Planning for a (Less) Rainy Day: Evaluating the Regional Welfare Impacts of Water Infrastructure Investment

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Abstract: Continued provision of low-cost municipal and industrial water is anticipated to be a challenge for many cities in the western United States in coming decades. To address this, many cities are considering large-scale infrastructure projects to expand water availability. Optimal infrastructure planning requires information on economy-wide benefits and costs. In this article, we evaluate the economy-wide distributional impacts of an ongoing water infrastructure project in the Las Vegas-Henderson-Paradise metropolitan area in Southern Nevada. We do this by developing a general equilibrium model that includes a detailed representation of municipal and industrial water use by industry and housing type (single-family, multi-family, etc.). Numerical simulations indicate that investment in large-scale infrastructure to increase water supplies decreases medium run (2030) household welfare but leads to an increase in welfare by 2050.

Key words: General equilibrium, Water conservation, Water infrastructure, Water resources
1. Introduction

Providing low-cost water for municipal and industrial (M&I) use is an important policy objective for cities in the United States and throughout the world. The cost of M&I water influences business location and investment decisions, as well as household location and welfare through its impact on cost-of-living and urban quality-of-life (Klaiber, Abbott, and Smith 2017). Continued provision of low-cost M&I water, however, is anticipated to be a challenge for many cities in the western United States in coming decades as a result of increasing demand and declining supplies (Watson and Davies 2011). To address this challenge, many western cities are considering – or have begun work on – large-scale infrastructure projects to expand their water portfolios. In this article, we evaluate the overall and distributional impacts of a large-scale water infrastructure project currently underway in the Las Vegas-Henderson-Paradise metropolitan statistical area in southern Nevada (henceforth Las Vegas). To do this, we develop a general equilibrium (GE) model that captures the important economy-wide role of water, and then parameterize it using data from Las Vegas. The parameterized model provides a detailed description of M&I water use in Las Vegas, and allows an evaluation of the economic (population, production, fiscal) and distributional impacts of the project.

Like many cities in the West, Las Vegas has experienced rapid population growth in the post-war period, and this growth is expected to continue in the coming decades (Center for Business and Economics Research 2016). Correspondingly, Las Vegas’ projected demand for water is expected to increase. Projected water demand is expected to exceed currently available water resources in Las Vegas within the lifetime of most current residents (Southern Nevada Water Authority 2017). Further, Las Vegas is likely to have to meet projected increases in water demand while simultaneously facing declines in its current water resources. Las Vegas depends
on a snowmelt-fed water system – the Colorado River – for the majority of its water. Snowmelt-fed water systems are particularly vulnerable to declines in water supply due to climate change (Harpold et al. 2017). The U.S. Bureau of Reclamation has projected a high possibility of water shortage in the Colorado River Basin in the next 50 years (U.S. Bureau of Reclamation 2012).

Las Vegas can only significantly expand its water portfolio by building new infrastructure to access novel sources. The city has nearly exhausted its ability to transfer ground- or surface-water from nearby agriculture to M&I use (Southern Nevada Water Authority 2017). Further, it is unlikely that Las Vegas will be able to purchase permanent water resources from outside the region using current infrastructure given that as a result of population growth and climate change, 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). This imbalance suggests that the other lower basin members the Colorado River Compact (California, Arizona, and Mexico) are unlikely to be in a position to permanently transfer portions of their annual allotments to Nevada.

Our empirical case focuses on the Southern Nevada Water Authority (SNWA)’s Groundwater Development Project (GWD), which is a high profile, on-going project to exploit groundwater resources in eastern and central Nevada for M&I use in Las Vegas. Our analysis compares the economic impacts of the GWD against a baseline case where scarce water limits the growth of the residential housing stock in Las Vegas and leads to higher home prices. The case where scarce water limits the growth in housing is the most plausible pathway for Las Vegas to balance M&I supply and demand given that the region currently recycles almost 100% of indoor water and has already implemented one of the most aggressive conservation programs

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1 Limited water restricts growth directly both by reducing the number of housing units demanding water and by shifting the composition of the housing stock towards smaller, less water-intensive units. It also indirectly affects regional growth by reducing regional demand for industrial output and, hence, industrial water use.
in the United States, which suggests that future conservation efforts may encounter decreasing returns (SNWA 2017).2

This article makes three contributions to the literature. First, we develop a GE model to analyze the benefits and costs of a water infrastructure project that expands a region’s water supply. The need for GE models to analyze public infrastructure projects is widely acknowledged (Morrison and Schwartz 1996; Haughwout 2002; Rioja 2003). Given that infrastructure projects are irreversible and often entail large public debt and permanent operating and maintenance costs, overestimating future demand for these investments can result in large public costs without commensurate benefits (Brueckner and Picard, 2015). Following previous studies (Goulder and Williams 2003; Caliendo and Parro 2015), a GE framework allows us to analyze the distributional impacts of the GWD across households, sectors, and over time. Intergenerational equity is an important consideration when evaluating any large infrastructure project because current rate-payers/taxpayers must finance investments to meet future needs.

Second, we model the municipal water sector as a regulated monopoly operating under a cost-recovery (zero-profit) mandate that requires the utility to set rates to cover long-run costs (including the costs of servicing debt incurred to finance infrastructure projects) and prohibits the utility from earning economic rents from customers on the water rights held in their portfolio. Dixon (1990) models pricing policy of a public water utility in a GE framework, but does not consider this common feature of public utilities. Other studies, such as Watson and Davies (2011), assume that the water utility can lease water to other sectors in the economy to maximize the economic rent on the water assets in their portfolio, which runs counter to their cost-recovery mandate. We assume that the municipal water sector’s cost-recovery mandate allows it to set

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2 SNWA reports that between 2002 and 2016, the region reduced its net gallons per capita per day by 38% (SNWA 2017).
water rates to service the debt incurred to finance the GWD. Allowing the GWD to be financed by rate payers rather than from general tax revenue or outside investment, as is typical in the literature (Seung and Kraybill 2001; Rioja 2003; Strzepek et al. 2008; Bom and Ligthart 2014), provides a more realistic description of how the GWD and other large-scale water infrastructure projects will impact regional households and firms.

Finally, we develop an empirical approach that uses micro-billing data on household and firm water consumption from the Las Vegas Valley Water District (LVVWD) to get an accurate picture of payments to the municipal water sector from industries and households in Las Vegas.

The analysis focuses on the impact of the GWD for Las Vegas in 2030 and 2050. We find that the GWD reduces welfare in 2030. In 2030, the additional water supplied by the GWD is not needed and the increased price of municipal water required to service the debt related to the GWD raises water costs for households and firms. In contrast, we find that the GWD improves welfare in 2050. In 2050, the additional water from the GWD prevents the system from becoming supply constrained and allows Las Vegas to avoid high home prices driven by water scarcity. The results suggest that the magnitude of these intertemporal trade-offs are significant, with substantial welfare losses from the GWD in 2030 (annual loses of $200-$2,200 per household, depending on household income group) and substantial benefits in 2050 (annual benefits of $400-$2,900). Additional results focus on the implications of the GWD for employment and output in specific sectors and local and state government tax revenue.
2. A General Equilibrium Model with a Regulated Water Utility

This section develops a three-sector GE model of a closed-economy to illustrate how we model the municipal water sector in our empirical GE model and how the impact of a water infrastructure project on regional welfare depends on water supply and demand.

2.1 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

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

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

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

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

$$w L_i = \alpha_i p_i Y_i \quad \text{and} \quad r K_i = (1 - \alpha_i) p_i Y_i, \quad (3)$$

$$MC_i = [A_i (\alpha_i)^{\alpha_i} (1 - \alpha_i)^{1-\alpha_i}]^{-1} w^{\alpha_i} r^{1-\alpha_i} + \theta_{j,i} p_j + \theta_{l,i} p_l, \quad (4)$$

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 output are used as intermediate inputs, but that housing services are not (i.e., $\theta_{s,m} = \theta_{s,u} = 0$).

2.2 Water Utility

Three key assumptions underlie how we model the municipal water sector. First, we assume that regulated water utility operates under a cost-recovery mandate that requires that its equilibrium profit equals zero and that it not earn economic rents on the water rights held in its portfolio.

This latter assumption 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,

\[ Y_{rw,u} = \theta_{rw,u} Y_u, \theta_{rw,u} \leq 1, \]  

(5)

where \( \theta_{rw,u} < 1 \) in the case where the utility employs water recycling in order to provide a greater volume of treated water than its raw water input.\(^3\)

Second, we assume that the water utility employs sector-specific capital, such as pumping stations, water treatment facilities, and pipelines, that can only be employed in the provision of municipal water. The water infrastructure investments analyzed in this article are assumed to be sector-specific capital. We assume that the water utility must employ sufficient sector-specific capital to provide treated water to a region of population \( L \), and that this capital is not a complement or substitute with other factor of production and, as such, does not appear in (1). Further, we assume that while the utility’s cost-recovery mandate prevents it from earning economic rents on its sector-specific capital, it is permitted to earn revenue in excess of variable cost in order to service debt acquired to finance investments in sector-specific capital.

Third, the water utility faces a water supply constraint:

\[ (\theta_{rw,u})^{-1} Y_{rw} = Y_u \geq Y_u, \]  

(6)

where \( Y_{rw} > 0 \) is the volume of raw water available to be treated by the utility given the water rights held in its portfolio. We assume that when (5) binds, water availability limits the supply of housing services so that water demand and supply are in equilibrium. That resource rent from scare water are captured in the housing sector reflects the practice that developers must obtain water rights and donate them to water utilities in order to undertake new construction. This practice implies that an increase in the cost of acquiring water rights due to water scarcity will

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\(^3\) The assumptions that raw water is a Leontief intermediate input with zero marginal cost imply that raw water does not impact the cost-minimizing input demands in (2) and (3).
limit new construction and, as a consequence, increase the demand (and, hence, price) for existing housing.

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

$$
\pi_m = (p_m - MC_m)Y_m = 0,
$$

$$
\pi_s = (p_s - MC_s - \lambda_s)Y_s = 0,
$$

$$
\pi_u = (p_u - MC_u)Y_u - S_u = 0,
$$

where $\lambda_s = p_s - MC_s \geq 0$ are resource rents to scare water in the housing sector and $S_u \geq 0$ are debt payments for sector-specific capital in the $u$-sector. $\lambda_s$ is determined by the complementary-slackness condition

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

The equilibria in the $u$- and $s$-sectors when (i) $\bar{Y}_u > Y_u$ and (ii) $\bar{Y}_u = Y_u$ are illustrated in Figure 1.

### 2.3 Households

The representative household is assumed to:

$$
\max_{y_{m,h}, l_{s,h}} U(Y_{m,h}, Y_{s,h}) = Y^\beta_{m,h} Y^{1-\beta}_{s,h}
$$

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

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 $Y_{m,h} (Y_{s,h})$. The representative household consumes treated water indirectly through their consumption of $m$- and $s$-sector output. The representative household earns income, $I$, from supplying labor, $L$, and capital, $K$, and from resource rents in $s$-sector, $\lambda_s Y_s \geq 0$. Utility-maximizing demand functions and indirect utility function are:
\[ Y_{m,h} = \frac{\beta}{p_m} I, Y_{s,h} = \frac{1 - \beta}{p_s} I, \text{ and } v(p_m, p_s, I) = \left( \frac{\beta}{p_m} \right)^\beta \left( \frac{1 - \beta}{p_s} \right)^{1 - \beta} I. \]  

(9)

2.4 Model Closure

The equilibrium is defined by the three market-clearing conditions for m-, s-, and u-sector output

\[ Y_m = Y_{m,h} + Y_{m,s} + Y_{m,u}, Y_s = Y_{s,h}, \text{ and } Y_u = Y_{u,m} + Y_{u,s}, \]  

(10)

the two factor market-clearing conditions,

\[ L = L_m + L_s + L_u \text{ and } K = K_m + K_s + K_u, \]  

(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 \((p_m, p_s, p_u)\) and factor prices \((w, r)\), factor demands for labor \((L_m, L_s, L_u)\), capital \((K_m, K_s, K_u)\), and intermediate inputs \((Y_{m,s}, Y_{m,u}, Y_{u,m}, Y_{u,s}, Y_{r,w,u})\), final output \((Y_m, Y_s, Y_u)\), household consumption \((Y_{m,h}, Y_{s,h})\), and resource rents to scare water \((\lambda_s)\).

2.5 Welfare Impacts of a Water Infrastructure Project

We define the compensating variation (CV) for a new water infrastructure project as

\[ v(p_{m,0}, p_{s,0}, I_0 + CV) = v(p_{m,1}, p_{s,1}, I_1), \]  

(12)

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

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

(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 \(\lambda^s_{s,0} = 0\)), 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 \((S_{u,1} - S_{u,0} > 0)\).

The increase \(p_u\) will increase production costs, and, as a result, output prices, in the \(m\)- and \(s\)-sectors \((p^*_{m,1} > p^*_{s,0}\) 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 reduce regional welfare.\(^4\)

Second, when the system is supply-constrained without new infrastructure \((Y^*_{u,0} = \bar{Y}_{u,0}\) and \(\lambda^s_{s,0} > 0)\) and the new infrastructure allows the water utility to increase reduce price \((p^*_{u,1} < p^*_{u,0})\), the sign of \(CV\) is ambiguous. The decrease \(p_u\) will reduce output prices in the \(m\)- and \(s\)-sectors \((p^*_{m,1} < p^*_{s,0}\) and \(p^*_{s,1} < p^*_{s,0}\)) and increase payments to factors of production \((w^*_1 > w^*_0\) and \(r^*_1 > r^*_0)\), both of which increase \(CV\); however, the new infrastructure will also eliminate rents to scarce water in the housing sector \((\lambda^s_{s,0}Y^*_{s,0} > 0)\), thereby reducing \(CV\).\(^5\) Evaluating the welfare impacts of a specific water infrastructure project in this case, therefore, requires an empirical GE model.

### 2.6 Changes in Supply and Demand for Municipal Water

Changes in water supply and demand also have an ambiguous impact on \(CV\). From (11), when the system is supply-constrained without new infrastructure \((Y^*_{u,0} = \bar{Y}_{u,0})\),

\[
\frac{\partial CV}{\partial Y_{u,0}} = I_1 \bar{p}_m^\beta \bar{p}_s^{1-\beta} \left[ \frac{\beta}{\bar{p}_m} \frac{\partial p_{m,0}}{\partial Y_{u,0}} + 1 - \beta \frac{\partial p_{s}}{\partial Y_{u,0}} \right] - \left( \frac{\partial w_0}{\partial Y_{u,0}} L + \frac{\partial r_0}{\partial Y_{u,0}} K + \frac{\partial (\lambda_{s,0} Y_{s,0})}{\partial Y_{u,0}} \right),
\]

(12)

where \(\bar{p}_m = p_{m,0}/p_{m,1}\) and \(\bar{p}_s = p_{s,0}/p_{s,1}\). The increase in \(\bar{Y}_{u,0}\) reduced \(p^*_{u,0}\), which reduces the prices the \(m\)- and \(s\)-sector output \((\frac{\partial p_m}{\partial Y_{u,0}} < 0, \frac{\partial p_s}{\partial Y_{u,0}} < 0)\) and increase payments to factors of

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\(^4\) 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., \(Y^*_{u,1} < Y^*_{u,0} = \bar{Y}_{u,0}\).

\(^5\) The welfare implications for this second case apply when the system is also supply constrained after the new infrastructure investment, i.e., \(Y^*_{u,0} = \bar{Y}_{u,0}, Y^*_{u,1} = \bar{Y}_{u,1}\)
production \( \frac{\partial w_0}{\partial Y_{u,0}} > 0, \frac{\partial r_0}{\partial Y_{u,0}} > 0 \), both of which increase CV, but will reduce water-scarcity rents in the s-sector \( \frac{\partial(\lambda_{s,0}Y_{s,0})}{\partial Y_{u,0}} < 0 \). These countervailing effects imply that the sign of \( \frac{\partial CV}{\partial Y_{u,0}} \) is ambiguous. Similarly, from (11), an increase in population, \( L \), which will increase water demand,

\[
\frac{\partial CV}{\partial L} = \left( \frac{\beta}{p_m} \frac{\partial \bar{p}_m}{\partial L} + \frac{1 - \beta}{p_m} \frac{\partial \bar{p}_s}{\partial L} \right) I_1 + \frac{\partial w_1}{\partial L} L + w_1 + \frac{\partial r_1}{\partial L} K \frac{\bar{p}_m}{p_s}^{1-\beta} - \left( \frac{\partial w_0}{\partial L} L + w_0 + \frac{\partial r_0}{\partial L} K + \frac{\partial (\lambda_{s,0}Y_{s,0})}{\partial L} \right).
\]  

(13)

The large number of countervailing effects and partial derivatives of unknown sign (i.e., \( \frac{\partial w_1}{\partial L}, \frac{\partial w_0}{\partial L} < 0, \frac{\partial r_1}{\partial L}, \frac{\partial r_0}{\partial L}, \frac{\partial (\lambda_{s,0}Y_{s,0})}{\partial L} > 0 \), and \( \frac{\partial \bar{p}_m}{\partial L}, \frac{\partial \bar{p}_s}{\partial L} \leq 0 \)) imply that the sign of (13) is ambiguous.

That the signs of (12) and (13) are ambiguous further underlines the necessity of using an empirical GE model to analyze the welfare impacts of a specific water infrastructure project.

3. Empirical General Equilibrium Model for Las Vegas

We use the intuition developed in the previous section to build an empirical general equilibrium model that extends the three-sector framework to a small open economy that includes 14 industrial sectors, 9 household groups, 9 wage groups for labor, 4 government sectors, and 6 housing types based on home value. Following Berck, Golan, and Smith (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 C-D production function described above) with three types of primary factor inputs – labor, capital, and land – and Leontief intermediate inputs.

Except housing services and treated water, other industrial sectors in the model are tradable sectors, and their outputs are 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 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 9 income groups. Each group is modeled with a 
representative household that receives factor income from labor wages, capital and land rents, as 
well as social security transfers from the federal government. After paying income tax and 
property tax, each representative household allocates its disposable income to private 
consumption, housing, savings, and income transfers to other regions. Each representative 
household’s demand functions are derived by maximizing a Cobb-Douglas utility function 
subject to post-tax income. 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 both employees and employers. The state government receives state sale 
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 household are determined by population 
growth and net migration. Net migration of households is further determined by average wage,
household disposable income, the unemployment rate, and regional consumer price index. Sectoral capital supply is investment plus initial capital stock minus depreciation. Sectoral land supply is adjusted by equilibrium rent relative to its initial rent.

Model closure includes commodity and factor market clearing conditions. Foreign ownership of capital and land, net exports, 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. Appendix A shows the detailed mathematical presentation of the model.

3.1 Data and Parameterization

Data for our empirical model are organized in a Social Accounting Matrix (SAM), building on the method developed by Schwarm and Cutler (2003) and Hannum et al. (2017), but augmented using detailed data from the LVVWD. A SAM is a comprehensive data framework representing regional economic accounts (Lofgren et al. 2002). The SAM for Las Vegas allows us to estimate the exogenous variables and parameters in our general equilibrium model. The benchmark year of data is 2013.

The data on revenues and expenditures by industry come from the IMPLAN Input-Output (I-O) Table. The employment and wage data are obtained from the 2013 five-year American Community Survey (ACS) Public Use Microdata Sample (PUMS) in the U.S. census. Capital and land inputs for productive sector and housing service sectors are from Clark county assessor’s office and Nevada Department of Employment, Training & Rehabilitation (DETR).6

6 The Clark county assessor office keeps detailed information for each parcel of the land in the county. The DETR data identify each firm in the state with the six-digit North American Industry Classification System (NAICS) code. We merge commercial parcel data with employment data from the DETR through the street address and GIS information. By doing this, we can generate money and physical flows of land and capital for each productive sector in Las Vegas area. Similarly, we also aggregate residential parcel data into six groups based on property values and lot sizes, and distribute six housing service sectors across nine household groups using PUMS household records.
The challenge for constructing the water sector is that IMPLAN does not explicitly report water utility data. To create the water sector, we use micro billing 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: water billing record from LVVWD, Clark County Assessor data, and DETR data. Merging water bill with assessor data gives us water use per parcel; merging assessor data with DETR data allows us to assign a NAICS code to each parcel. For residential data, we merge LVVWD data with the assessor data to get water use by housing service category. Since LVVWD service area only accounts for approximately 70% of total water consumption in Clark County, we scale-up our water use by industry and household for the LVVWD service area to match the total water consumption of Clark County provided by the SNWA.

In Las Vegas, treated water is not sold outside the region or imported from other regions. For this reason, 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 the water-specific capital/infrastructure.

The model’s elasticities are selected from previous literature. The exogenous parameters are calculated from the SAM. We first reproduce our SAM by calibrating the equilibrium of the

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7 One way of constructing the water sector is to separate the water utility from the sector of “other local government enterprises” in the IMPLAN based on the number of employment. However, our preliminary investigation shows that the approximation of water utility using the IMPLAN data will not work for Las Vegas because approximated total revenue for the water utility using this method is less than half of the total revenue calculated using LVVWD billing data.

8 Since 2013, local water agencies in the Las Vegas area initiated the infrastructure charge to all water customers for funding facilities such as Intake No.3 and the Low Lake Level Pumping Station in the Lake Mead. The infrastructures are built on the federal land (underneath the Lake Mead), so our method that uses the assessor records is impossible to measure the capital cost of the infrastructure on federal land. Thus, we use the surplus to represent the current sector-specific costs of the infrastructure that cannot be measured by the assessor office.

9 The elasticities used in our simulation are as follows: elasticities for residential and commercial land are 2 and 1 (Cutler and Davies 2007). Labor supply elasticity in response to the labor average wage ranges from 0.1-0.8 regarding to different household groups; labor supply elasticity in response to household taxes ranges from -0.55 ~ -0.15; migration elasticity to after tax earnings ranges from 1.5 – 2.3; migration elasticity to unemployment ranges
base year, 2013. All prices are set to the unity in the model calibration. The detailed procedure of model implementation is presented in Appendix B.

3.2 Impact of the GWD on Water Supply

The largest water resources in the region come from the Colorado River apportionment established under the 1922 Colorado River Compact and the Boulder Canyon Project Act (BCPA). Southern Nevada’s total entitlement of the Colorado River is 272,205 acre-feet per year (AFY) (consumptive use), which is currently extended to 476,359 AFY (diversion equivalent) of water used by households and firms in Las Vegas by the return-flow credits from water recycling. We simulate the Las Vegas economy in 2030 and 2050 under the expected shortage conditions of the Colorado River as predicted in the SNWA’s 2017 Resource Plan (SNWA 2017).

Total water supplies in 2030 and 2050 under the projected long-term shortage conditions are 510 thousands AFY. In addition to using the SNWA’s water supply projections, we also include average customer (industrial and residential) conservation projections of 2.9% by 2030 and 7.3% by 2050 (SNWA 2015).

To address the projected water shortage, SNWA proposed the Groundwater Development Project GWD to convey groundwater from central and eastern Nevada to Las Vegas. Once completed, the SNWA-GWD is estimated to cost $15.5 billion (2011 dollar) and to transfer 83,988 AFY of raw water into Las Vegas annually. SNWA estimates that water from the project will be available in the long term (2050) but not in the near future (2030). The annualized cost of

from -0.7 to -0.2 (Berck et al. 1996). The elasticity of substitution between primary factors is set to 0.8 (Watson and Davies 2011). Income elasticities for household private consumption, and own-price elasticities are from Blanciforti et al. (1986). Particularly, the income elasticities are: 0.48 – 0.5 for agriculture and food, 0.52 for utilities, 0.8 for retail, 0.7 for service, 0.35 for hospital and health, 1.7 for durable and manufacture consumptions, 1 for other “miscellaneous” sector. The own-price elasticities are: -0.3 for agriculture and food, -0.5 for utilities, -0.4 for retail, -0.2 for service, -0.3 for hospital and health, -0.42 for durable and manufacture consumptions, -1 for other “miscellaneous” sector. We observe a broader range of income elasticities for housing services from previous literature, and the elasticities range from 0.14 ~1.4. In our study, the housing service is an agent sector including houses for selling, renting, and maintaining. We first select 0.8 to run our simulation, and then provide a sensitivity analysis in regard to the elasticities.
$15.5 billion over 30 years is $668 million. In our SNWA-GWD scenarios where the cost of the projected is paid by rate payers, we impose equation (21) to ensure that the infrastructure cost is paid for by water utility customers.

3.3 Model Simulations

Following previous studies (Watson and Davies, 2011; Burnett, Cutler, and Davies, 2012), we mimic the expected growth of the Las Vegas region by simulating both population and export growth. Population growth is implemented by exogenously imposing a natural population growth rate in the model. Las Vegas is expected to have a 30% increase in population by the year 2030 and 50% by 2050. Export growth is implemented by increasing exports of health, construction, transportation and warehousing, accommodation, and food services10. Our growth projections are taken from the Clark County Comprehensive Planning, and we perform sensitivity analysis on these assumptions (see Appendix C).

The simulation with population and export growth provides our baseline scenario (henceforth *baseline*). In this case, water supplies do not increase and as population grows, water becomes scarce. We compare this to the GWD scenario that increases both water costs and availability (henceforth *GWD scenario*).

In the baseline scenario, there are equilibrium rents in the housing sector if the system becomes supply constrained. We assume that these rents are redistributed to households in

---

10 We use the long-term economic forecast from the Clark County Comprehensive Planning to mimic the potential economic growth. See the link: http://www.clarkcountynv.gov/comprehensive-planning/Pages/default.aspx The projection reports that the employments for health, construction, transportation and warehousing, accommodation, and food services will increase 60%, 45%, 40%, 25%, and 25% in 2030, and 160%, 150%, 100%, 40%, and 40% in 2050; these provide the targets for our simulation. However, when we simulate the 2050 scenarios, both capital supply and productivity parameters need to be increased largely to keep our model solvable, because the targets of potential growth are extremely large. In the absence of further information about technology improvement and physical capitals in next 50 years, we cut the growth targets in half for each sector. We do not intend to focus on the projection for the future growth and this is not our main purpose of the study, because the future growth is unpredictable. We also adjust technology (TFP) and physical capital growth (capital supply) slightly across simulations to keep our model is solvable. We assume that both TFPs and physical capitals for productive sectors are increased 1% and 2% by the year 2030 and 2050.
proportion to land and capital ownership in the model. We use General Algebraic Modeling System (GAMS) with a non-linear solver, CONOPT, to solve for the equilibrium conditions of the parameterized model.

4. Results

In this section, we use the empirical general equilibrium model developed in the previous section to evaluate the economic impact of the GWD for Las Vegas in 2030 and 2050. This section describes the impacts of the GWD for regional population, employment, and production, county and state tax revenue, household housing expenditures and total disposable income, and household welfare. In addition, this section 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 (and, hence, water demand).

4.1 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 rate payers through an increased price of treated water in 2030. As we demonstrated in our three-sector GE model presented in Section 2, the increase in the price of municipal water implies that the GWD project will reduce welfare in 2030 compared to scenarios where the GWD is not invested. Table 2 reports that the GWD nearly doubles the average price of treated water in 2030, which leads to reductions in population, county and state tax revenue, and industrial revenue.

---

11 In our baseline parameterization, “2030” or “2050” refers to when the population is increased by 25% or 50%, respectively.
In 2050, on the other hand, our simulations predict that without the new water resources from the GWD, the system is supply constrained in “shortage” years for the Colorado. Table 2 reports that population in 2050 is only 0.20% higher in the GWD scenario compared to the base scenario. As with population, the fiscal impacts of the GWD are modest in 2050. From Table 2, county tax revenues and state tax revenues from Clark County in the GWD scenario are increased by $18 million (0.52%) and $41 million (1.26%) respectively compared to the base scenario.\footnote{Given that we assume that water rate payers finance the cost of the GWD, the additional tax revenue in the GWD scenario is net of the cost of the GWD.}

Table 3 reports employment and output by industrial sector in 2050. Employment and industrial output in the GWD scenario is approximately 1% higher, on average, in 2050 compared to the base scenario. Sectoral use of capital and land follow similar patterns as employment and are not reported. In Table 3, sectors are ordered from least water intensive to most water intensive.\footnote{Water intensity here refers to share of water in total costs of sectoral production.} All else equal, the higher price of water in the GWD scenario increases the cost of 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 relative 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 on both total employment and the distribution of employment across sectors, with the least water intensive sectors experiencing the largest increases in employment.

### 4.2 Housing and Household Income

Table 4 reports results for the housing services sector in 2050. We focus on housing because households purchase water in the model through their purchases of housing services, so that
increases in residential water prices impact households through increased cost of housing. Table 4 shows that in 2050, housing prices are significantly lower in the GWD scenario relative to the base scenario (4.7% - 6.4% depending on housing types). Table 4 also shows that consumption of housing services is higher in the GWD scenario relative to the base scenario, but that the net effect of higher prices and lower consumption is that total expenditure on each category of housing services is higher in the base scenario compared to the GWD scenario.

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 each household group. Table 5 shows that real disposable income is higher in 2050 in the GWD scenario compared to the base scenario for each household group and that these differences become more pronounced when income net of housing expenditures is considered. The results in Table 5 indicate that when compared to the GWD scenario, the negative impacts on household disposal income of increased housing costs in the base scenario is not offset by the additional household income from equilibrium profits in the housing sector (resource rents from scare water).

4.3 Household Welfare

Table 6 reports the household income and compensating variation for the groundwater development project by household group in 2030 and 2050. Compensating variation 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 on Table 6 correspond higher household welfare in the base scenario; positive values correspond to higher household welfare in the GWD scenario. Table 6 indicates that in 2030, the model predicts the welfare losses from the GWD are significant, with compensating variation to avoid
the increased water price due to the GWD ranging from approximately $240 for the least wealth households (HH1) to over $2,160 for the wealthiest households (HH9). In contrast, the GWD makes all households groups in Las Vegas better-off in 2050 compared to the baseline. Particularly, households in 2050 have positive compensating for GWD of between approximately $440 and $2,860 per year compared to the baseline.

These results highlight the distributional and intergenerational considerations related to the GWD project and 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, but also benefit the most in 2050. Further, the general equilibrium effects work against wealthier household in 2030, where a smaller economy in the GWD scenario implies lower returns to factors of production, 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. This result indicates that GWD involves significant intergenerational equity issues, with substantial welfare losses in 2030 balanced by substantial welfare gains in 2050.

4.4 Colorado River Water Supply

The previous sub-section 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 absent 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) (shortage), 545,000 AFY (normal supply), and 475,000 AFY (additional shortage). We use the shortage scenario as our baseline because it is viewed as the most likely scenario given U.S. Bureau of Reclamation forecasts for water supply in Colorado River Basin over the next 50 years.

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 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.

4.5 Las Vegas Population

Table 8 considers how our results change when the rate of 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 are wrong in the other direction (understating future growth), our results would simply understate the economic case for the GWD.

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 absent the project, but that water is more expensive in the GWD scenario than in the water price scenario and, as a result, water use is lower. As such, Las Vegas would be better-off balancing M&I supply and demand through conservation pricing or another conservation strategy in 2050. These results highlight the fact that whether the GWD project ultimately benefits Las Vegas depends on the region continuing to grow rapidly over the next half century.

5. Conclusions

This paper develops a general equilibrium model to analyze the economic and distributional impacts of a large-scale water infrastructure project that can significantly expand regional water portfolio. The model captures the salient features of the decision-making of a municipal water sector that operates as a regulated monopoly operating under a cost-recovery mandate. We then extend our analytic model and calibrate it to measure the welfare impacts of a ground water development project in the Las Vegas-Henderson-Paradise metropolitan statistical area. We use data from several sources including, micro-billing data on household and firm water consumption to ensure that the model provides an accurate picture of payments to the municipal water sector from industries and households in Las Vegas.

The results demonstrated that while the GWD project eventually improves household real income and welfare, the increased cost of municipal water required to service the debt related to the GWD project reduces real income and welfare in years before the additional water provided by the GWD is needed. Our results suggest that the magnitude of these inter-temporal trade-offs are significant, with substantial welfare losses from the GWD in 2030 (annual loses of $200-
$2,200 per household) and substantial benefits in 2050 (annual benefits of $400-$2,900).

Sensitivity analysis revealed that whether the system is supply constrained absent 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 loses, it does suggest the conditions under which this intergenerational compensation criteria is likely to be met (i.e., low Colorado River water supplies, high population growth for Las Vegas).

We find that the GWD has limited impact on many of the top-line economic indicators for Las Vegas. 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 where 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 expenditure, 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 would be more pronounced. Studies have suggested that turf and trees moderate heat island effects and improves urban quality-of-life in cities in the southwest United States (Klaiber, Abbott, and Smith 2017).
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 increase output and employment in all sectors, the largest employment gains in the least water intensive sectors relative to the housing scenario. This is due to the fact that while more water is available to Las Vegas in 2050 in the GWD scenario, the increase in the cost of municipal water required to service the debt from the GWD project shifts industrial composition away from water intensive sectors. This counterintuitive result suggests that if large water infrastructure projects are funded by rate payers, they may ultimately tilt metropolitan areas’ industrial composition towards less water intensive sectors while expanding industrial production as a whole.
Reference


# Tables

## Table 1. Structure of the Model and Data

<table>
<thead>
<tr>
<th>Account</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Productive Sectors:</strong></td>
<td></td>
</tr>
<tr>
<td>Sector</td>
<td></td>
</tr>
<tr>
<td>(1) Agriculture</td>
<td>Data sources</td>
</tr>
<tr>
<td>(2) Mining and Extraction</td>
<td></td>
</tr>
<tr>
<td>(3) Utilities excluding Water Utility</td>
<td></td>
</tr>
<tr>
<td>(4) Construction</td>
<td></td>
</tr>
<tr>
<td>(5) Manufacture</td>
<td></td>
</tr>
<tr>
<td>(6) Warehousing and Transportation</td>
<td></td>
</tr>
<tr>
<td>(7) Retail</td>
<td></td>
</tr>
<tr>
<td>(8) Service</td>
<td></td>
</tr>
<tr>
<td>(9) Hospital and Health</td>
<td></td>
</tr>
<tr>
<td>(10) Accommodation</td>
<td></td>
</tr>
<tr>
<td>(11) Gambling (excluding Casino Resorts)</td>
<td></td>
</tr>
<tr>
<td>(12) Food, Drinking, and Restaurant</td>
<td></td>
</tr>
<tr>
<td>(13) Casino Resorts</td>
<td></td>
</tr>
<tr>
<td>(14) Water utility</td>
<td>221310</td>
</tr>
<tr>
<td><strong>Housing Service Sectors</strong></td>
<td>LVVWD</td>
</tr>
<tr>
<td>Housing types</td>
<td>Size</td>
</tr>
<tr>
<td>HS1</td>
<td>Lot Size &lt; 1 acre</td>
</tr>
<tr>
<td>HS2</td>
<td>Single family housing</td>
</tr>
<tr>
<td>HS3</td>
<td>Lot Size &gt; 1 acre</td>
</tr>
<tr>
<td>HS4</td>
<td></td>
</tr>
<tr>
<td>HS5</td>
<td></td>
</tr>
<tr>
<td>HS6</td>
<td>Multi-family housing</td>
</tr>
<tr>
<td>Factor</td>
<td>Labor demand and supply are obtained from PUMS data. Labor is divided into nine groups by wages or salary income past 12 months.</td>
</tr>
<tr>
<td>Capital &amp; Land</td>
<td>Capital and land values are the land improvement and land value assessed by the county office.</td>
</tr>
<tr>
<td>Government Sectors</td>
<td>Federal government in Clark County</td>
</tr>
<tr>
<td>State government</td>
<td>State government in Clark County</td>
</tr>
<tr>
<td>Local government - Administration</td>
<td></td>
</tr>
<tr>
<td>Local government - Safe</td>
<td></td>
</tr>
<tr>
<td>Tax sectors</td>
<td>Excise and other taxes (to County)</td>
</tr>
<tr>
<td>Sale tax (to State)</td>
<td>Property tax (to County)</td>
</tr>
<tr>
<td>Sale tax (to County)</td>
<td></td>
</tr>
<tr>
<td>Room tax (to County)</td>
<td>Live tax (to State)</td>
</tr>
<tr>
<td>Gaming tax (to State)</td>
<td></td>
</tr>
</tbody>
</table>

**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 ≤ HH4 < $35,000 | $75,000 ≤ HH7 < $100,000 |
| $10,000 ≤ HH2 < $15,000 | $35,000 ≤ HH5 < $50,000 | $100,000 ≤ HH8 < $150,000 |
| $15,000 ≤ HH3 < $25,000 | $50,000 ≤ HH6 < $75,000 | HH9 ≥ $150,000 |

<sup>14</sup> IMPLAN Clark County regional I-O Table were validated by Center for Economic Development, University of Nevada, Reno.

<sup>15</sup> The employment is validated by PUMS and DETR data.

<sup>16</sup> 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.
<table>
<thead>
<tr>
<th>Resource Constraint Bind</th>
<th>Base Scenario</th>
<th>GWD Scenario</th>
<th>Base Scenario</th>
<th>GWD Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Constraint (1000 AFY)</td>
<td>510</td>
<td>510</td>
<td>510</td>
<td>594</td>
</tr>
<tr>
<td>Residential Conservation Equivalent</td>
<td>na</td>
<td>na</td>
<td>11.3%</td>
<td>na</td>
</tr>
<tr>
<td>Infrastructure cost ($1,000,000 2013)</td>
<td>0</td>
<td>668</td>
<td>0</td>
<td>668</td>
</tr>
<tr>
<td>Housing Sector Profits</td>
<td>na</td>
<td>na</td>
<td>YES</td>
<td>na</td>
</tr>
<tr>
<td>Water Use Q* (1000 AFY)</td>
<td>498</td>
<td>494</td>
<td>-0.88%</td>
<td>510</td>
</tr>
<tr>
<td>Water Price (Unity price)</td>
<td>1.00</td>
<td>1.96</td>
<td>95.79%</td>
<td>1.03</td>
</tr>
<tr>
<td>Population (# of HH)</td>
<td>876,458</td>
<td>875,320</td>
<td>-0.13%</td>
<td>1,041,812</td>
</tr>
<tr>
<td>Total County Tax</td>
<td>2,793</td>
<td>2,780</td>
<td>-0.50%</td>
<td>3,352</td>
</tr>
<tr>
<td>Sale Tax to State</td>
<td>2,720</td>
<td>2,705</td>
<td>-0.54%</td>
<td>3,258</td>
</tr>
<tr>
<td>Total Output</td>
<td>71,737</td>
<td>71,497</td>
<td>-0.33%</td>
<td>79,662</td>
</tr>
</tbody>
</table>
### Table 3 Sectoral Employment and Output

<table>
<thead>
<tr>
<th>Sector</th>
<th>Housing Scenario</th>
<th>GWD Scenario</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Employment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mining and Extraction</td>
<td>1,625</td>
<td>1,664</td>
<td>2.40%</td>
</tr>
<tr>
<td>Utilities excluding water utility services</td>
<td>4,089</td>
<td>4,133</td>
<td>1.08%</td>
</tr>
<tr>
<td>Gambling (excluding casino resorts)</td>
<td>33,434</td>
<td>34,246</td>
<td>2.43%</td>
</tr>
<tr>
<td>Construction</td>
<td>103,262</td>
<td>104,672</td>
<td>1.37%</td>
</tr>
<tr>
<td>Warehousing and Transportation</td>
<td>92,867</td>
<td>94,127</td>
<td>1.36%</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>34,561</td>
<td>34,932</td>
<td>1.07%</td>
</tr>
<tr>
<td>Service</td>
<td>303,736</td>
<td>307,276</td>
<td>1.17%</td>
</tr>
<tr>
<td>Hospital and Health</td>
<td>150,935</td>
<td>152,323</td>
<td>0.92%</td>
</tr>
<tr>
<td>Retail</td>
<td>149,807</td>
<td>151,831</td>
<td>1.35%</td>
</tr>
<tr>
<td>Casino Resorts</td>
<td>126,319</td>
<td>126,618</td>
<td>0.24%</td>
</tr>
<tr>
<td>Accommodation</td>
<td>83,306</td>
<td>83,629</td>
<td>0.39%</td>
</tr>
<tr>
<td>Food, Drinking, and Restaurant services</td>
<td>97,005</td>
<td>96,917</td>
<td>-0.09%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1,180,946</td>
<td>1,192,368</td>
<td>0.97%</td>
</tr>
</tbody>
</table>

| **Output**                     |                  |              |                    |
| Mining and Extraction          | 146              | 149          | 2.31%              |
| Utilities excluding water utility services | 1,148            | 1,159        | 0.95%              |
| Gambling (excluding casino resorts) | 1,579            | 1,616        | 2.37%              |
| Construction                   | 8,234            | 8,337        | 1.26%              |
| Warehousing and Transportation | 7,307            | 7,387        | 1.10%              |
| Manufacturing                  | 3,056            | 3,084        | 0.92%              |
| Service                        | 22,032           | 22,246       | 0.97%              |
| Hospital and Health            | 10,821           | 10,904       | 0.77%              |
| Retail                         | 7,496            | 7,579        | 1.10%              |
| Casino Resorts                 | 9,704            | 9,716        | 0.13%              |
| Accommodation                  | 3,737            | 3,748        | 0.29%              |
| Food, Drinking, and Restaurant services | 4,345            | 4,339        | -0.14%             |
| **Total**                      | 79,603           | 80,264       | 0.83%              |

Notes:
Percent difference from the Housing scenario.
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. Agricultural has the lowest water intensity of all sectors in our model. While it is the case that most agriculture in Las Vegas is indoor, this low water intensity suggests that agricultural producers in Las Vegas are likely using water not obtained through the municipal water system (e.g., groundwater via small wells).
Total Revenue of Productive Sectors does not include the water utility sector.
Dollar figures in millions of 2013.
## Table 4. Housing Services in 2050

<table>
<thead>
<tr>
<th>Housing Services: Price (Unity Price)</th>
<th>Base Scenario</th>
<th>GWD Scenario</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS1</td>
<td>1.5</td>
<td>1.42</td>
<td>-5.33%</td>
</tr>
<tr>
<td>HS2</td>
<td>1.53</td>
<td>1.45</td>
<td>-5.23%</td>
</tr>
<tr>
<td>HS3</td>
<td>1.61</td>
<td>1.52</td>
<td>-5.59%</td>
</tr>
<tr>
<td>HS4</td>
<td>1.41</td>
<td>1.32</td>
<td>-6.38%</td>
</tr>
<tr>
<td>HS5</td>
<td>1.54</td>
<td>1.46</td>
<td>-5.19%</td>
</tr>
<tr>
<td>HS6</td>
<td>1.5</td>
<td>1.43</td>
<td>-4.67%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Housing Services: Consumption</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HS1</td>
<td>11,645</td>
<td>11,920</td>
<td>2.36%</td>
</tr>
<tr>
<td>HS2</td>
<td>864</td>
<td>883</td>
<td>2.29%</td>
</tr>
<tr>
<td>HS3</td>
<td>360</td>
<td>367</td>
<td>1.99%</td>
</tr>
<tr>
<td>HS4</td>
<td>116</td>
<td>119</td>
<td>2.56%</td>
</tr>
<tr>
<td>HS5</td>
<td>170</td>
<td>174</td>
<td>1.97%</td>
</tr>
<tr>
<td>HS6</td>
<td>2,349</td>
<td>2,400</td>
<td>2.21%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Housing Services: Expenditure</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HS1</td>
<td>17,467</td>
<td>16,926</td>
<td>-3.10%</td>
</tr>
<tr>
<td>HS2</td>
<td>1,321</td>
<td>1,281</td>
<td>-3.06%</td>
</tr>
<tr>
<td>HS3</td>
<td>580</td>
<td>558</td>
<td>-3.71%</td>
</tr>
<tr>
<td>HS4</td>
<td>163</td>
<td>157</td>
<td>-3.98%</td>
</tr>
<tr>
<td>HS5</td>
<td>262</td>
<td>253</td>
<td>-3.32%</td>
</tr>
<tr>
<td>HS6</td>
<td>3,523</td>
<td>3,433</td>
<td>-2.56%</td>
</tr>
</tbody>
</table>
Table 5. Real Income per Household in 2050 (2013 $)

<table>
<thead>
<tr>
<th>Housing Scenario</th>
<th>GWD Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>HH1</td>
<td>21,954</td>
</tr>
<tr>
<td>HH2</td>
<td>20,174</td>
</tr>
<tr>
<td>HH3</td>
<td>30,526</td>
</tr>
<tr>
<td>HH4</td>
<td>41,770</td>
</tr>
<tr>
<td>HH5</td>
<td>43,548</td>
</tr>
<tr>
<td>HH6</td>
<td>56,590</td>
</tr>
<tr>
<td>HH7</td>
<td>86,463</td>
</tr>
<tr>
<td>HH8</td>
<td>113,644</td>
</tr>
<tr>
<td>HH9</td>
<td>165,598</td>
</tr>
</tbody>
</table>

Note: Real income (in 2013 dollars) is nominal income divided by the consumer price index (CPI) for each household group.
Table 6. Compensating Variation for Ground Water Development Project

<table>
<thead>
<tr>
<th></th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH1</td>
<td>-238</td>
<td>446</td>
</tr>
<tr>
<td>HH2</td>
<td>-252</td>
<td>668</td>
</tr>
<tr>
<td>HH3</td>
<td>-399</td>
<td>784</td>
</tr>
<tr>
<td>HH4</td>
<td>-566</td>
<td>1,189</td>
</tr>
<tr>
<td>HH5</td>
<td>-661</td>
<td>1,336</td>
</tr>
<tr>
<td>HH6</td>
<td>-957</td>
<td>2,380</td>
</tr>
<tr>
<td>HH7</td>
<td>-1,310</td>
<td>2,857</td>
</tr>
<tr>
<td>HH8</td>
<td>-1,545</td>
<td>2,430</td>
</tr>
<tr>
<td>HH9</td>
<td>-2,157</td>
<td>654</td>
</tr>
</tbody>
</table>
### Table 7. Colorado River Water Supply in 2050

<table>
<thead>
<tr>
<th></th>
<th>Baseline (510,000 AFY)</th>
<th>Additional Shortage (475,000 AFY)</th>
<th>Normal Supply (545,000 AFY)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
<td>GWD</td>
<td>Base</td>
</tr>
<tr>
<td>Supply Constraint (1000 AFY)</td>
<td>510</td>
<td>594</td>
<td>475</td>
</tr>
<tr>
<td>Water Use Q* (1000 AFY)</td>
<td>510</td>
<td>517.1</td>
<td>475</td>
</tr>
<tr>
<td>Population (# of HH)</td>
<td>1,041,812</td>
<td>1,043,844</td>
<td>1,031,399</td>
</tr>
<tr>
<td>Total County Tax</td>
<td>3,352</td>
<td>3,370</td>
<td>3,254</td>
</tr>
<tr>
<td>Sale Tax to State</td>
<td>3,258</td>
<td>3,299</td>
<td>3,090</td>
</tr>
<tr>
<td>Total Output</td>
<td>79,662</td>
<td>80,325</td>
<td>76,750</td>
</tr>
</tbody>
</table>

Note:
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

<table>
<thead>
<tr>
<th></th>
<th>50% Pop. Growth (base)</th>
<th>30% Pop. Growth</th>
<th>40% Pop. Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
<td>GWD</td>
<td>Base</td>
</tr>
<tr>
<td>Supply Constraint (1000 AFY)</td>
<td>510</td>
<td>594</td>
<td>510</td>
</tr>
<tr>
<td>Water Use Q* (1000 AFY)</td>
<td>510</td>
<td>517</td>
<td>503</td>
</tr>
<tr>
<td>Population (# of HH)</td>
<td>1,041,812</td>
<td>1,043,844</td>
<td>910,852</td>
</tr>
<tr>
<td>Total County Tax</td>
<td>3,352</td>
<td>3,370</td>
<td>2,943</td>
</tr>
<tr>
<td>Sale Tax to State</td>
<td>3,258</td>
<td>3,299</td>
<td>2,888</td>
</tr>
<tr>
<td>Total Output</td>
<td>79,662</td>
<td>80,325</td>
<td>74,039</td>
</tr>
</tbody>
</table>

Note:
Total Revenue of Productive Sectors does not include the water utility sector and housing services.
Dollar figures in millions of 2013.
Figures

Figure 1. Model Equilibria with Water Supply Constraint

Caption: 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.
Appendix A. Mathematical Presentation of Model

### Indices & Sets

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P, J$</td>
<td>Productive Sectors</td>
</tr>
<tr>
<td>$H$</td>
<td>Housing sectors</td>
</tr>
<tr>
<td>$W$</td>
<td>Water Utility</td>
</tr>
<tr>
<td>$L$</td>
<td>Federal, State Brothers</td>
</tr>
<tr>
<td>$N$</td>
<td>Local Brothers</td>
</tr>
<tr>
<td>$F$</td>
<td>Factor Tax</td>
</tr>
<tr>
<td>$A$</td>
<td>Sale tax and other local tax</td>
</tr>
<tr>
<td>$G$</td>
<td>Income tax</td>
</tr>
<tr>
<td>$I$</td>
<td>Internal government transfer</td>
</tr>
<tr>
<td>$T$</td>
<td>Internal Transfer</td>
</tr>
<tr>
<td>$L$</td>
<td>Labor</td>
</tr>
<tr>
<td>$K$</td>
<td>Capital</td>
</tr>
<tr>
<td>$L$</td>
<td>Land</td>
</tr>
<tr>
<td>$H$</td>
<td>Household</td>
</tr>
<tr>
<td>$W$</td>
<td>Rest of world</td>
</tr>
</tbody>
</table>

### Variable

**Price-related endogenous variables**

- $\text{CPI}_{i}$: Consumer price index
- $\text{P}_{i}$: Aggregated price of market goods paid by intermediate sectors, household, and governments
- $\text{PD}_{i}$: Producer price (domestic price) of sector $i$
- $\text{PV}_{A_i}$: Value-added price of productive sectors $I$
- $\mu$: Shadow price of housing services
- $\lambda$: Shadow price of water utility (water scarcity price)
- $\text{RA}_F$: Economy wide scalar rental rates of factors
- $\text{R}_{F,J}$: Factor rental rates such as wage, land value, and capital rent
- $\text{R}_{L,GN}$: Labor wage rates for government sectors

**Demand-related endogenous variables**

- $\text{CG}_{i,G}$: Government consumption including federal, state, and local government
- $\text{CH}_{i,H}$: Household consumption or consumer purchase
- $\text{CN}_{i}$: Gross investment by sector of source
- $\text{CX}_{i}$: Export demand
- $DD_{i}$: Domestic demand
- $DS_{i}$: Domestic supply
- $\text{FD}_{F,J}$: Factor demand for industrial sector $I$
- $\text{FD}_{F,G}$: 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**

- $\text{GVFOR}_{G}$: Government outflow
- $\text{HH}_{H}$: Number of Household
- $\text{HW}_{H}$: Number of working household
- $\text{HN}_{H}$: Number of household not working
- $\text{IGT}_{G,XX}$: Internal government transfer
- $\text{KFOR}_{X}$: Capital outflow
- $\text{KS}_{X,GC}$: Capital supply
- $\text{NG}_{X,J}$: Gross investment by sector of destination
- $\text{NK}_{I}$: Net capital inflow
- $\text{LAS}_{L,AG}$: Land supply for each sector
- $\text{LNFOR}_{LA}$: Land outflow
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_G$</td>
<td>Government Savings</td>
</tr>
<tr>
<td>$S_H$</td>
<td>Household savings</td>
</tr>
<tr>
<td>$SPI$</td>
<td>Personal income</td>
</tr>
<tr>
<td>$YH_H$</td>
<td>Household income</td>
</tr>
<tr>
<td>$YF_F$</td>
<td>Factor income including labor income $YF_L$, land income $YF_{LA}$, capital income $YF_K$</td>
</tr>
<tr>
<td>$YG_G$</td>
<td>Government and tax income ($Y_{GN}, Y_{GZ}$), and an agent sector, tax pool ($Y_{taxpool}$)</td>
</tr>
<tr>
<td>$YD_H$</td>
<td>Household disposable income</td>
</tr>
<tr>
<td>$YK_H$</td>
<td>Local household capital income</td>
</tr>
<tr>
<td>$YLA_H$</td>
<td>Local household land income</td>
</tr>
<tr>
<td>$HR_{HS}$</td>
<td>Housing rent (profit) caused by the water scarcity issue</td>
</tr>
<tr>
<td>$WR$</td>
<td>Water rent by conservation rate</td>
</tr>
<tr>
<td>$UTL_H$</td>
<td>Household utility</td>
</tr>
<tr>
<td>$CV_H$</td>
<td>Compensating variation</td>
</tr>
</tbody>
</table>

**All exogenous variables**

- $CCM_j$: Capital investment from commodity
- $NRPG_H$: Natural rate of population growth
- $PIT_{G,H}$: 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
- $K_{out_k}$: Share of Capital inflow-outflow
- $LA_{out_{LA}}$: Share of Land inflow-outflow
- $GV_{out_G}$: Share of Government inflow-outflow
- $HH_{out_H}$: Income inflow-outflow per HH
- $FC$: Fixed cost of water utility sector
- $W_{s,inf}$: 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**

- $CG0_{G,H}$: 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)
- $DO_i$: Initial value of ratio of domestic supply to domestic demand
- $DD0_i$: Initial value of domestic demand
- $DS0_j$: Initial value of domestic supply
- $FFD0_i$: Initial value of factor demand
- $GV0_{F0G}$: Initial value of government outflow
- $HH0_H$: Initial value of number of households
- $HW0_H$: Initial value of number of working households
- $KS0_{K,JC}$: Initial capital stock from baseline data (SAM)
- $LAS0_{LA,I}$: Initial land stock from baseline data (SAM)
- $MO_i$: Initial value of imports
- $MIO0_i$: Numbers of household migrate in
- $M000_H$: Numbers of household migrate out
- $NO_{E,I}$: Initial value of gross investment by sector of destination
- $PO_i$: Unity price = $1
- $PIT0_{G,H}$: Nominal tax per working household
- $R0_{F,J}$: Factor rental rates calculated from baseline data (SAM)
- $SO_H$: Household saving from baseline data (SAM)
- $VO_i$: Initial value of intermediate demand
- $YGO0_i$: Initial value of government income
- $YFO0_i$: Initial value of factor income including labor income $YF0_L$, land income $YF0_{LA}$, capital income $YF0_K$
Nominal HH disposable income
Nominal HH income
Initial value of household capital income
Initial value of household land income
Initial value of housing rent (profit) caused by the water scarcity issue
Initial value of water rent by conservation rate
Household utility
Compensating variation

Parameter:
Elasticity
\( \lambda_{ij} \)  Cross price elasticity
\( \beta \)  Income elasticity for demand
\( \rho_i \)  CES top level function exponent: \( \rho_i = (1 - \sigma) / \sigma \)
\( \delta \)  Elasticity of CES top level function
\( \eta^e_i \)  Elasticity for export demand
\( \eta^d_i \)  Domestic share price elasticity
\( \eta^m_i \)  Import elasticity with respect to domestic price
\( \eta^{le}_{K,j} \)  Capital elasticity (Land and Capital elasticity)
\( \eta^{le}_{L_A,j} \)  Land elasticity (Land and Capital elasticity)
\( \eta^a_H \)  Labor supply elasticity with respect to average wage
\( \eta^{pt}_H \)  Household response to transfer payments
\( \eta^{pt}_H \)  Labor supply elasticity with respect to taxes
\( \eta^I_H \)  Responsiveness of immigration to after tax earnings
\( \eta^I_H \)  Responsiveness of immigration to unemployment
\( \eta^{pt}_H \)  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)
\( a_{H,L_A} \)  Share of land supply by each HH
\( a_{H,K} \)  Share of capital supply by each HH
\( a_{d,f,j} \)  Share of domestic input-output coefficient
\( a_{f,j} \)  Share of factors in production function
\( c_{d,j} \)  Consumption elasticity for commodities in the Cobb-Douglas utility function
\( a_{g,C,L} \)  Shares of government expenditure
\( t_{sx,G,L} \)  Tax to Federal, State, and Local (Tax pool) government
\( t_{sx,G,L} \)  Share of tax redistributing back to local government (administration and safe department)

Tax Rates
\( t^s_{G,S,j} \)  Average sales tax rates
\( t^f_{G,F,S,j} \)  Factor input taxes including labor, land, and capital tax
\( t^{fl}_{G,L} \)  Factor tax: labor
\( t^{fl}_{G,L_A} \)  Factor tax: labor
\( t^{fl}_{G,K} \)  Factor tax: capital
\( t^{fn}_{G,F,P} \)  Aggregated factor taxes
\( t^{fl}_{G,F,S,j} \)  Factor taxes (for counterfactual-CF scenario)

Other Parameters
\( \gamma_k \)  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)
\( jobcor_{rs} \)  Correction factor between workers from households H and labors L

Model Equation
Household block
Consumer Price Index:
\[
CPI_H = \frac{\sum_j P_j \cdot \left( 1 + \sum_{G,S} t^s_{G,S,j} \right) \cdot CH_{j,H}}{\sum_j P_{0j} \cdot \left( 1 + \sum_{G,S} t^s_{G,S,j} \right) \cdot CH_{j,H}}
\]
Capital income redistributed to the local household
\[
Y_{KH} = \sum_K (a_{KH}^{HWg}) \cdot (Y_K + KFOR_K)
\]
Land income redistributed to the local household
\[
Y_{L} = \sum_{LA} (a_{LA}^{HWg}) \cdot (Y_{LA} + LNFOR_{LA})
\]
Household Income:
(A4) \[ Y_H = \sum_{g} (a_{H,H} \cdot HW_{H,g}) \cdot Y_{g} \cdot (1 - \sum_{g} \tau_{g,H}^{f}) + YLA_{H} \cdot \left(1 - \sum_{g} \tau_{g,LA}^{f}\right) + YK_{H} \cdot \left(1 - \sum_{g} \tau_{g,K}^{f}\right) \]

Housing rent redistributed to the local housing owner
(A5) \[ HR_{H} = \mu \cdot DS_{H} \cdot \left(1 + \frac{\text{KPFOR}_{K} \cdot \text{LNFOR}_{LA}}{\sum_{g} \text{VCA}_{g} \cdot \sum_{g} \text{VF}_{g}}\right) \]

Water scarcity rent redistributed to the local household and business owner
(A6) \[ WR = \lambda \cdot DS_{w} \cdot \left(1 + \frac{\text{KPFOR}_{K}}{\sum_{g} \text{VF}_{g}}\right) \]

Disposable income = Household factor income + government transfer + housing rent redistribution + water rent redistribution + income tax + property tax + compensating variation
(A7) \[ YD_{H} = Y_{H} + H \cdot Hout_{H} \cdot HH_{H} + \sum_{g} TP_{H,g} \cdot HH_{H} + (\sum_{g} HR_{H,g}) \cdot (\frac{(V_{H} + YLA_{H})}{\sum_{g} (V_{H} + YLA_{H})}) + WR \cdot \left(\frac{(V_{H})}{\sum_{g} (V_{H})}\right) - \sum_{g} \tau_{H} \cdot HH_{H} + CV_{H} \]

Household consumption for market goods and housing services (derived from Cobb-Douglas utility function)
(A8) \[ C_{H,H} = CH_{0,H} \cdot \left(Y_{D_{H}} / Y_{D_{H}}\right)^{\frac{1}{\theta}} \cdot \prod_{j} \left(P_{j} \cdot \left(1 + \sum_{g} \tau^{g}_{g,j}\right)\right)^{\theta} \]

Household saving = Disposable income – Consumption
(A9) \[ S_{H} = YD_{H} - \sum_{j} P_{j} \cdot CH_{H,j} \cdot \left(1 + \sum_{g} \tau^{g}_{g,j}\right) \]

Cobb-Douglas utility function
(A10) \[ UT_{L,H} = \prod_{j} C_{H,j}^{v_{a,j}} \]

Producer Equations
Value-added price for productive sectors and housing sectors excluding the water sector
(A10) \[ PV_{A_{INW}} = PD_{INW} - \sum_{j} a_{j,INW} \cdot P_{j} \cdot \left(1 + \sum_{g} \tau^{g}_{g,j}\right) \]

Value-added price for the water sector
(A11) \[ DS_{w} \cdot PV_{A_{w,w}} = DS_{w} \cdot PD_{w} = \sum_{j} a_{j,w} \cdot P_{j} \cdot \left(1 + \sum_{g} \tau^{g}_{g,j}\right) \cdot DS_{w} - Inv \]

CES value-added production function
(A12) \[ DS_{j} = \gamma_{j} \cdot \left(\sum_{i} \alpha_{f,j} \cdot FD_{j,w}^{-\rho_{j}}\right)^{\frac{1}{\theta}} \]

Factor demand: FOC of Unit cost production function
(A13) \[ R_{F,j} \cdot RA_{F} \cdot \left(1 + \sum_{g} \tau^{g}_{g,F,j}\right) = \alpha_{F,j} \cdot \left(\frac{FD_{F,j}}{\gamma_{j}^{\frac{1}{\rho_{j}}} + \sum_{i} \alpha_{f,j} \cdot FD_{F,j}^{-\rho_{j}}}\right) \cdot PD_{F,j} \cdot \left(\sum_{i} \alpha_{f,j} \cdot FD_{F,j}^{-\rho_{j}}\right)^{-1} \]

Intermediate Demand
(A14) \[ V_{INW} = \sum_{j} A_{D,INW} \cdot DS_{j} \]

Water demand
(A15) \[ V_{WU} = \sum_{j} a_{d,w,US} \cdot DS_{H} + \sum_{i} a_{d,w,i,u} \cdot DS_{i} + a_{d,w,u,u} \cdot DS_{w} \]

Labor income:
(A16) \[ Y_{F_{L}} = \sum_{j} R_{L_{j,L}} \cdot RA_{L_{j}} \cdot FD_{L_{j}} \]

Land income:
(A17) \[ Y_{F_{L}} = \sum_{j} R_{L_{j,L}} \cdot RA_{L_{j}} \cdot FD_{L_{j}} \]

Capital income:
(A18) \[ Y_{F_{K}} = \sum_{j} R_{K_{j,L}} \cdot RA_{K_{j}} \cdot FD_{K_{j}} \]

Land outflow from the region
(A19) \[ LNFOR_{LA} = LA_{out}_{LA} \cdot Y_{F_{LA}} \]

Capital outflow from the region
(A20) \[ KPFOR_{K} = Kout_{K} \cdot Y_{F_{K}} \]

Trade Equations
Export function
(A21) \[ LX_{IP} = CX_{0,IP} \cdot \left(\frac{PD_{IP}}{PW_{0,IP}}\right)^{\frac{1}{\rho_{IP}}} \cdot \left(1 + \sum_{g} \tau^{g}_{g,IP}\right)^{\frac{1}{\theta}} \cdot \left(\sum_{g} \tau^{g}_{g,IP}\right)^{\frac{1}{\theta}} \]

Share of domestic consumption that is produced/supplied locally, exogenous world price
(A22) \[ D_{IP} = D_{0,IP} \cdot \left(\frac{PD_{IP}}{PW_{0,IP}}\right)^{\frac{1}{\rho_{IP}}} \]

Import demand
(A23) \[ M_{IP} = (1 - D_{IP}) \cdot D_{IP} \]

Average price faced by domestic consumption, world price is exogenous.
Endogenous transfer to local government

Investment Equations

Net investment

Domestic Investment

Capital stock and investment

Factor supply equation

Participation rates determined by wages, taxes, and transfer payments

Migration function = natural population growth + migrate in-out (income, CPI, employment rates et al.)

Land supply function:

Government Equations

Government Income = sale tax + factor tax + income tax + property tax + transfer + other tax

Government Endogenous Purchases of Goods and Services

Government factor input: factor demand * rental rates = factor input share * total expenditure

Government Endogenous Savings = income + outflow - consumption - factor input

Government Exogenous Savings = income + outflow - HH transfer - internal transfer

Tax distribution = share of tax redistribution * (tax collecting + outflow - transfer to HH)

Endogenous transfer

Endogenous transfer to local government

Government outflow

Government closure

State personal income (Objective function)
\( SPI = \sum_{H} Y_H + \sum_{H,G} TP_{H,G} \cdot HH_H + \sum_{H} HHout_H \cdot HH_H \)

Labor market
\( A(45) \quad \left( \sum_{H} HW_H \cdot JOB\ COR_{H,L} \right) = \sum_{I} FD_{L,I} + \sum_{I} FD_{L,0N} \)

Land market
\( A(46) \quad LAS_{L,I} = FD_{L,I} \)

Capital market
\( A(47) \quad KS_{K,I} = FD_{K,I} \)

Commodity market clearance
\( A(48) \quad DS_{INW} = DD_{INW} + CX_{INW} - M_{INW} \)

Water clearance condition
\( A(49) \quad DS_{WU} = BD_{WU} = V_{WU} + \sum_{G} CG_{WU,G} \)

Domestic market:
\( A(50) \quad DD_{IP} = V_{IP} + \sum_{H} CH_{IP,H} + \sum_{G} CG_{IP,G} + CN_{IP} \)

Domestic market for housing sector
\( A(51) \quad DD_{H5} = \sum_{H} CH_{H5,H} \)

Weak inequality constraint of water resource
\( A(52) \quad W_{S,INW} \geq DS_{WU} \)
Appendix B. Model Implementation

Table B describes scenarios implemented in this paper. Scenarios 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. $\mu$ 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 equation 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 equation 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.
<table>
<thead>
<tr>
<th>Method of Implementation</th>
<th>Housing price</th>
<th>Water Price</th>
<th>Constraints</th>
<th>Slack variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. No infrastructure</td>
<td>$p_{hs} = PD_{hs} + \mu$</td>
<td>$p_{wu} = PD_{wu}$</td>
<td>$DD_{w} = DS_{wu} \leq W_{s,inf = 0}$</td>
<td>$\perp \mu$</td>
</tr>
<tr>
<td>b. Infrastructure</td>
<td>$p_{hs} = PD_{hs} + \mu$</td>
<td>$p_{wu} = PD_{wu}$</td>
<td>$DD_{w} = DS_{wu} \leq W_{s,inf = 1}$</td>
<td>$\perp \mu$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Infrastructure Cost</td>
<td>$ADB_{inf}$</td>
</tr>
</tbody>
</table>

Notation

- $DD_{w}$: Domestic demand of water utility
- $DS_{w}$: Domestic supply of water utility
- $\bar{DS}$: Upper bound of water resource
- $\bar{DS}_{new}$: New water resource from the infrastructure
- $ADB_{inf}$: 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
- $\tau$: Housing rent
- $\lambda$: Water scarcity price when the resource constraint binds
- $\varphi$: Infrastructure charge