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# Efficient Water Allocation when Climate is Changing: An interdisciplinary approach

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# EFFICIENT WATER ALLOCATION WHEN CLIMATE IS CHANGING: An interdisciplinary approach

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## ABSTRACT

This study analyzes the effects of rising water supply variability provoked by climate change on the welfare of a society whose economy heavily depends on water availability. Several studies recommend that communities should impose policies that ensure a minimum level of water allocation for human consumption. We compare two contracts, one where society allocates to the firm a fixed proportion of the annual water-runoff; and the other one, where due to the uncertainties of climate change, the community instead allocates to human consumption a fixed annual amount of water-runoff. We consider a risk-averse community. We show that, unless water supply is absolutely fixed, a higher variability and scarcity of water supply does not necessarily imply that society is better off choosing a contract that assures a minimum water for human consumption. Depending on the characteristics of water supply frequency distribution, particularly the third moment, it is possible that society would not benefit by switching to the fixed allocation contract for human consumption. We illustrate the main analytical results using data and runoff climate change projections from a water basin located in the central region of Chile, showing that in this case the community is better-off sticking to the current contract.

Key words: Water economics, Climate change, Runoff variability, Water policies.

JEL Classification: Q54, Q25, Q58

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# 1 INTRODUCTION

Allocating and protecting natural resources for both productive purposes (i.e. mining, agriculture, forestry, aquaculture and so on) and human consumption are critical for a healthy functioning of ecosystems and human well-being (Stern, 2007; Figueroa and Calfucura, 2010).

In the last decades, economic growth based on the exploitation of natural resources has been widely questioned due to the cumulative degradation of natural capital, the large levels of pollution generated, and the lack of suitable policies (SCOS, 2019; OECD, 2013; World Bank, 2011; Stern, 2007). There is a general awareness of the need to reorient the objectives of economic growth; this is not related only to the health of the planet, but also to the economy itself. Development is unthinkable without purposely designing specific policies for the use of renewable and non-renewable natural resources (López & Figueroa, 2016; Taylor et al, 2014). This is why several of the seventeen United Nations´ Sustainable Development Goals defining the 2030 agenda for achieving global sustainable development are directly concerned with improving the use, management and protection of natural resources (UN, 2018).

In this context, economic analysis has been important in considering natural capital as a factor of production, as well as making a distinction between clean and dirty industries and considering the irreversibility of the stock of natural capital (López & Yoon, 2014; López & Yoon, 2016). The transition to a clean economy is complex, as it depends on characteristics of each country and the actual needs of the world economy (ECLAC, 2016; OECD, 2016).

A key natural resource that illustrates much of the above concerns is water, which is in part a renewable resource (rivers, aquifers, lakes) as well as a non-renewable one (rock and surface glaciers, icefields). On the other hand, water is a factor of production that is essential to practically all industries and has a fundamental value as consumption good.

Water is the primary resource through which climate change influences Earth's ecosystem, thus affecting the livelihood and well-being of societies (UN-Water, 2010). The most sensitive element to climate change has probably been its effect on water availability and its increasing variability (Levitus, 2009; Hansen et al., 2010). The heterogeneous nature of water, both in terms of its physical properties, either spatial or temporal, has turned it into a permanent concern nowadays, when we are faced to a specific scenario of anthropogenic climate change (IPCC, 2014; IPCC, 2007; Schmidt, G). Water scarcity affects more than 40% of the global population and is projected to rise; and, over 1.7 billion people are currently living in river basins where water use exceeds recharge (UN, 2018). Moreover, higher temperatures and extreme, less predictable, weather conditions are projected to affect availability and distribution of , 2014, snowmelt, river flows and groundwater, and further deteriorate water quality; additionally, more floods and severe droughts are predicted. Changes in water availability will also affect health and food security and have already proven to trigger refugee dynamics and political instability (UN-Water, 2019a). Under present climate variability, water stress is already high, and climate change adds even more urgency for action. Moreover, without improved water resources management, the progress towards achieving the Sustainable Development Goals are seriously jeopardized. In fact, adaptation to climate change is mainly about better water management (UN-Water, 2019b).

Spatial distribution and extreme natural events are important factors impinging upon the availability and quality of water (Wan Alwi, 2008). In this sense, one should raise many complex questions requiring interdisciplinary analyses such as the one made in this study. This way of thinking allows picturing the water allocation problem taking into consideration fundamental elements that have not been satisfactorily added to economic models so far, including the timeframe of records for decision making, trade-offs between variability and resource preservation, productive role and human consumption assurance (Lenzen et al., 2007).

In this context of increased uncertainty, there is a remaining certainty: increased water stress and meeting future demands will undoubtedly require increasingly tough decisions about how to allocate water resources between competing water uses. Such as for human consumption versus irrigation, for human direct use versus production goals, for home use versus ecological flow, etc., including for climate change mitigation and adaptation. Moreover, to create a sustainable future, business as usual is no longer an option and water management needs to be scrutinized through a lens that focus on the increased climate variability in a planet whose climate is affected by human activities and the resulting global warming (UN-Water,2019c).

Dealing with the increased uncertainty caused by global climatic conditions needs a policy framework that deals explicitly with the new water problems (Hansen et al., 2012; ECLAC, 2016). The tools currently available allow reducing the risks on key aspects, such as human consumption, where general circulation models gain significance, as they allow making runoff forecasts in different regions (IPCC, 2014).

When discussing problems of water scarcity, it is important to consider that this is not only linked to the physical availability of the resource. Aspects such as the lack of appropriate infrastructure or inefficient public policies, can lead to serious problems of scarcity in areas where there is enough water, even considering climate change projections (Barbier, 2019).

In this study, an interdisciplinary analysis is performed to provide insights on the most efficient policies that ensure water allocation for human consumption, using an economic model that explicitly takes into consideration the crucial role of the variability of water runoff as treated in hydrological models. To illustrate the results obtained using the conceptual model and their implications, we present an empirical application to a water basin of the southern Central part of Chile.

Studying the case of Chile is interesting on several grounds. World Bank (2011) is the most significant study on Chile’s water, which discusses multiple components regarding resources and provides an accurate diagnosis. It emphasizes the need for a national water policy that captures the heterogeneous nature of the country’s climate and that takes future scenarios into account. Several studies emphasize the need for economic and social approaches (Garreaud, 2011), in consideration of the fact that 70% of Chile’s current environmental conflicts are directly related to water (INDH, 2012). Various studies on the economics of water and climate change in Chile have been performed (CEPAL, 2009; Figueroa and Calfucura 2010; Vicuña et. al, 2012). These studies have had a significant impact; however, none of them has addressed the close link between climatic variability, economic production and water allocation for human consumption.

In the model proposed here, we consider a society hosted in a hydrological catchment, which bases its economy in its water resource, and it has property rights over it, which allows society to charge for the use of the water resource by a firm using it. The firm produces goods employing labor and water as inputs. Society´s income comes from labor income of workers employed by the firm and from the extraction of part of the firm´s economic rent through taxation (Wessel, 1967). The relationship between the society and the firm is defined by a contract, which rules the sharing of the water resource between them. Two types of contracts are analyzed: 1) the firm is bestowed the use right over a fixed proportion of the annual water resources available and the rest is allocated to human consumption; and, 2) society assures a fixed amount of water for its own consumption needs and the remaining water, if exists, is allocated to the firm.

A common hypothesis which is implicitly or explicitly imbedded in water policies of different countries is that, under conditions of increased water scarcity and variability, caused for example by climate change, contracts akin to the second one of the two contracts just mentioned should be preferable to those similar to the first one (IPCC, 2014; World Bank 2011). The main objective of this paper is to theoretically and empirically assess this hypothesis.

An important issue in deciding water policies is the institutional context. A key institutional factor is the existence of water trading systems which allow communities to buy or sell water to other communities. (Meinzen-Dick et al., 2002; Gazmuri & Rosegrant, 1996). This is important because water scarcity is not homogenous within countries or regions even in conditions of water stress caused by climate change. Water surplus regions coexist with water scarce ones, often separated by not too great distances. This renders the possibility of water trade among communities. (Dinar & Saleth, 2005; Grey & Sadoff, 2007; Vatn, 2010). Moreover, many countries have the capacity to desalinize sea water which brings another opportunity to water-scarce regions to buy desalinized water. Of course, the cost of purchasing water from other regions or from desalinizing plants can be quite steep, which is a feature that is considered by the ensuing model. (Meinzen-Dick et al., 2002; Ahmed et al., 2017; Baawain, 2015)

The model in this paper assumes that water trade is feasible, allowing water scarce communities to purchase water, albeit at high prices. It is the option of water trading that brings into question the conventional advice to first assure water for human consumption and then allow the residual water to be used for productive purposes. This assumption makes the model more relevant to middle income and developed countries which often have the institutional conditions that allow water trading among communities and/or have the capacity to produce water desalination. The conventional advice may be correct for poor countries that do not have these capacities.

There are many experiences in the world of water exchange within the same basin and between nearby basins, countries such as the United States, Australia, Canada, Spain, Chile and India show the active role of water rights markets which has allowed the water transfer between basins, conditioned by the regulatory framework and the existing infrastructure (Maestu, 2013). Climate change has accelerated the pressure for the mobility of water resources in countries with high hydro-climatic heterogeneity (Rayl, 2016). The case of Spain has been recognized as one of the most successful experiences of interregional water trade in the world (De Stefano & Llamas 2012). Chile has high climate heterogeneity and a market for flexible exploitation rights; in its northern zone, in a context of severe water scarcity and low Government participation as a regulator, the purchase of water, previously used for agricultural and domestic purposes, by mining localities is quite common (Bitran et al., 2014).

## 2 THE MODEL

Assumptions:

- The model considers a small and open local or regional economy (represented by the water basin).
- The total water annually available from natural local sources is assumed to be exogenously given. It is determined by a climatic factor where the future is represented with different states of nature.
- Society in the region or basin can buy water from elsewhere at a cost which can be considerable.[4]
- The production function of the firm located in the region uses labor and water as inputs and exhibits constant returns to scale.
- When the firm's labor demand is less than the basin's labor supply, the surplus workers may find employment in another basin.
- If the labor demand is greater than the basin's labor supply, the firm may hire workers from outside the basin. The salary is constant, so it will be considered $w=1$.[5]
- Population in the basin is fixed.
- Society has a well-defined concave utility function.

*Contract 1*

- The firm must pay to the community, in the form of a local tax, a fixed proportion of its income net of labor costs obtained every year.
- The firm must hire labor from the basin and can only hire people from outside the basin after full employment is reached in the basin.
- The firm fully uses every year their fixed portion of the total runoff.

*Contract 2*

- Conditions of Contract 2 are identical to Contract 1 except that the firm can only use the surplus water after the water consumed by society instead of a fixed portion of the total water available.

Parameters:

[4] This assumption reflects the fact that water availability is not homogenous across all regions or basins; even in very dry years some communities may experience substantial water surplus part of which could be sold to other communities that are experiencing water shortage. Also, this assumption is consistent with the fact new technologies allow the extraction of water from non-conventional sources such as sea water via desalinization at more reasonable costs.

[5] That is, the labor market in the basin is integrated with the rest of the country so that the society is a wage taker.

$\overline{L}$ = Fixed number of workers in the basin.
$\alpha$ = Coefficient associated with the water factor in the production function
$1-\alpha$ = Coefficient associated with the labor factor in the production function
$\beta$ = Portion of the firm's income net of labor cost which is paid to society every year for use of the society's water
$\theta$ = Fraction of annual volume allocated to the firm in the form of water use rights
$1-\theta$ = Fraction of annual volume allocated as use for human consumption rights
$a$ = Exogenous cost of supplying water from other sources (e.g., from desalinization of sea water).
$C_h$ = Volume of water needed for human consumption, assumed fixed.

Endogenous Variables (Contract j=1,2)

$R_j$ = Optimal income of the firm net of labor cost.
$L_j$ = Optimal labor demand.
$V_j$ = Expected utility of the society.

Exogenous Variables (states of nature i =1, …, I)

$p_i$ = Probability that the volume of water is the one associated to the state i of nature.
$q_i$ = Probability that the volume of water for human consumption in the state i of nature is lower than the water needed for human consumption.
$N_i$ = Total water volume associated to the state i of nature.

Objective of a benign policymaker or planner

The key objective of the analysis below is to ascertain which of the two contracts would maximize Society's expected utility. Importantly, we do not necessarily assume that society maximizes its expected utility, rather we try to mimic the choice of a policy advisor or planner who has all the information needed to solve the expected utility maximization problem.

## 2.1 Firm´s optimization problems

### 2.1.1 Contract 1

The community allows the firm to use a fixed proportion $\theta N$ of the total water available and therefore there is a volume $(1-\theta)N$ of water left for consumption of the community. If $(1-\theta)N < C$ then the community must purchase water for its consumption at a price per unit equal to $a$. The firm's production is assumed to be a Cobb-Douglas function of water ($\theta N$) and labor ($L_1$)

The income of the firm net of labor cost is:

$$R_1 = (\theta N)^{\alpha} {L_1}^{1-\alpha} - wL_1 \qquad [1]$$

The firm maximizes the income using labor as a variable. Noting that by choosing the appropriate units of labor we can assume that $w$=1, we have:

$$máx_{L_1}\left[(\theta N)^{\alpha} {L_1}^{1-\alpha} - L_1\right] \qquad [2]$$

By solving the optimization problem, the firm's labor demand is obtained:

$$L_1 = [1-\alpha]^{\frac{1}{\alpha}} \theta N \qquad [3]$$

By replacing the optimal labor demand [3] in the firm income function [1], we get the optimal income net of labor cost for the firm:

$$R_1 = A\theta N \qquad [4]$$

Where $A \equiv \left[[1-\alpha]^{\frac{1-\alpha}{\alpha}} - (1-\alpha)^{\frac{1}{\alpha}}\right]$

Given that $\alpha < 1$ we have that 0 < A < 1. Thus, the net income of the firm is proportional to the amount of water available to the firm.

### 2.1.2 Contract 2

In the case of Contract 2 the community first assures itself full consumption from the local water availability sources and allows the firm to use the remnant available.

For Contract No. 2, the firm uses the total water volume available minus the water for human consumption which in this case is a fixed amount. If such remnant is positive then the income of the firm net of labor cost is,

$$R_2 = (N - C_h)^{\alpha} {L_2}^{1-\alpha} - L_2 \qquad [5]$$

The firm maximizes its net income using labor as a variable:

$$máx_{L_2}\left[(N - C_h)^{\alpha} {L_2}^{1-\alpha} - L_2\right] \qquad [6]$$

By solving the optimization problem, we get the firm's labor demand,

$$L_2 = [1-\alpha]^{\frac{1}{\alpha}} (N - C_h) \qquad [7]$$

By replacing the optimal labor demand [7] in the firm´s income [5], we get the optimal income net of labor cost for the firm in a period:

$$R_2 = A \cdot (N - C_h) \qquad [8]$$

## 2.2 Society's expected utility

The analysis considers the expected value for I states of nature. Although each state of nature corresponds to a series of time, the theoretical analysis focuses on one period, without loss of generality. In the empirical analysis, time is explicitly considered.

### 2.2.1 Contract 1

Society's total income has three components: the labor income; the portion $\beta$ of the firm´s rent that society obtains via a tax; and the cost of ensuring human consumption of water in years of deficit. Assuming that $q$ is the probability that the total volume of local water is lower than the volume needed for human consumption, society's income under Contract 1 for estate of nature $i$ is:

$$S_{1,i} = w\overline{L} + \beta R_1 - q_i a[C_h - (1-\theta)N_i] \quad [10]$$

For simplicity, we can omit without loss of generality the labor income, which will always be the same for all contracts; then replacing [3], [4] and [9] in [10] we have:

$$S_{1,i} = \beta A\theta N_i - aq_i \cdot [C_h - (1-\theta)N_i] \quad [11]$$

Thus, the expected value of the utility of the community is,

$$V_1 = \sum_{i=1}^{I} p_i \cdot u\left[\beta A\theta N_i - q_i a \cdot [C_h - (1-\theta)N_i]\right] \quad [12]$$

Where $u(S)$ is the utility function of the community, assumed to be increasing and strictly concave.

### 2.2.2 Contract 2

The analysis here is similar to the one for Contract 1, but in this case, there is no cost associated to ensure human consumption of water. Then, from the previous analysis, we have derived the expressions [13] and [14] below for the society's income at state $i$ and its expected utility.

$$S_{2,i} = \beta A(N_i - C_h) \quad [13]$$

$$V_2 = \sum_{i=1}^{I} p_i \cdot u[\beta A(N_i - C_h)] \quad [14]$$

# 3 ANALYSIS OF THE ALTERNATIVE CONTRACTS

## 3.1 Comparison under uncertainty

Since $u > 0$ , $u' > 0$ and the probabilistic structure of runoff is the same under both contracts, for a given state of nature $i$, Contract 1 will yield higher income than Contract 2 if:

$$\beta A\theta N_i - aq_i \cdot [C_h - (1-\theta)N_i] > \beta A(N_i - C_h) \qquad [15]$$

To perform an uncertainty analysis considering the expected utility for the I states of nature, we use a third order Taylor approximation of the utility function around the income´s mean, $\mu_S$. Then we express the expected utility function in terms of three first central moments of income as follows:

$$E[u(S)] \cong E\left[u(\mu_S) + u'(\mu_S)\sum_{i=1}^{N}(S-\mu_S) + \frac{u''(\mu_S)}{2}\sum_{i=1}^{N}(S-\mu_S)^2 + \frac{u'''(\mu_S)}{6}\sum_{i=1}^{N}(S-\mu_S)^3\right]$$

Thus, we have:

$$E[u(S)] \cong u(\mu_S) + \frac{u''(\mu_S)}{2}\sigma_s^2 + \frac{u'''(\mu_S)}{6}\gamma_s \qquad [16]$$

Where $\sigma_{si}^2$ and $\gamma_{Si}$ $(i = 1{,}2)$ are the variance and third moment[6] of the income under contracts 1 and 2, respectively. A key issue is that the moments of the income distribution are, in turn, determined by the moments of the distribution of the water runoff. Climate change thus affect the distribution of water runoff, leading to concomitant changes in the income distribution moments, which in turn affect the expected utility under each of the contracts in a differential way. From (16) it is clear that, given that the utility function is identical for both contracts, the level of the expected income (the first moment of the distribution) and hence of the expected water runoff level affect the expected utility under each contract identically. Therefore, for the purpose of comparing the two types of contract we need to focus only on the higher order moments of the distribution. The differential effect of climate change under each contract concerns only the second and third moments of the distribution of water runoff and hence second and third order moments of the resulting income distribution.

***Central Proposition***. Contract 2 should be preferred to contract 1 if and only if:

[6] Note that $\gamma$ is the third central moment of the income distribution, which is different from the income skewness (or its coefficient of skewness) which is equal to $\gamma/\sigma^{(3/2)}$. It is important to keep in mind this difference for our analysis below regarding the relevance of the income's asymmetry to deciding whether contract one or contract two is preferred. In order to be able to separate the effects of the variance and the asymmetry of income on this decision, we use the third moment instead of the coefficient of skewness.

$$\sigma_{s2}^2 - \sigma_{s1}^2 + \frac{1}{3}\frac{u'''}{u''}[\gamma_{S2} - \gamma_{S1}] < 0 \qquad [17]$$

Where, $u'''/u''$, is the so-called “prudence coefficient” (Kimball, 1990) (with $u'''$ and $u''$ representing the third and second derivates, respectively).

***Proof***.

Using equation [16] we have the expected utility for both contracts:

$$E[u(S_1)] \cong u(\mu_S) + \frac{u''(\mu_S)}{2}\sigma_{S_1}^2 + \frac{u'''(\mu_S)}{6}\gamma_{S_1}$$

$$E[u(S_2)] \cong u(\mu_S) + \frac{u''(\mu_S)}{2}\sigma_2^2 + \frac{u'''(\mu_S)}{6}\gamma_{S_2}$$

The Contract 2 should be preferred to contract 1 when:

$$E[u(S_1)] - E[u(S_2)] < 0$$

Or equivalently (Taylor approximation of the utility function around the income´s mean, $\mu_S$):

$$\frac{u''(\mu_S)}{2}\sigma_{S_1}^2 + \frac{u'''(\mu_S)}{6}\gamma_{S_1} - \frac{u''(\mu_S)}{2}\sigma_2^2 - \frac{u'''(\mu_S)}{6}\gamma_{S_2} < 0$$

Multiplying by $\frac{2}{u''(\mu_S)}$ the above equation and factorizing we have that Contract 2 should be preferred to contract 1 if and only if:

$$\sigma_{s2}^2 - \sigma_{s1}^2 + \frac{1}{3}\frac{u'''}{u''}[\gamma_{S2} - \gamma_{S1}] < 0$$

⊠

In the following analysis for the sake of simplicity we assume a strictly concave Cobb-Douglas utility function, $u(\mu_S) = \mu_S^\varepsilon$, where $1 > \varepsilon > 0$ is a fixed parameter. Then we have that the prudence coefficient is,

$$\frac{u'''}{u''} = \frac{\varepsilon - 2}{\mu_S} < 0.$$

Now, using (17) and evaluating it at the runoff mean we have that contract 2 is preferred to contract 1 if and only if,

$$\sigma_{s2}^2 - \sigma_{s1}^2 < \frac{1}{3}\frac{(2-\varepsilon)}{(\bar{N} - C_h)A\beta}[\gamma_{S2} - \gamma_{S1}] \qquad [18]$$

The main justification used by the proponents of contract 2 is to reduce the variance of the income received by society each year. Thus, the case of interest consists of the one in which $\sigma_{s2}^2 < \sigma_{s1}^2$ and, from the inequality obtained in [18]. Clearly, if the distribution of income and water runoff were merely normal, contract 2 should indeed always be preferred to contract

1. However, since there is no *a priori* reason to assume a normal distribution, we consider the case of a more general distribution which has non-zero higher order moments. Assuming that the third order moment is non-zero, we obtain the following two propositions.

***Proposition 3.1.1***

*Assume $\sigma_{s2}^2 < \sigma_{s1}^2$ , if the income third moment associated with contract 2 is greater or equal than that associated with contract 1, $\gamma_{S2} \geq \gamma_{S1}$ , then contract 2 should be preferred.*

***Proof*.**

By construction the following term of equation [18] is always positive,

$$\frac{1}{3}\frac{(2-\varepsilon)}{(\bar{N}-C_h)A\beta} > 0$$

Then, if $\gamma_{S2} \geq \gamma_{S1}$, the right side of the equation [18] will be grater or equal to cero,

$$\frac{1}{3}\frac{(2-\varepsilon)}{(\bar{N}-C_h)A\beta}[\gamma_{S2}-\gamma_{S1}] \geq 0$$

Finally, considering that $\sigma_{s2}^2 - \sigma_{s1}^2 < 0$ , the inequality [18] will be satisfied for any combination of parameters and average runoff.

⊠

***Proposition 3.1.2***

*Assume $\sigma_{s2}^2 < \sigma_{s1}^2$ , if the income third moment associated with contract 2 is lower than that associated with contract 1, $\gamma_{S2} < \gamma_{S1}$ , then the choice of the best contract is ambiguous.*

*Proof*.

Then, if $\gamma_{S2} < \gamma_{S1}$, the right side of the equation [18] will be lower than cero,

$$\frac{1}{3}\frac{(2-\varepsilon)}{(\bar{N}-C_h)A\beta}[\gamma_{S2}-\gamma_{S1}] < 0$$

Considering that $\sigma_{s2}^2 - \sigma_{s1}^2 < 0$, the inequality [18] indicates that,

- Contract 2 will be preferred to contract 1 if only if,
  $$\sigma_{s2}^2 - \sigma_{s1}^2 - \frac{1}{3}\frac{(2-\varepsilon)}{(\bar{N}-C_h)A\beta}[\gamma_{S2}-\gamma_{S1}] < 0$$

- Contract 1 will be preferred if only if,
  $$\sigma_{s2}^2 - \sigma_{s1}^2 - \frac{1}{3}\frac{(2-\varepsilon)}{(\bar{N}-C_h)A\beta}[\gamma_{S2}-\gamma_{S1}] > 0$$

⊠

*Corollary 3.2.1*.

*Ignoring the income´s third moment leads to choose contract 2, but including it in the analysis, may under certain conditions render contract 1 optimal.*

*Proof*.

Follows directly from Proposition 3.1.1 and Proposition 3.1.2.

⊠

Thus, the fact that many analyses focus exclusively on the effect of climate on increasing the runoff variance may lead them to wrong policy conclusions. The choice of the optimal is thus in general ambiguous. Moreover, it is also possible that the optimal contract choice switches over time as the endogenous weights attributed to the second and third order moments may vary over time. This is what we call the "switching effect".

## 3.2 The switching effect

The equation [18] can be expressed as,

$$\varphi_1({\sigma^2}_{S2} - {\sigma^2}_{S1}) - \varphi_2\,(\gamma_{S2} - \gamma_{S1}) < 0 \qquad [19]$$

where,

$$\varphi_1 \equiv (\bar{N} - C_h)A\beta$$

$$\varphi_2 \equiv \frac{1}{3}\,(2 - \varepsilon)$$

The fact that $\varphi_1$ is a function of $\bar{N}$ (the total availability of water) implies that its value may change over time; on the other hand, $\varphi_2$ is constant. In a climate change context water availability may change in a non-monotonical way over time, that is, $\frac{d\bar{N}}{dt}$ could be positive or negative, depending on the geographical region in which the hydrological catchment analyzed is located.

***Proposition 3.2.1***

*If the effect of climate change in a particular region implies that $\frac{d\bar{N}}{dt} < 0$, the reduction of $\varphi_1$ lowers the importance of the income's variance differential $({\sigma^2}_{S2} - {\sigma^2}_{S1})$ and, therefore, the income´s third moment differential $(\gamma_{S2} - \gamma_{S1})$ may acquire greater relevance on the contract decision. That is, as climate change proceeds the likelihood of preferring Contract 1 over Contract 2 increases. On the other hand, if the effect of climate change on the geographical region under analysis implies that $\frac{d\bar{N}}{dt} > 0$, the income´s third moment differential loses relevance on the contract decision.*

***Proof****.*

If $\frac{d\bar{N}}{dt} < 0$, then from equation [19], $\frac{d\varphi_1}{dt} < 0$ and $\frac{d\varphi_2}{dt} = 0$.

Since $\varphi_1$ decreases and $\varphi_2$ remains constant over time, from equation [19] it is easy to see that the third moment differential acquires greater relevance along time on the contract decision.

The proof for the case $\frac{d\bar{N}}{dt} > 0$ is like the opposite case.

⊠

*Corollary 3.2.2*

In a climate change context, and in a particular geographical region where $\frac{d\bar{N}}{dt} < 0$, *if the* third moment of income *under contract 2 is lower than under contract 1, it is possible to choose contract 2 in the period* $[0, t^*]$ *and then switch to contract 1 in the period* $[t^* + 1, T]$. *Therefore, the temporal income´s third moment differential could produce a switching effect in the society's contract decision.*

Thus, the conventional wisdom advising communities to choose contract 2 may be right in the early phases of climate change. However, for regions experiencing a continuous decline in precipitation it is possible that this choice ceases to be optimal beyond a certain point in time.

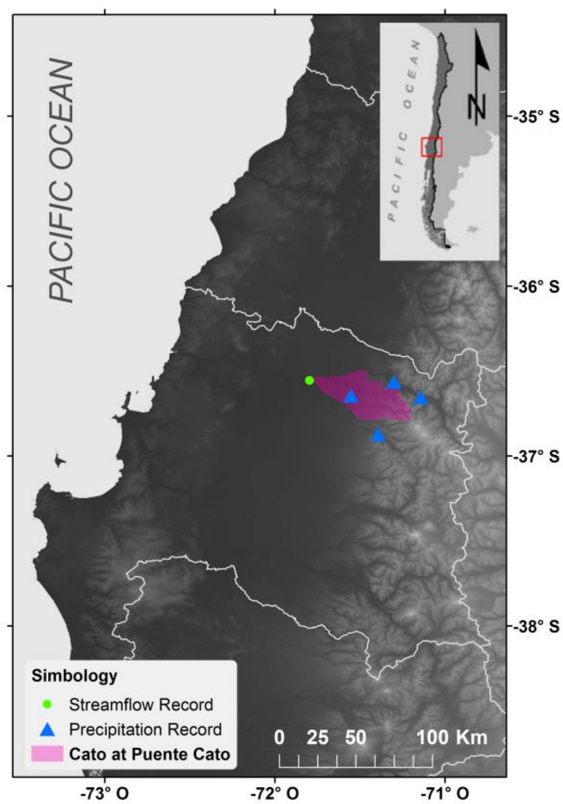
# 4 Empirical Analysis

## 4.1 Runoff projections

In this section, we illustrate the analysis regarding the optimality of either of the two contracts under study applying the model to data from the catchment “Cato at Puente Cato”, located in the Central South Region of Chile (Figure 1). We use data of runoff projections for the period 2020-2050 arising from climatological models, and representative values of the key parameters.

The central south region of Chile corresponds to a very sensitive zone in terms of the effects of climate change, whose impacts are amplified because this region concentrates intensive economic activities in the use of water, like mining, hydroelectricity, agricultural, forestry, tourism, etc. (Garreaud, 2011; World Bank, 2011: Rubio-Álvarez, et al., 2010). Moreover, while this region tends to experience a relatively low availability of water runoff it is not far from other catchment areas which often have significant water surplus, a situation which is expected to continue even under pessimistic climate change conditions. This validates our assumption that is possible to buy water from other regions in periods of necessity, albeit at relatively steep prices due to the high costs of transferring water from other catchment areas.

Figure 1
**Chile: Cato at Puente Cato catchment location**




Source: Own elaboration based on Barría et al., 2017.

It is also important to note that this case study corresponds to a geographical region in which the projected climate change effect is a significant reduction in the annual runoffs. Thus, in terms of section 3, we are analyzing a case in which $\frac{d\bar{N}}{dt} < 0$ (see Figure 2).

Future water availability is assessed by running a hydrological model driven by projections from global climate models (GCMs). Uncertainties in these projections arise from three main sources: the GCM used for simulating the future climatic variables (temperature and precipitation), the downscaling methodology used to translate the variables to the catchment scale, and the hydrological model used to estimate water runoff (Barría et. al 2017).

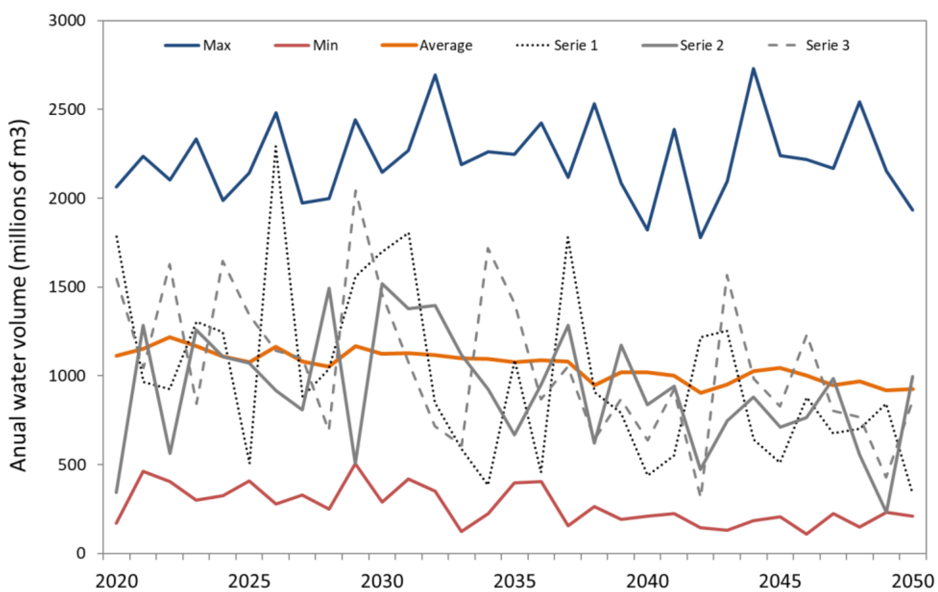
In this way, considering 83 projections of precipitation and annual temperature for the period 2020-2050 (GCMs), we can generate 83 independent series of annual runoff, using a Precipitation Evaporation Runoff model (PERM) (Barría et al. 2017; Peel et al. 2015). Each one of the independent series is assumed to have the same probability. We have used the same downscaling methodology.

Figure 2 presents the average, the maximum and the minimum value at each year, for the 83 runoff annual series generated; also, it presents only 3 time series, chosen at random from the 83-projection series.

Figure 2

**Chile: Example of 3 projected runoff series for Cato catchment**

(Millions of cubic meters)




Source: Own elaboration based on data obtained from Barría et al., 2017.

Figure 2 shows that the average annual runoff will decrease from 1,112 MM $m^3$ to 927 MM $m^3$ over the 2020-2050 period, an 8% reduction. This reduction of the average runoff is accompanied by an increase in the runoff variability. The latter is even noticeable in the increase range between the minimum (red line) and maximum values (blue line) of runoff associated with the 83 series shown. This reflects both the uncertainty of the projections and the fact that climate change increases extreme events, both drought and abundance of water runoff (IPCC, 2014; World Bank 2011).

In this way, there are 83 runoff values for each year (states of nature), with which it is possible to calculate for each one of the two contracts, and for each year: 83 values for the society's annual income, mean, variance and third moment, of society’s income, as well as society´s expected utility.

## 4.2 Parameters

We assume the existence of a representative agricultural firm in the basin, and a downstream town whose inhabitants work in the firm and capture a portion of the rent, via local taxes. The town dwellers consume water from the basin, but they also have the possibility of buying water from elsewhere. We consider the case of buying water from other catching regions or water desalinization as the main external sources. Below are the values used for the parameters.

$A$ **:** As defined in section 2.1, A is a function of the parameter $\alpha$.The value of $\alpha$ is estimated at around 0.5 for a representative agricultural firm (Kijne et al., 2003); then A takes a value of 0.25.

$\theta$: The proportion of the total water used by the agricultural firm is 0.7. This value is based on data showing the relative proportion between human consumption and agriculture water demands in the central south region of Chile (DGA, 2017).

$C_h$: Annual water consumption per person is estimated at 75 $m^3$ (DGA, 2017). So, knowing the population in the basin we obtain the total value of human water consumption.

$\beta$: For Chile the net income tax rate applicable to firms is 0.27 (27% of the firm´s income)[7]. We assume that the central government captures half of this amount and the rest stays in the locality; then the estimated value for the parameter is 0.135.

$a$: Alternative cost of water purchases. This cost is estimated around 0.75 USD/$m^3$, considering the location of the catchment (Ahmed et al., 2017; Baawain et al., 2015). The annual water consumed per person is 75 $m^3$ (DGA, 2017), and for the annual income of a person we use the annual legal minimum wage for Chile of 5,000 USD[8]. Then the value of the parameter is 0.10.

### 4.2.1 Simulation results

Table 1 shows the values of the parameters used,

<u>Table 1</u>

**Parameters used in the simulation**

[7] https://www.leychile.cl/Navegar?idNorma=6374

[8] https://www.bcn.cl/leyfacil/recurso/sueldo-minimo,-sueldo-base-derecho-a-semana-corrida

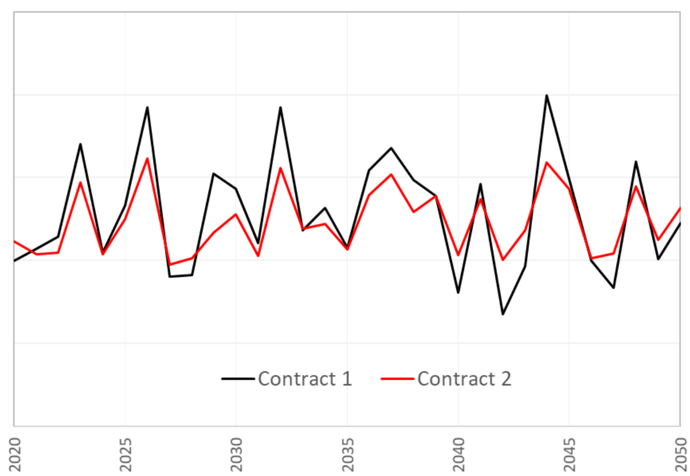
| Parameter | Value |
|---|---|
| $A$ | 0.250 |
| $\beta$ | 0.135 |
| $\theta$ | 0.700 |
| $a$ | 0.100 |
| $C_h$ | 0.300 |
| $\varepsilon$ | 0.700 |

Source: Own elaboration.

Figures 3 below shows the variance of income for the 83 runoff scenarios considered for each year under contracts 1 and 2. Figure 4 shows the same data for the third order moment of income. Similarly, Figure 5 shows society´s expected utility for each year, also considering the outcome of the 83 scenarios in each year.

Figure 3

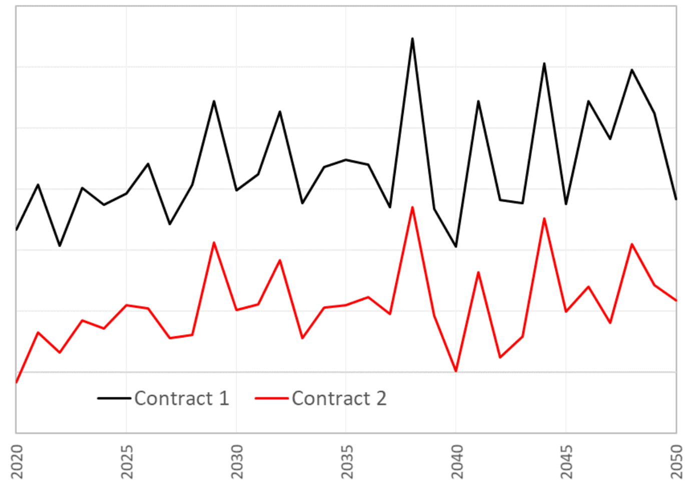
**Income´s Variance**




Source: Own elaboration.

Figure 3 shows that, as expected, the income variance under contract 2 in fact tends to be lower than under contract 1. While there are switching effects in some years, the income variance under contract 2 is lower than under contract 1 in about 75% of the years. Income variance under contract 1 is lower than under contract 2 in years with high water abundance when the probability of not satisfying human consumption is very low.

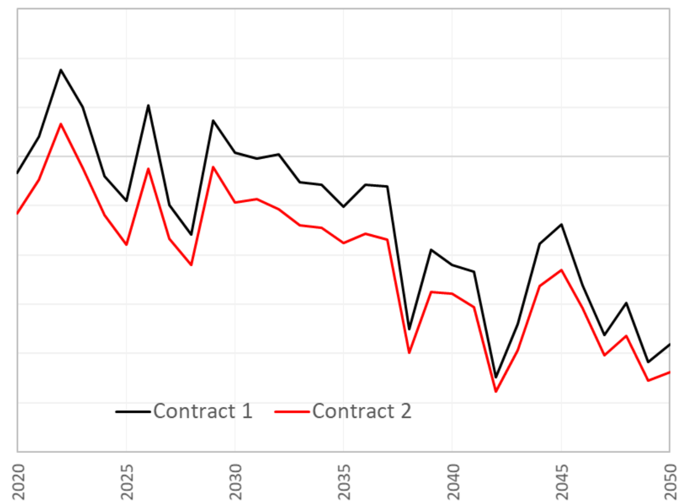
Figure 4
**Income´s Third Moment**




Source: Own elaboration.

Figure 4 shows that the income third moment is consistently lower under contract 2 than under contract 1 in all years. Thus, there is a trade-off between the contracts as the one that tends to exhibit a higher variance also has higher third moment. Hence, the net expected utility effect is potentially ambiguous. However, as Figure 5 shows, the expected utility is higher under contract 1 than under contract 2 in all periods. That is, the third moment effect dominates the variance effect.

Figure 5
**Society's Expected Utility**




Source: Own elaboration.

### 4.2.2 Sensitivity: An increase in alternative cost of water

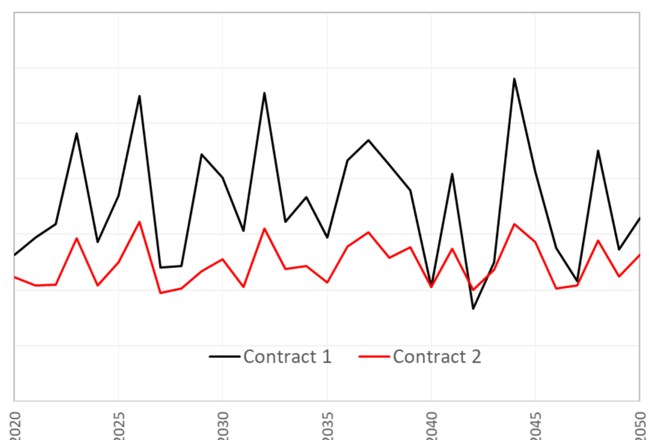
Suppose that the cost of water purchases increases by 33,3%, from 0.75 to 1.00 USD/$m^3$, then the value of $a$ changes to 0.15. All other parameters in Table 1 remain the same. Figure 6 shows the new society´s expected utility.

When the cost of external water increases contract 1 becomes costlier. This reduces the expected utility differences between the contracts compared to the previous simulation. In fact, for some years the expected utility under contract 2 is now higher than under contract 1. As was seen in the theoretical analysis, contract 2 is better than contract 1 when the relative importance of the income´s variance dominates the relevance of income´s third moment.

When the alternative cost of water increases there is a substantial increase of the income variance under contract 1 (Figure 6). This is because the income variance is increasing in $a$. With respect to contract 2, the income variance is not affected by the value of $a$.

<u>Figure 6</u>

**Income´s Variance (new simulation with a = USD 1/$m^3$)**

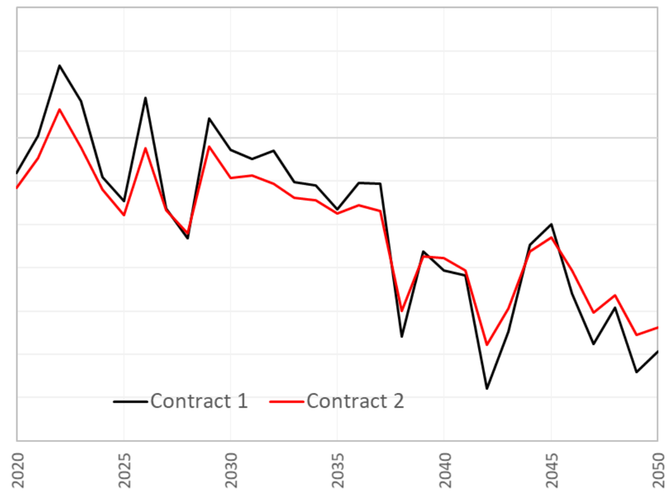



Source: Own elaboration.

On the other hand, the value of the third moment is not affected by the level of $a$ under both contracts 1 and 2. Hence, the third moment differentials between the two contracts remain unaffected; Figure 4 is still valid in this case.

Figure 7 below shows the evolution of the expected utilities for each of the two contracts considered. As can be seen in the Figure in this case we do have a switching effect. The expected utility of contract 2 is now higher than under contract 1 for the first 15 or 16 years, of the period analyzed, but a switch does occur in the year 2035 when contract 1 becomes the preferred choice. This switching in the latter part of the period is consistent with the fact that water runoff becomes scarcer over time, which as shown in the theoretical model, eventually makes the importance of the third moment differential between the contracts to become higher vis-à-vis the second moment differential.

Figure 7
**Society's Expected Utility (new simulation with a = USD 1/m$^3$)**




Source: Own elaboration.

## 5 CONCLUSION

Mitigation and adaptation to climate change and global warming requires urgent and large improvements in water resources management. From a national, a regional or a basin context, adaptation to climate change is in large part about better water management and requires wise decisions about the alternative use of hydrological resources, especially in those geographical areas where they are expected to be scarcer and to exhibit a greater variability (UN-Water, 2019b).

Using a multidisciplinary approach, combining modeling from economic and hydrological sciences, we have shown the importance of incorporating the expected increase in future water variability in water management and in water allocation decisions. In fact, in the theoretical model proposed here we have shown the role played by the variability (second moment) as well as by the asymmetry (third moment) of the probability distribution of the annual income of a society.

We derived the theoretical conditions under which society should prefer one of two different contracts that assign the annual available water between human consumption, on one hand, and productive activities carried out by a firm that pays to the society for the use of water, on the other hand. These conditions allow us to analyze conceptually and to test empirically a hypothesis that is commonly imbedded in water policies advices to different countries, prescribing that, under conditions of increased water scarcity and variability caused by climate change, contracts assuring human consumption provision should be preferred. We theoretically show that the choice between the two contracts considered is complex particularly in the general case in which the water runoff and hence income distribution is asymmetric. We derived the conditions under which the above prescription is indeed optimal and cases in which it is not. We used the theoretical insights from our model and we empirically apply the model using data and parameters of a catchment area located in the Central South Region of Chile, as well as data on the water runoff projections for this catchment for the period 2020-2050.

For the basin studied in Central Chile, the empirical data used, and the parameters considered in our empirical model lead to an ambiguous case in which the analyzed hypothesis in not necessarily sustained. In fact, our results indicate that contract 1 (assuring to the productive firm the provision of a given percentage of the annual water availability) should be preferred to contract 2 (assuring human consumption) in most cases, even when water scarcity and variability increase over time. This is because the effect of the symmetry of society´s income (its third moment) is determinant in this case, since it turns out to dominate the effect of the variance of society´s income under most scenarios. Thus, we provide here an empirical example that contradicts the commonly used hypothesis we are testing. That is, even though the society´s income variance is greater under contract 1 than under contract 2, this is not enough to unambiguously make contract 2 optimal (the contract that assures human consumption). However, if the cost of alternative water increases, it is possible that there is a switch effect, and contract 2 may become optimal in certain periods.

Evaluating which contract is better for society by analyzing only the variance of runoff, and therefore of society´s income, is insufficient and can lead to a wrong decision. As shown in this paper, incorporating in the analysis the third moment (asymmetry) of water runoff admits the possibility of an ambiguous case, in which it will be better to prefer a water allocation scheme in which the best way to ensure human consumption is through purchases of water outside the basin, instead of assuring the water provision from the runoff in the basing itself.

The most important lesson of the present paper is that water management policy recommendations require in-depth analyses of the water catchment area considered, as well as of the possibility and costs of water purchases from other catchment areas or from water desalinization sources that may be available. General and sweeping policy recommendations risk making serious mistakes which may negatively affect the welfare of communities.

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