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The economic impact of climate-driven changes in water availability in Switzerland

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Abstract

The broad objective of this study is to estimate the economic impact of changes in water availability due to climate change in Switzerland with a 2050 time horizon. To do so, the sectoral structure of the computable general equilibrium model GEMINI-E3 is being extended. Raw water resources are introduced as a production factor into the model and a drinking water distribution sector is specified for Switzerland to allow for a precise analysis of the economic consequences of restricted water supply. Predictions of water availability in 2050 are taken from a hydrological model and alternative climate change scenarios are considered. Simulations show possible restrictions in water resource availability to increase raw water prices substantially compared to the baseline. However, the global economic impact for Switzerland is rather small due to the low price of raw water in Switzerland and its small value in the benchmark scenario. Finally, the simulation of scenarios featuring alternative levels of endogenous adaptive capacity of the economy highlights the importance of the ability to reduce water losses and to transform production processes to decrease their water intensity in determining the extent of welfare losses provoked by a decrease in water availability.

Keywords: Adaptation; Climate change; Computable general equilibrium model; Switzerland; Water resources

1. Introduction

Climate change is bound to impact water resources worldwide (Kundzewicz *et al*., 2007). The economy-wide consequences of changes in the hydrological cycle need to be better understood. The broader economic role of water as a consumption good and intermediate input in numerous industries requires analysis, and particularly the macroeconomic consequences of future changes in water accessibility have to be apprehended for the drinking water distribution sector and all other water-using sectors to plan ahead and adapt to future conditions and for the development of adequate policies.

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The efficient management of water resources and questions surrounding the economic impact of changes in water availability are calling for answers all over the world. Switzerland is no exception to such developments. Known as the water tower of Europe, Switzerland traditionally disposes of abundant high-quality water resources. The country's hydrological cycle will nonetheless be affected by climate change (Intergovernmental Panel on Climate Change (IPCC), 2007; Organe consultatif sur les changements climatiques (OcCC), 2008). The annual evolution of water resource availability is still very uncertain, but changes in seasonality are projected to lead to a decrease in runoff and groundwater levels during the summer (Federal Office for the Environment (FOEN), 2012). These changes will alter water supply in multiple ways, thus highlighting the importance of understanding the impact of hydrological consequences of climate change on the Swiss economy.

This study contributes to the research about the economic role of water resources and the consequences of changes in water supply. It proposes a novel representation of water resources in a computable general equilibrium (CGE) model that models the water use of industrial and service sectors. The modeling accounts for water losses and allows all sectors to choose between extracting raw water themselves or buying drinking water. The new modeling is applied to Switzerland to estimate the economic consequences of possible changes in water availability for this country with a 2050 time horizon. Particular attention is devoted to the evolution of water prices and the impact of alternative levels of endogenous adaptive capacity measured by water-related elasticities of substitution, to find out where flexibility is most important and establish areas in which political action would be most efficient. To reach these objectives the sectoral structure of a CGE model is being extended in order to assess the economic impact of climate change on particularly sensitive sectors. To measure the consequences of changes in water availability, raw water resources are introduced as a production factor into the CGE model. Further, a drinking water distribution sector is specified for Switzerland to allow for a precise analysis of the economic consequences of restricted water supply.

The structure of the paper is as follows. Section 2 presents the context of the study and a review of the literature. Section 3 defines the CGE model and explains how water resources are represented. Section 4 presents the impact of climate change on water availability in Switzerland. Section 5 discusses the simulated scenarios and results. Finally, Section 6 highlights limitations of this work and potential areas for future research while Section 7 provides conclusions.

2. Context and literature review

Swiss water utilities are capturing about 980 million cubic meters of water a year (Swiss Gas and Water Association, 2009). Most of this is groundwater or spring water that account for 40% each of water captured, while the remaining 20% is surface water. The majority of this water is distributed to households and artisanry, while a lesser share of about 20% goes to industry. About 15% of the water extracted is lost by the utilities.

Water consumption in Switzerland, however, is not limited to water distributed by drinking water utilities. Indeed, both industry and agriculture are capturing an important share of their water themselves (Freiburghaus, 2009). Approximately 75% of the water used by Swiss industries was extracted directly in 2006, a share that does not account for cooling water needed by power plants. The chemical sector uses the most water among all industrial sectors, followed by waste disposal and consumption goods.

Agriculture also extracts a substantial share of the water it uses itself, mainly for irrigation. However, irrigation water represents only a small share of the total water use of the Swiss economy.

The physical impact of climate change on water resources in Switzerland and its economic consequences arouse a great deal of interest from the research community. While there are studies that forecast the physical consequences (FOEN, 2012), most analyses of the economic impacts remain descriptive (see, for example, IPCC (2007) and OcCC (2008)). Conflicts among different uses of the resource are identified as a potential future challenge, but a quantitative analysis of the consequences of changes in availability of water resources on the Swiss economy is still missing.

As mentioned above, water is used not only by households for drinking, cooking, washing and sanitation, but also by agriculture for irrigation and numerous other sectors as an input in their production processes. Changes in water availability and the allocation of the resources can thus potentially impact multiple industries. Consequently, CGE models are more and more often applied to evaluate the economic effects of climate change and of a whole range of water policy measures both at a local and global scale. Different studies analyze the consequences of a modification of the availability of water resources and the economic impact of various policies implemented to make the best possible use of the increasingly scarce resource.

Globally, a range of studies uses GTAP-W (Berrittella *et al.*, 2007, 2008; Calzadilla *et al.*, 2010, 2011, 2013), a global CGE model in which water resources have been modeled. In the GTAP-W model, raw water is introduced as a production factor for irrigating agricultural crops and water distribution only.

Roson & van der Mensbrugghe (2012) and Galeotti & Roson (2012) use the integrated assessment model ENVISAGE, in which modified water availability is modeled through changes in mean annual runoff that influence agricultural yield. Shares of water employed for municipal and industrial usage as well as water productivity are constant and water cannot be substituted by other inputs in production.

Other authors apply the CGE framework locally within one country or region but no such analysis has yet been carried out for Switzerland. These studies mostly concentrate on the impact of the implementation of policies like pricing, resource allocation or the introduction of water markets (for examples, see Roe *et al.*, 2005; Feng *et al.*, 2007; Letsoalo *et al.*, 2007; Strzepek *et al.*, 2008; Hassan & Thurlow, 2011; Juana *et al.*, 2011; Llop & Ponce-Alifonso, 2012). Recently, Brouwer *et al.* (2008) and Dellink *et al.* (2011) have used a CGE to study water quality issues in the Netherlands.

Some studies also look at the future economic impact of restricted water supply, be it a consequence of population and economic growth or climate change. Applications include Berck *et al.* (1991), Smajgl (2006), Diao *et al.* (2008), Diao *et al.* (2005), Briand (2009), Watson & Davies (2011), You & Ringler (2010), Lennox & Diukanova (2011), Ejaz Qureshi *et al.* (2012) and Wittwer & Griffith (2011). Most of these studies focus on agricultural and in some cases municipal water use. Consequently, these sectors and their water use are modeled in detail. However, it is important to represent other sectors of the economy (Ponce *et al.*, 2012).

3. The GEMINI-E3 model

This study uses a modified version of GEMINI-E3 (Bernard & Vielle, 2008), a CGE model that is specifically designed for the analysis of climate change and energy policies[1]. The model is a global

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[1] All information about the model can be found at http://gemini-e3.epfl.ch, including its complete description.

one, as the future evolution of the Swiss economy obviously depends on the world economy, and is built on the GTAP-6 database and the Swiss input–output table for 2001. Modeling of international trade is based on the Armington assumption, which assumes that a domestically produced good is treated as a different good than an imported commodity produced by a same foreign industry. GEMINI-E3 incorporates a global constraint of foreign trade balance (zero or exogenous deficit) for each region. The government collects taxes and distributes the resulting revenues to households and firms through transfers and subsidies. Wage is chosen as a numeraire in each region. The model is recursive dynamic, with backward looking (adaptive) expectations.

The sectoral structure[2] of the model is being extended for Switzerland in order to assess the economic impact of climate change on particularly sensitive sectors like agriculture and water distribution. In this study, a drinking water distribution sector is specified to allow for a precise analysis of the economic consequences of restricted water supply. This specification is added for Switzerland only, as water is a local good and is not imported to or exported from Switzerland. GEMINI-E3 focuses on Switzerland, but the rest of the world is also represented by five aggregated regions. The economy in the modified version of the model counts two primary factors related to water: raw water for irrigation and raw water for other uses. These factors are mobile between sectors but modeled as distinct goods, so raw irrigation water cannot be taken for any other use and vice versa (the modeling of raw water resources is explained in more detail in Section 3.1 below). In the model, it is assumed that water resources are the property of the central government that collects the payment for their use.

To be able to analyze the economic impact of a possible variation in water availability in Switzerland, GEMINI-E3 needs to explicitly account for water used by the different sectors and to model the water distribution sector. Hence the new version of GEMINI-E3 distinguishes two kinds of water: sectors may use raw water resources directly in production processes, or they may alternatively employ drinking (or tap) water, which is the output of the drinking water distribution sector.

3.1. Modeling raw water resources

Raw water quantities used by industry and service sectors originate from a study about the water consumption of the Swiss economy by Freiburghaus (2009). A study by Weber & Schild (2007) provides data on water use for irrigation, whereas for milk and animal products, water volumes are calculated based on information about water consumption per animal unit, the percentage of water extracted directly by farmers (Freiburghaus, 2009) and the number of animals in Switzerland (Federal Office for Agriculture, 2007; Muller, 2008)[3].

In Switzerland, raw water tariffs are defined at the cantonal or municipal level and are very heterogeneous both in terms of tariff structure and rate. Moreover, the country lacks a central database that would inform about the prices applied in the communes and cantons. However, water prices are, generally speaking, very low. This study follows Finger & Schmid (2007) and employs raw water tariffs from the canton of Zurich, that equal 0.01 USD_{2010} per cubic meter of raw water.

[2] See Appendix 1 for a description of the sectoral classification of the model (available online at http://www.iwaponline.com/wp/017/064.pdf).
[3] See Appendix 2 for an illustration of the direct water use intensity by sector (available online at http://www.iwaponline.com/wp/017/064.pdf).

Table 1. Elasticities of substitution.

Household consumption		
Nest 'Other'	σ_{hoth}	0.2
All sectors		
Capital, material, labor, energy	σ_{oth}	0.3
Water distribution, industry – services		
Raw water – water extraction	σ; σ_{wother}	0.025
Water – other factors	σ_{ind}	0.3
Industrial water – drinking water		
Metal, chemical, consumption goods	σ_w	0.3
Other industry and services	σ_w	0.1
Energy – capital	σ_{wcapen}	0.3
Agricultural sectors		
Irrigation – land aggregate – other factors	σ_{agr}	0.2
Irrigation – land		
Vegetable production	σ_{lw}	0.3
Animal production	σ_{lw}	0
Irrigation water – drinking water	σ_w	0.1

Raw water extraction does not only use raw water resources but further requires other production factors. In our study, these are capital (pumping equipment, network, etc.) and energy. Energy and capital cost for the extraction of one cubic meter of water are estimated from the cost structure of the water distribution sector.

Finally, raw water resources are separated into two distinct blocks, irrigation water and water for other uses. Indeed, climate change impacts differ considerably depending on the season. For instance runoff is predicted to increase from October to April but to decrease from May to September. To include seasonal impacts in an annual model like GEMINI-E3, irrigation water that is used seasonally is considered separately. Indeed, the three plant producing sectors of the model are assumed to need water mainly from the beginning of spring to the beginning of autumn, which corresponds to the main growing season of the plants. The two water types are impacted differently by climate change.

3.2. The drinking water sector

Drinking water distribution is the biggest raw water consumer in Switzerland. It captures raw water and transforms it into drinking water, a distinct good that is consumed by households and serves various production sectors as an input. The mean drinking water price for 2001 (1.20 USD_{2010} per cubic meter of water) is taken as the price of water.

The drinking water distribution sector is modeled through a nested constant elasticity of substitution (CES) production function[4]. We assumed that on top of the nested CES function, raw water can be substituted with other inputs that aggregate capital, materials, labor and energy.

In the model calibration, particular attention goes to the definition of the elasticities of substitution between the different inputs. The elasticities used in this study are presented in Table 1. Intuition

[4] For a representation of the production structure of the drinking water distribution and the agricultural sectors, see Appendix 3 (available online at http://www.iwaponline.com/wp/017/064.pdf).

commands the substitution elasticity between water and other inputs in drinking water distribution to be rather low. Some studies even use a zero elasticity of substitution, reducing to a Leontief production function for this particular nest (see, for example, Gomez *et al*., 2004). However in this study, this elasticity equals 0.025, allowing for adaptation strategies like for example the reduction of water distribution network losses through additional use of capital, energy, labor and other factors. Such a setting constitutes a better representation of reality. Indeed, utilities can reduce their water losses by investing in their network. Water losses in Swiss drinking water distribution have already gone down from close to 20% at the beginning of the eighties to less than 15% in 2010, an evolution attributed by the Swiss Gas and Water Association (Freiburghaus, 2012) both to the spread of technologies for the identification of leaks and the recommended average network renewal rate of 1.5–2% per year. From a cost minimization point of view, a study using data from 123 Swiss drinking water utilities for the year 2005 associates higher water losses to increased variable cost, highlighting that water utilities can benefit from better quality infrastructure (Faust, 2013).

3.3. Agricultural, industrial and service sectors and households

Not only drinking water distribution, but also numerous other industrial and service sectors use water as an input. The new production structure of these sectors distinguishes water as an input and allows them to choose between employing drinking water and extracting water themselves.

With the new production structure shown in Figure 1, the use of different types of water (industrial, produced with raw water, capital and energy, or drinking) and the possibility to substitute one by the

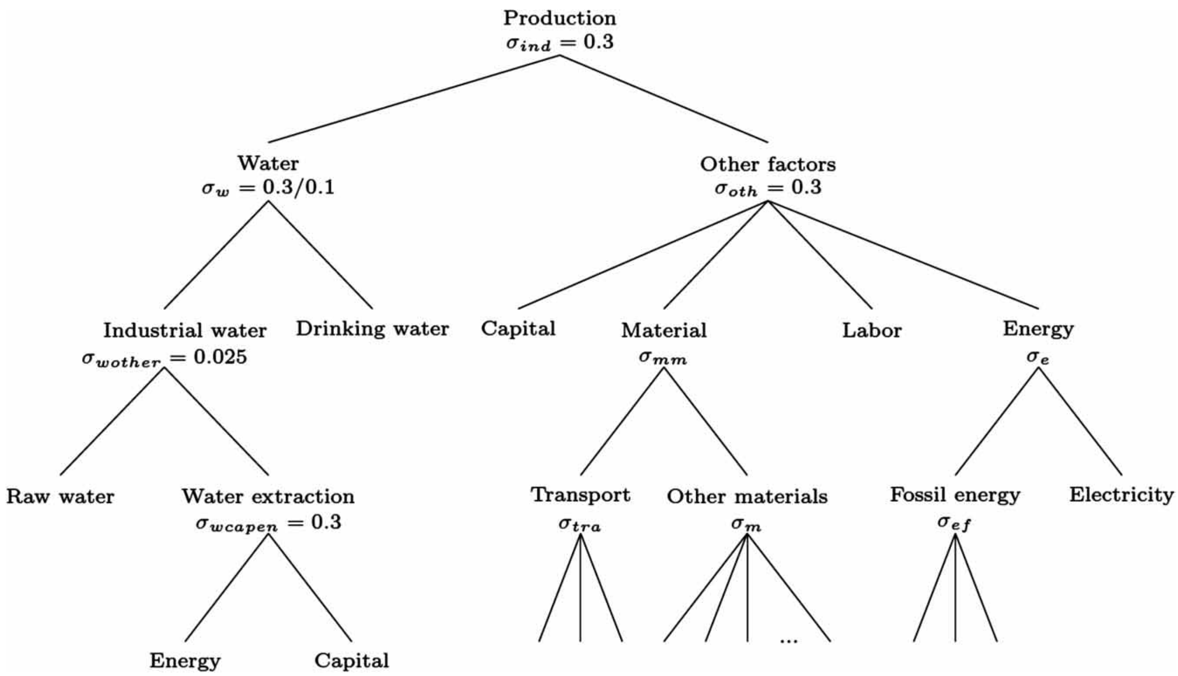

Fig. 1 Production structure of industrial and service sectors that use water as an input.

other are accounted for. Sectors get to choose among employing drinking water or extracting the water themselves, an important possibility as the prices of drinking and raw water differ substantially.

The literature shows real substitution possibilities between water, be it industrial or drinking, and other inputs. Indeed, production processes can be modified in order to be less water intensive, and water recycling systems can be implemented. This study uses an elasticity of 0.3, a value that equals the elasticity of substitution between water and capital proposed by Gomez *et al*. (2004) and is well compatible with Goodman (2000), who is testing for elasticities of 0.1, 0.25 and 0.5 between water and other inputs and finds a value of 0.1 to be too low, as it induces too high prices. This substitution possibility allows sectors to adapt to climate change by using more or less water intensive production processes.

Next, elasticities of substitution between industrial and drinking water have to be defined. Not many studies analyze the possibility to substitute drinking water with water extracted directly by firms. Reynaud (2003) has carried out a study for France on this topic. According to this study, possibilities to substitute drinking water with industrial water and vice versa appear to be generally rather limited. More specifically, the substitutability between raw water and drinking water is higher if the raw water needs to be treated, an intuitive result as drinking water and treated raw water are quite homogeneous goods. However, results by Freiburghaus (2009) indicate the possible substitution of drinking water by autonomous raw water extraction in Switzerland during the last 30 years. To allow the model to capture these possibilities, we employ positive yet low elasticities. We hence adopt elasticities equal to 0.3 in agreement with Reynaud (2003) for those sectors that treat a significant share of the raw water they extract. These are the metallurgical sector, the chemical sector and consumption goods (Reynaud, 2003). The other sectors use mostly non-treated water, that has a lower substitutability with drinking water, and thus an elasticity of 0.1 is attributed to them.

Finally, the production structure of the agricultural sectors is similar to that of industrial and service sectors, except for the use of land as a production factor that is specific to the agricultural sectors. Indeed, land is combined with irrigation to form an irrigation-land aggregate. An elasticity of substitution equal to 0.2, close to the 0.24 employed in agricultural sectors by Berrittella *et al*. (2007) is chosen between the irrigation-land aggregate and other production factors. It is possible to substitute land and irrigation with an elasticity equal to 0.3 in vegetable production. In milk and animal production, it is however impossible to substitute land for water and the elasticity equals zero. Water and land are used in fixed proportions, a modeling also found for example in Seung *et al.* (1998). The remaining production structure reflects the possibility for a firm to use either drinking water or to extract its own raw water and is identical to the structure used in service and industrial sectors.

Finally the representative consumer maximizes a nested CES utility function[5]. At the first level of the consumption function, households choose between tourism, housing, transport, agricultural products and all other consumption goods. Drinking water is situated at the second level of the function in the nest that includes all other consumption goods, that are linked with an elasticity of substitution equal to 0.2. Households consume only drinking water.

[5] For a representation of the structure of household consumption, see Appendix 4 (available online at http://www.iwaponline.com/wp/017/064.pdf).

4. The impact of climate change on water availability

To evaluate the economic consequences of climate change particularly on the water distribution sector and water prices but also on the Swiss economy as a whole, one has to be able to evaluate the physical consequences of climate change on water resources. To do so, this study uses the results of the CCHydro project (Forschungsanstalt für Wald, Schnee und Landschaft WSL, 2011; FOEN, 2012) that informs about possible evolutions of runoff and the water cycle from 2021 to 2100 for Switzerland for alternative climate-scenarios. The economic sectors represented in GEMINI-E3 use ground and surface water, consequently the variations of water resource availability in 2050 compared to the 1980–2009 reference period are calculated from the results of the CCHydro project that simulates projections for runoff and groundwater levels. From these projections, the evolutions of runoff and groundwater levels are combined proportionally to their present use in the Swiss economy. This simplifying assumption means that we suppose that the shares of groundwater and surface water use stay constant.

The CCHydro project simulates 10 different ENSEMBLES climate scenarios that are all based on the A1B emission scenario. In 2050, predictions on change in water resources differ strongly among scenarios and range from −6.8 to +9.4% for annual change and from −15.8 to −2.5% for irrigation water (period between April and October)[6]. The annual evolution of water resources is thus very uncertain and the majority of climate scenarios predict the climate change driven impact on the resources to be low. This can be explained by the nature of climate change impacts on runoff which will increase from October to April but decrease from May to September. As the evolution of available water resources is quite uncertain, different scenarios are used in this paper to simulate the economic impact of climate induced changes in water resource availability.

5. Simulated scenarios and results

5.1. The baseline scenario

Gross domestic product (GDP) and population growth assumptions that are used to simulate the baseline scenario are detailed in Faust (2013). The evolutions of water prices are determined endogenously in the model according to the future evolution of the economy and the availability of raw water resources. However, technological progress that captures improvements in water use efficiency is exogenous. We use forecasts from the European Outlook on water use (Floerke & Alcamo, 2004) that predict technological progress of 1% per year in the domestic and manufacturing sector, a rate we apply also to services and animal agricultural sectors. In irrigating agriculture, an annual technological progress of 0.5% is forecasted for Switzerland. In the baseline scenario, water availability is kept at its 2001 level until 2050. Price evolutions largely reflect assumptions about economic growth in Switzerland, that is forecasted to slow down from 2020 on, as well as technological progress in the use of water resources. Prices for raw water for irrigation reach 0.03 USD_{2010} per cubic meter in the baseline in 2050, raw water for other uses is valued at 0.12 USD_{2010} per cubic meter and finally drinking water prices are approximately 1.21 USD_{2010} per cubic meter.

[6] See Appendix 5 for a description of the evolution of water resources according to the 10 climate scenarios (available online at http://www.iwaponline.com/wp/017/064.pdf).

Table 2. Scenarios.

	Definition[a]	Changes in elasticity
1	ETHZ climate scenario	
2	SMHI climate scenario	
3	−20% drop in resource availability	
4	Low water extraction adaptation	$\sigma = 0$; $\sigma_{\text{wother}} = 0$
5	Low industry adaptation	$\sigma_{\text{ind}} = 0.1$
6	High industry adaptation	$\sigma_{\text{ind}} = 0.5$
7	Low agricultural adaptation	$\sigma_{\text{lw}} = 0.1$ in the plant growing sectors
8	High agricultural adaptation	$\sigma_{\text{lw}} = 0.5$ in the plant growing sectors
9	Low substitutability of industrial/agricultural and drinking water	$\sigma_w = 0.1$ for metal, chemical and consumption goods; $\sigma_w = 0.001$[b] for other sectors
10	High substitutability of industrial/agricultural and drinking water	$\sigma_w = 0.5$ for metal, chemical and consumption goods; $\sigma_w = 0.3$ for other sectors
11	Low household adaptation	$\sigma_{\text{hoth}} = 0$
12	High household adaptation	$\sigma_{\text{hoth}} = 0.4$
13	Low adaptation	$\sigma_{\text{ind}} = 0.1$; $\sigma_{\text{lw}} = 0.1$; $\sigma_w = 0.1/0.001$; $\sigma_{\text{hoth}} = 0$
14	High adaptation	$\sigma_{\text{ind}} = 0.5$; $\sigma_{\text{lw}} = 0.5$; $\sigma_w = 0.5/0.3$; $\sigma_{\text{hoth}} = 0.4$

[a]Scenarios 4–14 use the ETHZ climate scenario.
[b]With σ_w for other sectors = 0, the model does not converge.

5.2. The climate change scenarios

The scenarios simulated in this study are described in Table 2. The first three concentrate on investigating the impact of three distinct variations in raw water availability. Scenarios 1 and 2 impose water use constraints that replicate the predicted evolution of raw water resources according to the two most extreme CCHydro scenarios: ETHZ HadCM3Q0 CLM and SMHI HadCM3Q3 RCA. Indeed, raw water is included in the model as a fixed factor that is constrained. Consequently, water resources are linearly restricted or enhanced from 2002 onwards to reach availability levels predicted by CCHydro for 2050. For the ETHZ scenario, this corresponds to a restriction of water use by −6.8% for raw water and by −15.8% for raw water for irrigation by 2050. In the SMHI scenario, the availability of raw water resources for all uses except irrigation increases by 9.4%. This additional water becomes progressively available until 2050, while the availability of raw water for irrigation diminishes to reach a level corresponding to a 2.6% restriction of 2001 levels. The third scenario restricts both raw water for irrigation and other uses by an arbitrary share of −20% to simulate the consequence of a quite extreme constraint on water use.

In scenarios 4–14, raw water availability follows the ETHZ climate scenario. What distinguishes these scenarios are assumptions about key elasticities of substitution among water and other inputs in production, as well as water and other goods in household consumption. Hence, these scenarios can be interpreted as a sensitivity analysis to the results of scenario 1.

5.3. The alternative climate scenarios

The alternative climate scenarios are simulated to analyze the economic impact of climate-induced changes in water availability. The high uncertainty in climate predictions is reflected in economic forecasts. As shown in Table 3, the surplus indicates a welfare loss of 39.5 million 2001 USD_{2010} compared to the baseline scenario for the ETHZ scenario while the SMHI scenario results in a gain of 20.6 million USD_{2010}. An extreme reduction of the availability of both raw water for irrigation and raw water for other uses by 20% induces a welfare loss of 178.2 million USD_{2010}.

Raw water prices do vary very much and respond very sharply to changes in water availability, as shown in Table 3. These important relative price changes result from the difficulty to substitute away from water that is translated into a rather inelastic water demand in the model. The higher relative increase in the price of raw water for irrigation than in the price of raw water for other uses results from the higher reduction of water availability during the growing season of plants than annually (as the SMHI scenario even predicts an increase in annual water resource availability). Drinking water prices vary between +12.4% and −8.8% for the ETHZ and SMHI scenarios, with drinking water consumption going down by 3.2% and up by 2.6% respectively. In the −20% scenario, the relative drinking water price increase compared to the baseline scenario reaches 60.9% and drinking water consumption drops by 11.9%. Relative drinking water price increases are much lower than relative raw water price increases as the value share of raw water in drinking water production is relatively small. Further, the drinking water sector can reduce network losses by using more other inputs and, in doing so, softens the impact of changes in raw water availability.

The simulation results also illustrate some substitution of raw water use by drinking water as the relative prices of industrial and irrigation water compared to drinking water increase as a consequence of constraints on the use of raw water resources.

Globally, the economic consequences of these price variations remain rather limited because of the very low value of raw water and the small share of water expenses in the production cost of most sectors. The macroeconomic impact in terms of GDP loss is always inferior to 0.04%. This result confirms the conclusion of studies of authors like Briand (2009), who finds a 60% decrease in available water resources in the Seine estuary to greatly increase the prices of water but to have only a small impact on GDP. On the other hand, the studies of other authors suggest more important global consequences. Berck *et al*. (1991) find a 20% reduction of water resources to cause a 0.75% drop in GDP in the San Joaquin valley. In their model, only agriculture uses water, but the weight of irrigating agricultural sectors is much higher in the San Joaquin economy than it is in Switzerland.

Sectors most affected by changes in raw water availability in Switzerland are the most water intensive. These are, after water distribution, the chemical sector, agricultural sectors that use irrigation and the winter tourism sector that needs water for snowmaking. For example, variations of production range from +0.4% to −2% in the chemical sector, depending on the restrictions that are imposed on raw water use.

Furthermore, it is interesting to note that water losses are reduced when water availability is restricted. Already in the baseline, water losses in water distribution are reduced from 15% in 2001 to 7% in 2050. With restricted water availability, losses further go down to 5% in the ETHZ and to a level as low as 3% in the −20% scenario.

5.4. Sensitivity analysis

Scenarios 4–14 investigate the impact of endogenous adaptive capacity by altering the substitution options among different inputs. Such an analysis is important for two main reasons. First, this study uses elasticities of substitution taken from the literature that have not been estimated specifically for

Table 3. Simulation results, variations compared to the baseline for 2050.

Scenarios	ETHZ	SMHI	−20%	Low water extraction	Low industry adaptation	High industry adaptation	Low agricultural adaptation	High agricultural adaptation	Low substitutability industrial, agricultural & drinking water	High substitutability industrial, agricultural & drinking water	Low household adaptation	High household adaptation	Low adaptation	High adaptation
Climate scenario	ETHZ	SMHI	−20.0%	ETHZ	ETHZ	ETHZ	ETHZ	ETHZ	ETHZ	ETHZ	ETHZ	ETHZ	ETHZ	ETHZ
All uses except irrigation	−6.8%	9.4%	−20.0%	−6.8%	−6.8%	−6.8%	−6.8%	−6.8%	−6.8%	−6.8%	−6.8	−6.8%	−6.8%	−6.8%
Irrigation	−15.8%	−2.6%	−20.0%	−15.8%	−15.8%	−15.8%	−15.8%	−15.8%	−15.8%	−15.8%	−15.8%	−15.8%	−15.8%	−15.8%
Raw water	115.5%	−79.9%	575.0%	214.8%	222.6%	78.4%	116.0%	115.4%	123.2%	104.1%	130.6%	102.9%	371.7%	68.5%
Production price of the raw resource														
Raw water for irrigation	431.3%	50.3%	596.8%	880.4%	423.4%	434.2%	1630.7%	250.9%	448.4%	397.5%	429.7%	432.8%	1831.9%	242.7%
Production price of water														
Industrial water	46.6%	−32.8%	229.9%	53.0%	89.3%	31.8%	46.8%	46.5%	49.3%	42.2%	52.7%	41.5%	149.4%	28.0%
Irrigation water	64.6%	7.7%	88.9%	80.2%	63.4%	65.0%	240.1%	37.9%	67.1%	59.6%	64.4%	64.8%	269.7%	36.6%
Drinking water	12.4%	−8.8%	60.9%	18.1%	23.9%	8.4%	12.5%	12.4%	13.2%	11.2%	14.1%	11.0%	39.7%	7.3%
Drinking water consumption														
Total	−3.2%	2.6%	−11.9%	−4.3%	−3.2%	−3.3%	−3.2%	−3.2%	−3.7%	−2.4%	−2.3%	−4.0%	−2.2%	−3.2%
Households	−2.3%	1.9%	−9.1%	−3.3%	−4.2%	−1.6%	−2.3%	−2.3%	−2.5%	−2.1%	0.0%	−4.1%	0.0%	−2.8%
Macroeconomic indicators														
GDP	−0.007%	0.003%	−0.033%	−0.009%	−0.009%	−0.006%	−0.007%	−0.007%	−0.007%	−0.006%	−0.007%	−0.006%	−0.015%	−0.005%
Consumption	−0.010%	0.005%	−0.043%	−0.010%	−0.010%	−0.010%	−0.011%	−0.010%	−0.011%	−0.010%	−0.010%	−0.011%	−0.012%	−0.01%
Welfare (mios USD_{2010})	−39.5	20.6	−178.2	−48.1	−46.4	−37.2	−42.3	−39.2	−40.5	−38.0	−40.2	−39.1	−59.7	−35.8

Switzerland due to data availability constraints. It is consequently important to measure the sensitivity of simulated results to changes in these parameters. Second, this study is interested in measuring the impact of endogenous adaptive capacity, i.e. the capacity of the economy to adapt to changes in water availability. More specifically, the sensitivity analysis establishes the levels of the production structure of firms and consumption of households related to water at which changes in endogenous adaptive capacity have the biggest price and welfare effects.

All scenarios use the ETHZ climate scenario, and simulation results of scenarios 4–14 can be compared to the ones found in scenario 1. Scenario 4 reduces the possibility of replacing raw water by other inputs in water distribution and in all other water-employing sectors from 0.025 to 0. Consequently, water losses cannot be reduced. The economic consequences are quite noticeable. Indeed, as access to raw water gets restricted, prices of the resource go up. The drinking water sector reacts to this rise in the price of one of its inputs by increasing the price of drinking water and by trying to substitute away from raw water in production. It adapts by reducing water losses. The lower the substitution elasticity between raw water and other inputs, the more difficult this adaptation and the higher the impacts on prices and welfare will be. For other sectors using water as an input, the reaction will be quite similar, except for the fact that they have one more possibility to adapt: they cannot only reduce the global water intensity of their production processes, but may further substitute raw water with drinking water. In scenario 4, prices for water are further inflated when compared to the first scenario. The substitution of raw water by drinking water is less pronounced with lower adaptation options. Total welfare loss increases from 39.5 to 48.1 million. Projected welfare gains from more adaptation highlight the potential of measures like the reduction of water losses through investments in capital. This is particularly important in the drinking water sector, where the reduction of water losses is the only way to adapt to higher raw water prices and reduced raw water availability. As explained previously, water utilities have a cost minimization incentive to reduce water losses even today, and investment in the water network is already advocated in Switzerland (see Freiburghaus, 2012). In the face of climate change, further incentives for investment may be called for, especially in countries with scarce water resources and high levels of water losses. In the case of naturally monopolistic water distribution, these incentives can be provided through measures like investment-friendly regulation. The benchmarking of water losses and consequent obligation to provide a plan to the regulator on how to reduce these losses is another possibility.

Scenarios 5 and 6 analyze the possible consequences of altering the potential of non-agricultural sectors to replace industrial or drinking water use with other inputs. Changes in this elasticity are furthermost reflected in variations of the price of raw water for uses other than irrigation that increases between 78.4 and 222.6% depending on the flexibility in substituting water by other factors. These changes are translated in drinking water as well as industrial water prices. Welfare losses amount to 46.4 million USD_{2010} in the 'low industry adaptation scenario' and to 37.2 million USD_{2010} in the 'high industry adaptation scenario'. These results highlight the importance of technological progress that can make it easier to move to less water intensive production processes. Such progress could limit the economic consequences of changes in water availability.

Changes in the possibility to substitute land and irrigation water mostly affect prices of raw water for agriculture. As shown in scenarios 7 and 8, these increase much more in the low than in the high adaptation scenario. The economic impacts on other sectors are very restricted as raw water for irrigation is used in plant growing sectors only. Due to the restricted importance of agriculture in the Swiss economy, welfare impacts are rather low. Such results are bound to be different in regions in which agriculture plays a more prominent role and irrigation needs are higher.

Scenarios 9 and 10 investigate the consequences of variations in the difficulty to replace irrigation or industrial water with drinking water while the adaptive capacity of households is under scrutiny in scenarios 11 and 12. Global welfare impacts are rather robust to both changes in substitutability between the different types of water and allowing households to adjust their consumption more easily by reducing their water consumption.

The last two scenarios combine scenarios 5, 7, 9 and 11 (low adaptation, scenario 13) and scenarios 6, 8, 10 and 12 (high adaptation, scenario 14). Scenario 13 describes an economy in which it is difficult to adapt to climate change. Possibilities for substitution of industrial water by other factors, irrigation by land, drinking water by industrial or irrigation water and the capacity of households to adopt less water-intensive lifestyles are limited. Scenario 14 simulates the parallel case but with high elasticities of substitution.

Scenario 13 is characterized by important increases in the price of industrial water, irrigation water and drinking water of 149.4, 269.7 and 39.7% compared to the baseline, whereas much lower price variations of 28, 36.6 and 7.3% are observed in scenario 14. Globally, welfare losses are 59.7 million USD_{2010} in the low adaptation scenario and 35.8 million in the high adaptation scenario. The increase of adaptive capacity thus reduces welfare losses by approximately 40%, because it makes the demand for water more elastic.

Looking at scenarios 4–14, simulation results are most sensitive to substitution options between raw water and other factors in the production of drinking, industrial and agricultural water and to the difficulty of making production processes less water intensive. Restricting these substitution elasticities induces the highest welfare loss, implying that the degree of difficulty encountered in reducing water losses and the water intensity of production may be key factors in determining the extent of welfare losses provoked by a decrease in water availability. These results further pinpoint these areas as the ones where policy action for helping the economy to adapt to future changes in water supply could be most efficient. From a modeling point of view, the sensitivity analysis shows that particular attention should be paid to the estimation of the substitution elasticities between raw water and other inputs in the production of drinking, industrial and agricultural water as well as the substitution elasticities between water and other inputs in industrial production. Indeed, the elasticities have a substantial influence on simulation results, and a precise estimation of their value would further improve the model.

6. Limitations and future research

This study investigates the consequences of climate induced changes in water availability. It does not offer a global assessment of the impact of climate change as it does only partly consider changes in seasonality and does not integrate extreme events like floods and droughts. Further, potential changes in water quality are not accounted for. Future research could concentrate on directly coupling the CGE to a hydrological model to allow for feedbacks from economic activities to natural resources inside an integrated model. It is also important to highlight that the study simulates economic consequences of changes in water availability that are aggregated at the country level. This is a simplifying assumption employed because GEMINI-E3 is a national model. However, climate change impacts on water availabilities differ from one region to another. Industrial and agricultural sectors are not distributed equally over Switzerland, but rather tend to concentrate in some parts of the country. Consequently, sectors may face heterogeneous future water availability conditions. The model resolution does not allow for such a differentiated view, a caveat that could result in an over- or underestimation of economic impacts. Future research could therefore turn to the development of high spatial resolution regional models. It would also be interesting to analyze the consequences of world-wide changes in water availability on the Swiss economy, as other economies may be more badly affected by climate change, giving Switzerland a competitive advantage. Further, our study concentrates on the physical impacts of climate-induced variations in water availability in Switzerland. Legal water use restrictions may differ from these variations, for example in the case of transboundary rivers whose runoffs are regulated by international treaties. In such a case, Switzerland may be asked to reduce its water consumption further than indicated by physical observations in order to enhance the quantity of water available to neighboring countries whose water resources may be more severely affected by climate change.

Keeping these limitations in mind, the paper however creates a powerful tool for the economic analysis of water-related problems in Switzerland that describes water resources and their use in the economy in great detail. Contrary to most other models found in the literature, it allows for the direct extraction of raw water not only by agriculture and the drinking water sector but also by other industries like the chemical sector, a much better representation of reality. It further allows for the reduction of water losses as an adaptation strategy to possible increases in the price of raw water resources. The sensitivity analysis shows the important impact that this modeling has on prices and welfare effects. Imposing a Leontief structure that does not allow for any substitution in the way other studies do may thus lead to an overestimation of the economic consequences of water policy measures or restricted water supply. The model could for example be used to study various pricing policies of both raw and drinking water as well as the introduction of quotas for the global extraction of water or the use of certain actors only. Further, the precise modeling of water resources developed in this article could be applied in other countries to study water-related issues.

7. Conclusions

The future evolution of water resources is still quite uncertain which increases the importance of understanding the potential consequences of changes in the availability of this resource. This study adapts GEMINI-E3 by introducing raw water resources and a drinking water sector into this model to analyze the consequences of climate-induced variations of raw water availability in Switzerland until 2050. While many previous studies focus on irrigation water and in some cases municipal water distribution, this paper presents a novel modeling in which all water consuming sectors have the possibility to choose between buying drinking water or extracting raw water themselves.

The simulation of different restrictions of raw water resource availability mirroring predicted hydrological evolutions according to alternative climate scenarios leads to very important changes in prices of raw water resources in 2050 relative to the baseline. Compared to the high variations in water prices, global economic consequences remain relatively limited due to the low value share of water in production and household consumption both in 2001 and in 2050 in the baseline. These results also show potential taxes on water would have to be quite high if they were to be used as incentives to reduce consumption.

The study further presents a detailed sensitivity analysis of results of changes in endogenous adaptive capacity measured by water-related elasticities of substitution. Simulations highlight the importance of the capacity to reduce water losses and to transform production processes to decrease their water intensity in determining the extent of water price increases and welfare losses provoked by a decrease in water availability. Indeed, welfare losses diminish by 18% when allowing for the reduction of water losses and by 20% when increasing the possibilities to reduce the water intensity of production. These results also highlight the areas (the reduction of water losses and of the water intensity of production processes) where political action to increase adaptability is likely to show the highest welfare effects. However, a comparison of the results of the sensitivity analysis and of the simulation of alternative climate scenarios emphasizes that most of the uncertainty comes from the climate scenarios and not from the choice of the various elasticities of substitution.

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