exogenous.	
(A24)	$P_{IP} = D_{IP} \cdot PD_{IP} + \left(1 - D_{IP}\right) \cdot PWM0_{IP}$
Water price	
(A25)	$P_{WU} = PD_{wu} + \lambda$
Housing price	
(A26)	$P_{HS} = PD_{HS} + \mu$
Net foreign saving	
(A27)	$NKI = \sum_{I} M_{I} \cdot PWM0_{I} - \sum_{I} CX_{I} \cdot PD_{I} - \sum_{H} HHout_{H} \cdot HH_{H} - \sum_{LA} LNFOR_{LA} - \sum_{K} KPFOR_{K} - \sum_{G} GVFOR_{G}$
Investment Equations	
	Net investment
(A28)	$N_{K,I} = N0_{K,I} \cdot \left(\frac{R_{K,I}}{R0_{K,I}} \right)^{\eta^{ix}_{K,I}}$
Domestic Investment	
(A29)	$P_{I}\left(1 + \sum_{GS} \tau n_{GS,I}\right) \cdot CN_{I} = \sum_{j} \left[CCM_{i,j} \cdot \left(\sum_{K} N_{K,I} \right) \right]$

Table 9 (continued)

Model equation	
Capital stock and investment	
(A30)	$KS_{K,I} = KS0_{K,I} \cdot (1 - DEPR) + N_{K,I}$
Factor supply equation	
Participation rates determined by wages, taxes, and transfer payments	
(A31)	$\frac{HW_H}{HH_H} = \frac{HW0_H}{HH0_H} \cdot \left(\frac{\sum_L \frac{RA_L}{RA0_L}}{\frac{CPI_H}{CPI0_H}} \right)^{\eta_H^{ra}} \cdot \left(\frac{\sum_G \frac{TP_{H,G}}{CPI_H}}{\sum_G \frac{TP_{H,G}}{CPI0_H}} \right)^{\eta_H^{pt}} \cdot \left(\frac{\sum_{GI} PIT0_{GI,H} * HH_H + \sum_{GI} \tau_{G,H}^{h} * HH_H}{\sum_{GI} PIT0_{GI,H} * HH0_H + \sum_{GI} \tau_{G,H}^{h} * HH0_H} \right)^{\eta_H^{pit}}$
Migration function = natural population growth + migrate in–out (income, CPI, employment rates et al.)	
(A32)	$HH_H = HH0_H \cdot NRPG_H + MI0_H \cdot \left(\frac{\left(\frac{YD_H}{HH_H}\right)}{\left(\frac{YD0_H}{HH0_H}\right)} \Big/ \frac{CPI_H}{CPI0_H} \right)^{\eta_H^{yd}} \cdot \left(\frac{\left(\frac{HN_H}{HH_H}\right)}{\left(\frac{HN0_H}{HH0_H}\right)} \right)^{\eta_H^{u}} - MI0_H \cdot \left(\frac{\left(\frac{YD0_H}{HH0_H}\right)}{\left(\frac{YD_H}{HH_H}\right)} \Big/ \frac{CPI0_H}{CPI_H} \right)^{\eta_H^{yd}} \cdot \left(\frac{\left(\frac{HN0_H}{HH0_H}\right)}{\left(\frac{HN_H}{HH_H}\right)} \right)^{\eta_H^{u}}$
Land supply function:	
(A33)	$LAS_{LA,I} = LAS0_{LA,I} \cdot \left(\frac{R_{LA,I}}{R0_{LA,I}} \right)^{\eta_{LA,I}^{l}}$
Numbers of labors not working	
(A34)	$HN_H = HH_H - HW_H$

Table 9 (continued)

Model equation	
Government Equations	
Government Income = sale tax + factor tax + income tax +Property tax + transfer + other tax	
(A35)	$YG_{GX} = \sum_I \tau^q_{GX,I} \cdot V_I * P_I + \sum_I \tau^q_{GX,I} \cdot CX_I \cdot PD_I + \sum_{H,I} \tau^q_{GX,I} \cdot CH_I \cdot P_I + \sum_I \tau^q_{GX,I} \cdot CN_I \cdot P_I + \sum_{GN,I} \tau^q_{GX,I} \cdot CG_{I,GN} \cdot P_I$ $+ \sum_{F,I} \tau^{fx}_{GX,F,I} \cdot RA_F \cdot R_{F,I} \cdot FD_{F,I} + \sum_{F,GN} \tau^{fx}_{GX,F,GN} \cdot RA_F \cdot R_{F,GN} \cdot FD_{F,GN} + \sum_L \tau^{fh}_{GX,L} \cdot YF_L + \sum_K \tau^{fh}_{GX,K} * YF_K$ $+ \sum_{LA} \tau^{fh}_{GX,LA} \cdot YF_{LA} + \sum_H PIT0_{GX,H} \cdot HH_H + \sum_H \tau^h_{GX,H} \cdot HH_H + \sum_{GX1} IGT_{GX,GX1}$
Government Endogenous Purchases of Goods and Services	
(A36)	$P_I \cdot \left(1 + \sum_{GS} \tau^g_{GS,I}\right) \cdot CG_{I,GN} = AG_{I,GN} \cdot \left(YG_{GN} + GVFOR_{GN}\right)$
Government factor input: factor demand * rental rates = factor input share * total expenditure	
(A37)	$FD_{F,GN} \cdot R_{F,GN} \cdot RA_F \cdot \left(1 + \sum_{GF} \tau^{fx}_{GF,F,GN}\right) = AG_{F,GN} \cdot \left(YG_{GN} + GVFOR_{GN}\right)$
Government Endogenous Savings = income + outflow – consumption - factor input	
(A38)	$S_{GN} = YG_{GN} + GVFOR_{GN} - \left(\sum_I CG_{I,GN} \cdot P_I \cdot \left(1 + \sum_{GS} \tau^q_{GS,I}\right)\right) - \left(\sum_F FD_{F,GN} \cdot R_{F,GN} \cdot RA_F \cdot \left(1 + \sum_{GF} \tau^{fx}_{GF,F,GN}\right)\right)$
Government Exogenous Savings = income + outflow – *HH* transfer – internal transfer	
(A39)	$S_{GX} = YG_{GX} + GVFOR_{GX} - \sum_H TP_{H,GX} \cdot HH_H - \sum_G IGT_{G,GX}$
Tax distribution = share of tax redistribution * (tax collecting + outflow – transfer to *HH*)	
(A40)	$IGT_{G,GX} = TAXS_{G,GX} \cdot \left(YG_{GX} + GVFOR_{GX} - \sum_H TP_{H,GX} * HH_H\right)$
Endogenous transfer	
(A41)	$YG_{GT} = \sum_{GX} IGT_{GT,GX}$
Endogenous transfer to local government	
(A42)	$YG_{GNL} = TaxShare_{GNL} \cdot YG_{taxpool}$

Table 9 (continued)

Model equation	
Government outflow	
(A43)	$GVFOR_G = GVout_G * YG_G$
Model closure	
State personal income (Objective function)	
(A44)	$SPI = \sum_H Y_H + \sum_{H,G} TP_{H,G} \cdot HH_H + \sum_H HHout_H \times HH_H$
Labor market	
(A45)	$\left(\sum_H HW_H \cdot JOBCOR_{H,L}\right) = \sum_I FD_{L,I} + \sum_I FD_{L,GN}$
Land market	
(A46)	$LAS_{LA,I} = FD_{LA,I}$
Capital market	
(A47)	$KS_{K,I} = FD_{K,I}$
Commodity market clearance	
(A48)	$DS_{INW} = DD_{INW} + CX_{INW} - M_{INW}$
Water clearance condition	
(A49)	$DS_{WU} = DD_{WU} = V_{WU} + \sum_G CG_{WU,G}$
Domestic market:	
(A50)	$DD_{IP} = V_{IP} + \sum_H CH_{IP,H} + \sum_G CG_{IP,G} + CN_{IP}$
Domestic market for housing sector	
(A51)	$DD_{HS} = \sum_H CH_{HS,H}$
Weak inequality constraint of water resource	
(A52)	$W_{s,inf} \geq DS_{wu}$

Appendix B: Elasticity parameters

Elasticities we use in our simulation are as follows:

Elasticity	Value	References
Elasticities for residential land supply	2	Cutler and Davies (2007)
Elasticities for commercial land supply	1	
Labor supply elasticity in response to the labor average wage (*HH*1–*HH*9)	0.1– to 0.8	Berck et al. (1996)
Labor supply elasticity in response to household taxes (*HH*1–*HH*9)	−0.55 to −0.15	
Migration elasticity in response to after tax earnings (*HH*1–*HH*9)	1.5–2.3	
Migration elasticity in response to unemployment (*HH*1–*HH*9)	−0.7 to −0.2	
The elasticity of substitution between primary factors	0.8	Watson and Davies (2011)
Income elasticities for household private consumption		
Agriculture and food	0.48–0.5	Blanciforti et al. (1986)
Utilities	0.52	
Retail	0.8	
Services	0.7	
Hospital and health	0.35	
Durable and manufactured consumption	1.5	
"Miscellaneous" sector	1	
Housing services	0.8	
Own-price elasticities		
Agriculture and food	−0.3	Blanciforti et al. (1986)
Utilities	−0.5	
Retail	−0.4	
Services	−0.2	
Hospital and health	−0.3	
Durable and manufactured consumption	−0.42	
"Miscellaneous" sector	−1	
Housing services	−0.2	

Note that we observe a broader range of income elasticities for housing services from previous literature, where elasticities range from 0.14 to 1.4. In our study, housing services is an agent sector including sales, rentals, and maintenance. We ran a sensitivity analysis with regard to the elasticities and our major conclusions remain. The results can be provided upon your request.

Appendix C: Model implementation

Table 10 describes scenarios implemented in this paper. Scenario ***a*** presents a baseline of our simulation assuming that Las Vegas is unable to build up the infrastructure. If the resource constraint binds, the impact of water shortage is capitalized into the housing market. μ is a price slack variable associated with the resource constraint, and can be explained as the "profit" in housing market caused by the shortage. Our model then redistributes the "housing profit" back to the household as a lump sum income suggesting that owners of housing sectors receive all of the housing profits. Our empirical setting assumes that all of capital and land are owned by regional households and foreign investors. Hence, we first allocate the housing profit to local households and foreign investors (rest of the world) according to local and foreign ownerships of capital and land (see Eq. A5 in "Appendix A"), then we distribute the housing profit owned by local households to each household group based on households' ownerships of capital and land (see Eq. A7 in "Appendix A"). Scenarios ***b*** simulates the economic growth with the infrastructure. We assume all water customers in the region contribute toward funding the infrastructure. The infrastructure cost is imposed in Eq. (A11) in "Appendix A".

Table 10 Model implementation

	Method of implementation				
	Housing price	Water price	Constraints		Slack variable
(a) No infrastructure	$P_{hs} = PD_{hs} + \mu$	$P_{wu} = PD_{wu}$	Resource constraint	$DD_w = DS_{wu} \leq W\perp_{s,\mathrm{inf}=0}$	μ
(b) Infrastructure	$P_{hs} = PD_{hs} + \mu$	$P_{wu} = PD_{wu}$	Resource constraint	$DD_w = DS_{wu} \leq W\perp_{s,\mathrm{inf}=1}$	μ
			Infrastructure Cost	Inv	
Notation					
DD_w	Domestic demand of water utility				
DS_w	Domestic supply of water utility				
$\overline{DS}$	Upper bound of water resource				
$\overline{DS}_{new}$	New water resource from the infrastructure				
Inv	Annualized debt of the infrastructure				
P_{wu}	Consumer price of water utility				
PD_{wu}	Producer price of water utility				
P_{hs}	Consumer price of housing				
PD_{hs}	Producer price of housing				
μ	Housing rent				
λ	Water scarcity price when the resource constraint binds				
φ	Infrastructure charge				

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