

Economy-wide impact of changing water availability in Senegal: an application of the JRC.DEMETRA CGE model

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April 2018

Preliminary incomplete draft of the paper. Please do not quote and circulate.

Abstract

This study assesses the structural consequences of water availability scenarios in Senegal, following a multidisciplinary approach and a sequential integrated modelling methodology. This includes an assessment of future water availability, crop response to water availability change and a general equilibrium macroeconomic analysis of changes in agricultural productivity.

Understanding the role of water as an economic resource requires a complex integrated approach, to account for the role of ecosystems in producing and storing water, and a thorough analysis of its links with all sectors in the economy. We therefore follow an integrated and sequential modelling approach, where models coming from different disciplines and working at different time and spatial scales are soft-integrated. We advance the literature by coupling a dynamic computable general equilibrium (CGE) model, tailored on the economic features of developing countries, with separate water-hydrological and crop-biophysical models, where water is modelled explicitly with its links to the water cycle and agricultural production. In such a set-up, changes in key parameters of the CGE model reflecting changing in water availability are provided by the complementary models. The CGE model is calibrated on a self-developed 2014 Social Accounting Matrix for Senegal, disaggregated into the 14 Senegalese administrative divisions.

JEL codes: C68, Q25, O55.

Keywords: water scarcity, hydro-crop-economic modelling, agricultural productivity, water use competition, socio-economic scenarios.

1. Introduction

Water is crucial for human life, for the provision of essential ecosystem services and for many economic activities. Water is also a scarce good, unevenly distributed across space. Its availability is often season-dependent and highly vulnerable to future climate change (IPCC, 2014).

Agriculture is by far the biggest global user of freshwater resources and consequently highly vulnerable to climate change as well. In most developing countries, the agricultural sector provides the main livelihood and employment for most of the population and contributes considerably to national GDP. Therefore, possible reductions in agricultural production caused by climate change in the near future could seriously weaken food security and worsen the livelihood conditions for the rural poor (REF).

Senegal is among the developing countries that may be affected by changing water availability. This country heavily relies on water resources provided by four large transnational hydrological systems, of which the Senegal river basin is the largest. Currently, the country is not suffering a condition of water stress, as only 8% of total available water resources are withdrawn for economic uses (World Bank Statistic, 2018). However, the situation may worsen in the near future as climate change is expected to negatively affect the availability of water resources and runoff in the coastal countries of West Africa (IPCC, 2014). A steadily decline in annual precipitations has been observed since the end of the 1960s and the average temperature are expected to increase by about 1°C by 2030 under the RCP4.5 scenario (Kriegler et al., 2012), affecting crop evapotranspiration. Droughts have become more frequent since 1950 and rainfall per rainy day is expected to decrease in the near future, as well as land suitable for cropping. Under this scenario, the Senegalese agricultural production is put at risk as rain-fed agriculture represents about 80% of total production.

A second reason of concern comes from the demand side. Currently, agriculture in Senegal is responsible for 93% of total water withdrawals. Agriculture is an important sector of the economy, contributing to a substantial share of the GDP (17.5%) and employing one third of total labor.¹ Understanding to what extent water resources availability may constitute a bottleneck to economic growth is therefore crucial, for a country whose well-being relies heavily on rain-fed and irrigated agriculture (Roson and Damania, 2017). The remaining 7% is withdrawn by the industry and for domestic uses. Fast industrialization, economic growth, increasing population and changing dietary habits will increase the competition on the use of water among sectors, challenging the capacity of water resources to ensure future food security (Oyebande and Odunuga, 2010). For example, under the SSP2 "Middle of the Road" scenario (Kriegler et al., 2012; KC and Lutz, 2014; O'Neill et al., 2017), GDP and population are expected to grow by about 160% and 50% with respect to the 2010 levels.

The aim of this research is assessing the structural economic consequences of changing water availability in Senegal, with a focus on the agricultural sector, under uncertain climate change and socio-economic scenarios as described in the Representative Concentration Pathways (RCPs) and Shared Socio Economic Pathway (SSPs), at the year 2030. In such a context, evaluating the effects of changing water availability for the different economic sectors requires a complex modelling approach, where separate models are integrated, possibly under shared and common assumptions. Indeed, the modelling framework must capture both the economic processes at play and the biophysical condition of the water and crop systems. Further, the representation of water in many economic models is often "stylized", given the absence of water markets in most countries (Robinson and Gueneau, 2013). Since there is often no economic transaction, water use is not commonly reported in the national economic accounts, which hampers the analysis of water resources with economic models (Calzadilla et al. 2013).

¹ For the other countries located in the Senegal river basin the agricultural sector is even more important, contributing to 20.2% (Guinea), 27.4% (Mauritania) and 42.1% (Mali) of total GDP. Source: <https://data.worldbank.org>

In this study, we therefore follow an integrated and sequential modelling approach, where models coming from different disciplines and working at different time and spatial scales are soft-integrated. A number of studies propose a similar modelling integration, but focus on other countries and river basins (Robinson and Gueneau, 2013; Kahsay et al., 2017), or take a global perspective (Liu et al., 2017). We advance on this literature by coupling a dynamic computable general equilibrium (CGE) model, tailored on the economic features of developing countries, with separate water-hydrological and crop-biophysical models, where water is modelled explicitly with its links to the water cycle and agricultural production. In such a set-up, changes in key parameters of the CGE model reflecting changing in water availability are provided by the complementary models. The CGE model is calibrated on a self-developed 2014 Social Accounting Matrix for Senegal, disaggregated into the 14 Senegalese administrative divisions.

The remainder of the paper is organized as follows. The next section explains how water has been treated in the CGE modelling and water literature, and presents the DEMETRA model. The modelling framework and details of the sequential modelling procedure are provided in Section 3. Section 4 describes the simulation results. A final section concludes.

2. Water and Computable General Equilibrium models

Over the past decades, CGE models have been employed to investigate the interactions between economic and natural systems. This kind of models may be the ideal tool, as they allow to analyse the interlinkages between different sectors of the market economy and the competition on the use of available resources. Current approaches to account for water resources into these economic models are very useful as they provide a reference framework, yet they suffer from important deficits, which are related to the peculiar characteristic of water resources (water is a no-market good in most countries), the absence of reliable data and the weak link of CGE models with hydrological models.

Introduction of water to the CGE models dates back to Berck et al. (1991) and since then became quite popular in the CGE literature (Dudu and Chumi, 2008; Berrittella et al., 2005; Calzadilla et al., 2016). Modelling water as a factor of production or intermediate input has become the standard approach in the literature. Most of the effort spent refined this approach with better representation of the substitution possibilities of water with other factors of production by using different nesting structures (Dixon et al., 2010; Calzadilla et al., 2011; Osman et al., 2016; Gómez *et al.*, 2004; Calzadilla et al., 2016) or by introducing different irrigation technologies or water types to the models (Calzadilla et al., 2011; Decaluwé et al., 1999; Gomez et al., 2004). A number of contributions focus on the use of CGE models to explore issues related to the availability, usage and management of water resources (Berrittella et al., 2007), as well as the links between sustainable water use, food security and energy production (Bazilian et al., 2011). On a global level, Calzadilla et al. (2013) explicitly model water supply and the environmental linkages between agriculture and water.

The advantage of CGE models in analysing the economics of water is their ability to compare costs and benefits of using water in different sectors of the economy or within agriculture for different crop production systems. CGE models are indeed well capable of analysing the competition on water use between food and energy production systems, and derive important lessons and policy suggestions to better distribute water among alternative uses.

These studies have contributed significantly to the literature on the economics of water. However, most of them rely on some key hypotheses and assumptions that limit their ability to properly account for water resources within the economic modelling framework. Treating water as a factor of production relies on the crucial assumption of the existence of a functioning market for water, which is not the case for many countries in the developing world. In the lack of functioning water markets, it is virtually impossible to determine the real value of water, income generated by water use and distribution of this income among different economic agents. Although it is possible to deduce the information on the value added created by water by comparing the price of irrigated and rain-fed

land, this requires the existence of functioning land markets, which is not always the case especially in developing countries.

One major limitation regards the representation of the production function scheme. The typical way of dealing with production functions in CGE models is through the Constant Elasticity of Substitution (CES) function. In this specification, intermediate production factors (and/or intermediate inputs, like e.g. water) can be substitutes to each other (e.g., the use of less water in exchange for more land), when relative prices change, according to a given constant elasticity of substitution. The production function can also assume the form of nested CES, where different substitutability between production factors or intermediate is depicted (e.g., if the use of water is a direct substitute of land use, they will enter the same nest of the CES). The CES representation requires a careful exercise by modellers and a good knowledge of the production technologies and (in this context) crop yield response to changes in the use of different inputs, to describe the right substitution possibilities among factors. For example, is water substitutable directly with land or with land and fertilisers or with land and labour? Is it an efficient strategy to increase irrigation when fertilizers adoption is too low? However, this way of modelling production function has some immediate drawbacks. Firstly, the parametrization issue of the different CES nests is extremely complicated as should rely on robust estimation based on production survey data which are rarely available. Secondly, by definition, elasticities of substitution among factors are constant over time and cannot change endogenously as economic conditions of the productive system evolve. This limits the possibility to model rapidly developing economies or endogenous technological changes able to increase productivity of factors and reduce their use.

Additionally, modelling water in CGE, as in any economic simulation model, has drawbacks directly linked with the specificities of the water market around the world, which have not yet fully addressed. Most of these models adopt market structure which implies perfect competition, zero profit conditions while the water market is more close to what in economics can be defined as a natural monopoly. This has great implication on the price formation mechanism to be associated to this market. Moreover, all factors that enter the production function need to be evaluated in monetary terms, as the calibration of the parameters is based on market transactions data. In fact, most of the water used in agriculture comes freely to farmers from rain or groundwater reservoirs (especially in some African and Middle East countries). As a non-market public good, its cost is not entirely accounted for in the production costs. Water is also a scarce resource, and might rapidly deplete if not employed sustainably. These aspects are especially relevant when employing a CES function, because the marginal productivity of inputs/production factors never goes to zero. This implies that a "zero price" production factor (like water and other natural non-marketed resources) should be consumed in an infinite amount. All these considerations are rather complicated to be translated into the simplified representation of the reality which the models are. Lastly, the value of water is closely related to the climatic conditions and this makes the valuation issues even more complicated.

Some criticisms have already been raised in this literature. They mainly concern the valuation of water (Cakmak et al., 2008; Hassan and Thurlow, 2011); the perfect market assumption for water (Fadali et al., 2012); ignoring the role of water rights, the links to bio-physical (Dudu and Cakmak, 2017) and hydrological phenomena (Nechifor and Winning, 2017; Smajgl, 2006; 2009), as well as climate factors (Young and Ringler, 2010); the lack of direct links between investments in irrigation infrastructure and water availability (Ponce et al., 2012); and the inability to link water issues to poverty especially in the developing country context (Debela and Tamiru, 2016). Nonetheless, a consensus around an alternative approach to describe water issues in a CGE model is still lacking. In this paper, we make a tentative in this direction, following some pioneer contribution (Robinson and Gueneau, 2013; Kahsay et al., 2017; Liu et al., 2017). Clearly, the lack of an established and theoretical methodology inevitably implies the presence of some caveats and limitations, which will be discussed in the concluding section.

3. Methods

3.1 Modelling approach: Soft-link integration

The above discussed limitations can be overcome by adapting the modelling framework to the information available in the data. This would require abandoning the approach to model water as a factor of production. Since neither valuation nor the level and distribution of value added created by water are available, it is more appropriate to introduce water indirectly to the production system. Some recent studies follow indeed this approach (Roson and Sartori, 2015; Kahsay et al., 2017; Sartori et al., 2017), where water is not explicitly modelled, but is assumed to be an implicit or hidden factor of production.

One appealing option to this purpose is to link the CGE model to bio-physical models, where water resources are modelled explicitly with its links to the agricultural production. In such a set-up, key parameters for the CGE model, such as the change in crop yields as water availability changes, can be provided by the biophysical models. The latter do account for the water cycle and thus produces the needed information on the availability of water and its impacts on the technical conditions of agricultural production. The CGE model can then operate without the need to explicitly introduce the "water resources factor of production" into the model, and any value added created by water will be attributed to the irrigated land, which in general does not have any valuation or distribution problem. Robinson and Gueneau (2013) propose an integrated modelling framework to analyse water-economy links, and a dynamic CGE model is coupled with a regional water basin management model, to investigate the economy-wide impacts of changes in water resources in the Indus river basin. A multi-scale hydro-economic modelling framework is proposed by Liu et al. (2017). They use a global partial equilibrium grid-resolving model, SIMPLE-G, coupled with the global Water Balance Model, to simulate the consequence of reducing unsustainable irrigation for food security, land use change and terrestrial carbon. In all these examples, water is modelled as an indirect factor of production in the economic model. In Sartori et al. (2017) the GTAP CGE model is soft-linked with a climate change damage model and the LUISA land-use change model.

In this sequential modelling methodology (Figure 1), future water availability (i.e., water supply) is first estimated by the hydrological model, under different RCPs and SSPs scenarios (Kriegler et al., 2012; KC and Lutz, 2014; O'Neill et al., 2017).² Crops response to changes in water supply is then estimated by the crop model and incorporated into the CGE model as agricultural productivity shocks. Counterfactual simulations are run on a baseline scenario consistent with the SSPs projections of GDP and population growth. Water demand by industry is then estimated, using data on agricultural, industrial and municipal water withdrawals provided by Aquastat and Mekonnen and Hoekstra (2011). Among the water uses, water needs for the ecosystems services are also accounted for. The ultimate aim is computing a water stress indicator (WSI) for Senegal, to investigate the relationship between water availability, total use and the ecosystems needs.

² SSPs include a storyline or *narrative*, which describes plausible alternative changes in aspects of society such as demographic, economic, technological, social, governance and environmental factors. RCPs are ... In this preliminary version of the paper water availability is estimated under the combined RCP4.5 and SSP3 only. This choice is due to the current availability of estimates by the hydrological model used in this study. We are planning to extend the analysis to all SSPs socio-economic scenario as soon as estimates are available.

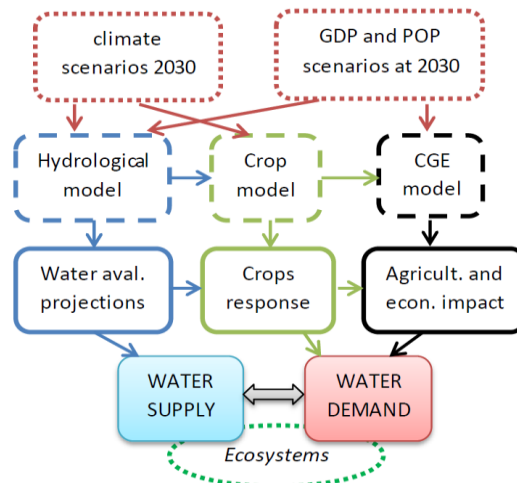


Figure 1. Sequential integrated modelling methodology.

3.2 The JRC.DEMETRA CGE model, the LISFLOOD hydrological model and the EPIC crop model

In study the soft-modelling integration combines three models. The economic model is DEMETRA, developed by the Joint Research Centre of the European Commission and derived from the STAGE_DEV model (Aragie et al., 2017). DEMETRA is a single-country, recursive dynamic CGE model used to analyse policy scenarios on agricultural economics, food security, fiscal policy and water nexus issues in developing countries. The model has been recently employed to simulate an expansion of small scale irrigation schemes through an increase in the supply of irrigated land and water in the agricultural activities in Kenya (REF JRC Reports on Kenya). The model is designed for calibration using a reduced form of a Social Accounting Matrix (SAM) that broadly conforms to the UN System of National Accounts (SNA).

DEMETRA incorporates additional behavioural relationships that better account for economic relationships in developing countries. In particular, it improves the representation of the dual roles of semi-subsistent (agricultural) households as non-separable producers and consumers. In a developing country context with a dominating agricultural sector and subsistence production, a focus on and thus detailed disaggregation of the rural economy in terms of agricultural activities and rural households is essential. Water is among the possible commodities that households either own-produce from their own consumption employing internal labour sources or consume from the market. Additionally, DEMETRA improves the representation of structural rigidities in developing economies, including un/underemployment, the use of time for activities outside the "production boundary", e.g., fetching water, introduces a detailed modelling of labour markets and migration, and distinguishes between irrigated and rain-fed agriculture.

LISFLOOD is a GIS-based hydrological rainfall-runoff model that can simulate the hydrological processes that occur in a catchment, primarily large river basins (van der Knijff et al., 2010; Burek et al., 2013). The model is designed to be applied across a wide range of spatial and temporal scales, for long-term water balance simulations (using a daily time step), individual flood events (using hourly time intervals, or even smaller) as well as the assessment of the effects of river regulation measures, land-use change and climate change. The model is driven by meteorological variables, which are precipitation intensity, potential (reference) evapotranspiration rate of a closed canopy, potential (reference) evaporation rate from a bare soil surface, potential evaporation rate from an open water surface, and average 24-hour temperature.

The Environmental Policy Integrated Climate (EPIC) model simulates crop production under different farming practices and operations, including fertilization and irrigation application rates and timing, and it considers nutrient losses to the environment. It has been thoroughly evaluated and applied from local to continental scale (Gassman et al., 2005) and used in global assessments (Liu et al.,

2008; Liu, 2009). The model has been applied for irrigation scheduling assessment (De Roo et al., 2012; Wriedt et al., 2009), climate changes studies (Mearns et al., 1999), biofuels production (Velde et al., 2009), crop management optimization (Pastori et al., 2011; Pastori et al., 2013) and yield prediction (Balkovič et al., 2013).

3.3 Computing water supply and water demand at the year 2030

The actual water consumption is represented by the sum of water withdrawals for different sectors of economy, including municipal uses. Data on current water withdrawals in Senegal are provided by the AQUASTAT database. Agriculture is responsible for 93% of total water withdrawals. The remaining is split between industrial (2.6%) and municipal (4.4%).

Water availability projections (Table 1) are generated by the LISFLOOD hydrological model, under the RCP4.5 scenario for greenhouse gas concentrations and radiative forcing and the SSP3 socio-economic scenario (O'Neill et al., 2014), by the Senegalese administrative divisions. Under the SSP3 it is assumed a slow economic growth, as a combination of multiple causes: lack of international cooperation, slow technological progress, low education levels and high population growth. A lack of development of clean technologies implies high global emission levels and thus severe mitigation challenges. The low income levels in developing countries, in turn, imply severe challenges to adaptation.

	Saint-Louis	Louga	Thies	Matam	Dakar	Diourbel	Tambacounda
2014	48,816.48	1,687.06	437.86	943.17	196.89	328.61	50,614.41
2015	29,679.35	813.59	175.74	384.12	54.71	195.60	33,828.90
2016	26,990.15	937.10	104.74	516.51	48.00	166.78	30,128.14
2017	47,576.10	2,006.74	509.75	948.88	260.88	380.59	48,412.58
2018	60,009.65	3,108.55	1,091.20	1,352.46	632.95	465.73	56,691.79
2019	34,202.09	1,176.76	167.40	533.74	137.11	284.07	36,700.77
2020	37,225.06	1,026.73	579.54	543.80	347.06	245.01	39,864.47
2021	52,638.27	2,633.22	1,108.89	1,323.14	676.70	494.69	51,247.71
2022	44,334.51	3,183.03	1,278.02	1,194.90	702.88	591.29	42,396.89
2023	55,781.71	3,148.84	1,075.94	1,404.78	593.15	667.50	52,507.37
2024	43,737.42	1,671.02	399.54	757.82	168.12	340.13	45,887.63
2025	33,816.44	1,049.61	318.33	507.72	223.64	241.93	37,535.66
2026	41,001.71	1,810.10	821.13	988.49	562.01	429.94	41,941.36
2027	37,509.70	1,490.11	369.94	689.11	229.61	318.45	40,200.71
2028	32,616.87	1,837.79	694.78	887.23	359.27	338.75	33,489.76
2029	43,818.17	2,038.16	995.94	897.64	508.69	369.69	42,715.39
2030	54,727.31	2,026.19	1,366.71	965.59	631.12	539.04	53,951.91

	Kaolack	Kaffrine	Fatick	Ziguinchor	Sedhiou	Kolda	Kedougou	SENEGAL
2014	1,071.64	652.70	1,336.04	4,194.84	2,589.37	1,432.92	3,666.05	117,968.05
2015	327.56	197.54	335.36	2,488.33	1,460.59	889.89	2,561.92	73,393.20
2016	280.12	166.66	323.10	1,664.00	953.31	564.86	2,516.13	65,359.59
2017	1,526.27	962.21	1,953.40	4,339.76	2,660.95	1,462.74	3,552.44	116,553.28
2018	1,806.13	1,083.92	2,767.10	4,759.80	2,503.20	1,364.27	3,987.98	141,624.72
2019	818.61	535.40	860.54	2,568.77	1,604.27	892.64	2,980.39	83,462.54
2020	708.17	344.88	1,323.49	3,500.13	1,934.75	1,084.44	3,551.85	92,279.38
2021	1,727.82	920.89	2,522.75	4,449.00	2,637.83	1,420.29	3,689.19	127,490.39

2022	2,009.46	1,058.66	2,737.20	3,426.04	1,933.42	1,088.91	2,901.81	108,837.00
2023	2,166.54	1,115.25	2,943.10	4,313.63	2,519.64	1,419.88	3,276.00	132,933.33
2024	912.14	531.02	1,023.24	3,162.05	2,173.45	1,281.14	3,386.05	105,430.77
2025	790.35	498.06	1,116.04	3,289.84	1,953.27	1,148.10	3,785.68	86,274.68
2026	1,541.86	850.99	2,334.28	3,529.82	1,891.82	1,049.54	2,975.12	101,728.16
2027	1,275.15	853.52	1,587.57	3,760.66	2,381.36	1,300.30	3,263.49	95,229.68
2028	989.29	576.51	1,398.65	2,944.68	1,630.70	892.47	2,734.10	81,390.86
2029	1,216.09	689.31	1,834.36	2,692.79	1,504.05	844.86	3,014.91	103,140.01
2030	1,897.60	965.54	2,928.15	4,956.52	2,832.67	1,542.15	3,776.66	133,107.19

Table 1. Projections on water availability by administrative divisions (in millions of m³). SSP3 and RCP4.5 scenarios.

The variation in water demand by the agricultural sector can only be assessed with a crop model that captures the impact of climate on evapotranspiration. Evapotranspiration of both rain-fed and irrigated crops is indeed dependent on several climatological factors including sunshine, temperature, wind speed and humidity as well as crop specific physical and physiological features (Allen et al., 1998). **[analysis with EPIC and DEMETRA to be done]**

	% var. in water availability (year-by-year)	% var. in water availability (wtr 2014)	% change in Agric. Wat. Dem. (tbd)	% change in Agric. Productivity (tbd)
2014	-38%	-38%		
2015	-11%	-45%		
2016	78%	-1%		
2017	22%	20%		
2018	-41%	-29%		
2019	11%	-22%		
2020	38%	8%		
2021	-15%	-8%		
2022	22%	13%		
2023	-21%	-11%		
2024	-18%	-27%		
2025	18%	-14%		
2026	-6%	-19%		
2027	-15%	-31%		
2028	27%	-13%		
2029	29%	13%		
2030	-38%	-38%		

Table 2. % changes in water availability, agricultural water demand and productivity. SSP3 and RCP4.5 scenarios.

Among non-agricultural water demand, we distinguish industrial and municipal consumptions, as well as ecosystems consumption.

Industrial and municipal water demand are estimated by following the procedure proposed by Roson and Sartori (2015). For industrial water demand, they relate water demand to the industrial output, which in turn is linked to changes in national income and in the share of manufacturing in total value added:

$$i = 0.46 \left(1 + \frac{s}{g} \right) g - 1$$

where g is the yearly percentage growth rate in national GDP coming from the SSPs scenarios; s is the (percentage change in the share of the manufacturing sector in total national value added estimated by the DEMETRA model; and 0.46 is the elasticity of water demand with respect to the industrial output volume estimated by Reynaud (2006). An improvement in water use efficiency by 1% per annum is also assumed Alcamo et al. (2003).

The annual growth rate of municipal water demand (m) is instead linked to variations in population (p) and income (g) and computed as follows:

$$m = p + 0.35g - 1$$

In addition to industrial and municipal water consumption, water resources are necessary to preserve a number of natural environments. Indeed, any integrated water resources management to support sustainable development cannot disregard environmental water allocation. According to Hirji and Davis (2009), Environmental Flow Requirements (EFRs) refer to the quality, quantity, and timing of water flows required to maintain the components, functions, processes, and resilience of aquatic ecosystems that provide goods and services to people. For the Senegal river basin, a reasonable share of water resources seems to be 23% of total water stock (Smakhtin et al. 2004). Results are shown in Table 3.

	% change in Ind. Wat. Dem. (tbd)	% change in Munic. Wat. Dem.	% of water for EFR
2015		4.38%	23%
2016		4.38%	23%
2017		4.38%	23%
2018		4.38%	23%
2019		4.38%	23%
2020		4.38%	23%
2021		4.06%	23%
2022		4.06%	23%
2023		4.06%	23%
2024		4.06%	23%
2025		4.06%	23%
2026		4.06%	23%
2027		4.06%	23%
2028		4.06%	23%
2029		4.06%	23%
2030		4.06%	23%

Table 3. % changes in non-agricultural water demand.

4. Results

tbd

5. Conclusions

tbd

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[to be updated]

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