Irrigation Management in Chile: Integrated Modeling of Access to Water

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Abstract

Fresh and clean water is one of the scarcest and most vital resources to humankind. Agriculture is the largest global water user. Irrigation managers must orchestrate water use at the catchment scale, balancing the management of supply and demand and taking into account the benefits from water use, its distribution among water users and environmental concerns. We present results from the integrated modeling of irrigation water use at catchment scale. An extended hydrological runoff model WaSiM-ETH that depicts inefficient surface irrigation was integrated with and coupled to a parametric model for irrigation water distribution, which is linked to the bio-economic multi-agent model MP-MAS that represents farmers as water users. Models were calibrated empirically, first as standalone models and then with increasing complexity of interactions. The integration of process across such long chain of reasoning resulted in an improved system understanding along disciplinary boundaries. The case study presented is irrigation water use within the Chilean Region of Maule. We analyze how farmers whose endowment with formal water rights is insufficient may depend on spillover water, and specifically the distribution of benefits from improvements in canal conductive efficiency across the farming community.

Keywords: Watershed management; Irrigation; Agent-based model; Integrated Modeling of Feedback

1 INTRODUCTION

1.1 Formal and informal access to water in Chile

Since the 1990s, Chile has become a model for successful free market economies, pairing a strong specialization into few competitive commodities and raw materials, with strong government that proactively supports its producers. With its unique location in the southern hemisphere, export agriculture for Northern markets has experienced rapid and sustained growth. The agricultural sector and its focus on high-quality products generates impressive revenues for producers, processors and traders and contributes significant resources to the government budget. Moreover, it absorbs unqualified and skilled labour and gives the nation a positive image. However, with increasingly modern production systems on one side and the remaining traditional systems, Chile’s income disparity has become one of the most extreme in the world and equitable access to productive resources is a core development objective [Lopez and Anriquez, 2007].

In Chile, water management has always been linked to agricultural development policies, because most of Chile’s agriculture relies on irrigation during the core growing season, December to February. The Water Code, the legal foundation for access to water, has evolved dynamically under different political climates. In 1981, the socialist code of 1973 was reformed and a totally market-oriented policy was adopted. This Water Code defined water as a ‘public property for private use’ and defines water rights as a water equivalent, defined in liters/second. Entitlements to surface water are separated from land ownership and can be traded freely and transferred to other uses, once they are inscribed (‘legalized’) with the Direccion General de Aguas. The long-term impacts of this Water Code are the subject of national and international debate [Bauer, 2005].

Today, many farmers have not yet fully legalized their water rights with the government. This process is costly and paper works consume time and require good literacy. Nationally, Hearne and Donoso [2005] estimate that 10 to 50 percent of all rights are still not legalized and remain ‘customary’.
Though protected by law [Donoso, 2006], neither is the quantitative value of such customary rights precisely defined, nor if flows may be used continuously or discontinuously [JdV Longavi, 2005]. Due to the volatility of river flows, available water can be less than the amount that right holders are entitled to. In such years, most user organizations interpret water rights ‘traditionally’ as percentages of river flows [Hearne and Donoso, 2005] and every right holder suffers equally from a proportional reduction of water delivery.

The Water rights of all farmers are managed by water user organisations (Juntas de Vigilancia), which ensure that all farmers receive their water. These user-based organisations are also responsible for the maintenance and improvement of the canal conductive system. Mandated by their members, they can also apply for government support for projects that improve the infrastructure of the water conduction system. Such work includes the maintenance, repair and extension of canals, aqueducts, distribution devices and inlets, water gages etc.

1.2 The Model Use Case

The Maule Region is located between Santiago and Concepcion. This area is dominated by the production of apples, pears, berries, vegetables, rice, corn and wheat, and pastures. During the hot and dry summers, temperatures often exceed 30°C and precipitation is as low as 4mm/month, so all summer crops and even pastures require irrigation. Winters are temperate and wet (200 mm/month). Irrigation water is taken from rivers that originate in the Andean mountains, which are fed by precipitation and snow melt that starts with the spring thaw in August and lasts well into January.

To study benefits from water use of heterogeneous farmers, Berger [2001] developed a bioeconomic multi-agent model. This model MP-MAS uses on Mixed Integer Linear Programming, a method established in agricultural economics for farm-level production analysis, and for developing optimal production plans under constrained asset endowments [Hazell and Norton, 1986]. This model estimates incomes and crop yields under water deficit, recursively updating farmers’ asset endowment. With a simulation that uses a statistical representation of every farmer in the study region, Berger used a diffusion of innovation model to demonstrate the impact of Chile’s integration into the Mercosur on different farm strata [Berger, 2001]. For the 2001 model, water rights registries were not available and the essential production input ‘water rights’ was quasi-randomly attributed to farmers. As a calibration benchmark, land use and census data (VI Censo Nacional Agropecuario 1997, INE) were used [Berger, 2001].

Within the project Integrating Governance and Modeling and as part of the CGIAR Challenge Program on Water & Food, Berger et al. [2007] conceptualized how deep integration of economic and hydrological science can generate new insights, extending the crop yield module and a hydrological bucket model that are already implemented in the MP-MAS software. A (semi)empirical model system was built that integrates the watershed-scale distributed hydrological model WASIM-ETH [Schulla and Jasper, 2007] with an intermediate bucket model that parameterizes the distribution of water from rivers, to canal sectors, to individual farmers. Ultimately, the bioeconomic, agent-based farm model MP-MAS is used for an economic analysis of agricultural water use. These models were integrated conceptually and specific components were added that link the cause-effect chains. The value added with a multi-agent model is the simulation of an additional interaction layer, the interactions between a heterogeneous population of farmers. The example elaborated in this paper is spillover water and its relevance for farmer’s access to water.

The intermediate and parametric bucket model pools water associated with the same delivery canals (called irrigation sector), handles canal conductive efficiency, agent-agent interactions such as return flows from inefficient irrigation, spillover water and surplus water that farmers abandon and finally leakage between canals and irrigation sectors (together subsumed as ‘non-attributed water’). Each irrigation sector $j$ is characterized by its total water delivery as a total of all water rights, its canal conductive efficiency $\eta_j$, the irrigation efficiency that is averaged over all fields pertaining to this sector, and the portions of water flows that remain in the pool of spillover water or are lost to other compartments (deep percolation or seepage into other sectors).

Technically, model components were first created as standalone software, to facilitate calibration by disciplinary experts. Interaction variables remained boundary conditions. Then, more complex model setups were created that internalize interactions within a hierarchical coupling scheme [Arnold, 2008].
This paper exemplifies the analysis of a single interaction component in a longer cause-effect chain, as a step toward more integrated system understanding.

Not having room to thoroughly introduce all models, only a few relevant processes are explained here. The multi-agent model represents farmers who transform inputs (land, water, fertilizer, seeds) with the help of investment goods (machinery, irrigation equipment, horses, etc.) into farm produce (crops, dairy products or meat). A range of production technologies are parameterized and may or may not be available to the farmer. As a rational actor, the farmer produces with the objective of maximizing his income, making optimal use of his limited or costly resources. Farmers make an annual production decision that is based on expectations of future markets and hydro-meteorological conditions. On a longer time scale, farmers may purchase investment goods or participate in land markets. Liquidity may be met through short- or longterm credits at the externally determined interest rate.

A wide range of empirical data was collected to parameterize the extended model, including two full agricultural censuses [INE 1997, 2007] with detailed data on land use, farming and irrigation technologies and crops [Troost, 2009], market prices, local crop parameters and hydro-meteorological time series, and complete land- and water right registries that were compiled with local water user organisations [Uribe et al., 2009]. The maximum obtainable yield of each production technology is parameterized. If plant water demands are not met, then yields are reduced using the CropWAT approach [Allen et al., 1998].

Within the larger research project, we were asked to assess the impact of investments into canal efficiency on the population of farmers, and how the existing governmental support program could be improved. The relevant cause-effect chain starts with the annual fluctuation of river flows (the source of irrigation water). River organisations distribute this water into a vast canal system, managed by a second layer of user organisations. Farmers receive irrigation water for cropping and the generation of income. However, the pool of ‘non-attributed’ water is an additional open access resource, as positive externality resulting from spills. This pool also includes a part of canal losses. Finally, farmers can collectively decide to improve the canal conductive system. This collective action feeds back on how much water each farmer receives.

This paper describes two processes: the creation, use and relevance of this pool of ‘non-attributed’ water, as an interaction between farmers that results in a cascade of farm-to-farm interactions. By comparing with-and-without scenarios, we illustrate how an improvement of canal conductive efficiency would impact on the amount of water that each individual farmers receives, in order to understand why user groups would engage into collective action and seek government support for canal improvements.

Data on impacts from canal improvements are not available and the current canal conductive efficiency was estimated through a farm survey. Depending on the irrigation sector, efficiency ranges from 0.5 to 0.9 of the original water delivery and is 0.65 for the largest and most representative sector that is used for illustration purposes.

2 AN INTERMEDIATE MODEL FOR ‘NON-ATTRIBUTED’ WATER AND ITS USE

With improved and more detailed registry data for both land and water [Uribe et al., 2009], we were confronted with a paradox: only 2301 out of the 3594 agents own water rights, and several of these own far less water than required to crop their land. For January of a representative and a dry year, the average water endowment was computed per hectare and farmers are counted for each farm size stratum (Table 1). Assuming a typical crop irrigation requirement for one hectare of 0.5 - 1 liters/second, only about 29% of all farmers have an adequate endowment of water rights in a normal year (23% in a moderately dry year). How do those without adequate water rights operate their farms?

Observing this phenomenon, Donoso [2006] mentions ‘surplus’ water that is taken from rivers and abandoned by their owners. Owners are believed to leave this surplus water in the canals once the irrigation demands of their crops are met. Other farmers, without rights, benefit from this pool of spillover water. Other sources of spillover water are inefficiencies of the canals and on-field irrigation methods. Experts acknowledge the abundance of spillover water in most years and describe the difficulty of enforcing the modest maintenance fees that are attached to legalized water rights in the presence of this free resource. Only in years with stronger droughts does this pool of spillover water
Table 1: Number of farmers and their level of water endowment, expressed in water right equivalents per hectare, given for normal/moderately dry years. With changing water availability, farmers shift between categories.

<table>
<thead>
<tr>
<th>Water Endowment group (liter/second per hectare)</th>
<th>Specialized small farm [3.5 - 5 ha]</th>
<th>Small farm [5 - 25 ha]</th>
<th>Medium farm [25 - 60 ha]</th>
<th>Large farm [60 - 200 ha]</th>
<th>absolute percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>184</td>
<td>943</td>
<td>126</td>
<td>40</td>
<td>1293 36%</td>
</tr>
<tr>
<td>&gt; 0 - 0.1</td>
<td>4/6</td>
<td>173/212</td>
<td>63/86</td>
<td>33/45</td>
<td>273/349 8%/10%</td>
</tr>
<tr>
<td>&gt; 0.1 - 0.25</td>
<td>13/16</td>
<td>238/305</td>
<td>108/132</td>
<td>33/27</td>
<td>392/480 11%/13%</td>
</tr>
<tr>
<td>&gt; 0.25 - 0.5</td>
<td>10/12</td>
<td>422/463</td>
<td>133/142</td>
<td>27/28</td>
<td>592/645 16%/18%</td>
</tr>
<tr>
<td>&gt; 0.5 - 1</td>
<td>24/24</td>
<td>522/434</td>
<td>128/92</td>
<td>14/10</td>
<td>688/560 19%/16%</td>
</tr>
<tr>
<td>&gt; 1</td>
<td>46/39</td>
<td>266/207</td>
<td>35/15</td>
<td>9/6</td>
<td>356/267 10%/7%</td>
</tr>
<tr>
<td>Total</td>
<td>281</td>
<td>2564</td>
<td>593</td>
<td>156</td>
<td>3594 100%</td>
</tr>
</tbody>
</table>

Dry out, leading to aggressive and sometimes violent conflicts over water access. For such an informal resource, empirical data is non-existent. Due to its enormous importance for farmers, any economic production analysis must take it into account.

**Types of non-attributed water.** Parts of the drainage from inefficient irrigation fields returns to the canal system. This return flow may be re-used by other irrigators downstream from the canal. The water that returns from fields into main canals and the river system is called return flows $RF_j$ to one sector $j$.

The surplus water, $S_i$, of one agent, $i$, creates is the water received from legalized rights, $L_i$, but not used because plant irrigation demand, $D_i$, is satisfied. The model (Berger 2001) was extended so that surplus water is first accumulated for each sector $j$ and then a share $\beta_c$ of it is re-distributed to all farms within that sector (informal arrangements that give preferential access to some are thus ignored):

$$S_j = \sum_{i \in j} S_i = \beta_c \cdot \sum_{i \in j} L_i - D_i$$

A third source of non-attributed water stems from canal losses due to low conductive efficiency $\eta_c$. A part of distribution losses within the canal system are added to the pool of spillover water (e.g. along cracks, weirs and junctions). This use share $\beta_c$ of these losses remains within the same sector, while the rest is lost to groundwater or downstream sectors. The total amount of water $T_j = \sum_r \sum_{i \in j} Q_rWR_i$ that is delivered to an irrigation sector $j$ aggregates the water rights $WR_i$ of all its farmers $i$ and on the river flow $Q_r$.

$$C_j = \beta_c \cdot (1 - \eta_c) T_j$$

**Access to non-attributed water.** Total water delivery $T_i$ to each agent $i$ combines access to legalized sources $L_i = \eta_c \sum_r WR_i Q_r$ from water rights and access to the pool of non-attributed (or informally managed) water. To describe the usage of canal losses, a flexible function $f$ was tested with a broad range of parameterizations, the most general one of which is presented here. Two options exist to re-partition non-attributed water to farmers:

1. Each farmer receives water proportional to his share of water rights, as a factor that averages out reuse within each sector. This can be interpreted as institutional allocation: water managers know that canals are inefficient but also know that losses re-appear downstream. Thus, each farmer receives

$$y = \lambda A^\frac{1}{\lambda}$$

Figure 1: Redistribution effect of $f^{\lambda_c}$, which benefits small farmers increasingly with larger $\lambda$ (normalized to 1 ha; model only permits farms $> 3.5$ ha).
more than the canals actually deliver, hoping that with reuse, every right holder can benefit.

Such ‘institutionalized reuse’ increases effective water use efficiency, but does not re-distribute water endowments to those who lack these.

\[ f^{WR} = \frac{\sum_r Q^r \cdot WR^r_i}{\sum_r \sum_i Q^r \cdot WR^r_i} \]  

(2) To test re-distribution based on farm size, a ‘root’-function relates farm area to the benefits from non-attributed water. For large \( \lambda_c \), small farms receive over proportionally (1)

\[ f^{\lambda_c} = \frac{\lambda_c}{\sum_{i \in j} A_i} \cdot (A_i)^{1/\lambda_c} \]  

For the final model, an equal mix of both modes provided a robust pattern of results. Different parametrization of return flows and institutionalized reuse had only minor re-distributional impact between different farmer groups. For reasons of consistency with the original model, farmers access return flows and surplus water according to their area share within their irrigation sector:

\[ T_i = L_i + f^{WR} + f^{\lambda_c} \cdot C_j + \frac{A_i}{\sum_{i \in j} A_i} \cdot (S_j + RF_j) \]

For model evaluation, results were first analyzed for total flow quantities, such as time series of total legalized water supply \( \sum_i L_i \) and total non-attributed water \( \sum_j (RF_j + S_j + C_j) \). As a reference scenario, canal efficiency was decreased by 10 percent, to estimate the impact of canal improvement ex-post. This reference scenario was tested with ten different canal model parameterizations, to capture the structural uncertainty embedded in model assumptions. The policy scenario then uses the actual canal efficiency data, with the same ten structural model variations. Taking reference and policy scenario of the identical structural model variation, the performance of each individual agent was compared under both scenarios. Indices ranged from the share of expected water supply actually met, over the ratio of expected yields actually harvested, actual revenues and the ratio of planned and actual income. Finally, agents were grouped according to farm size stratum and according to the percentage of plant irrigation water demand that they can satisfy through legalized water rights.

3 RESULTS

To model agricultural land use consistently with empirical data from both land cadastres and water registries, an additional process, e.g. the suggested mechanism with non-attributed water, must be taken into consideration. Only such a redistributive process makes agriculture physically feasible and economically viable for a sufficient number of farm agents. With this mechanism, only 322 agents quit farming over the study period (1996-2006). Without considering this water and while using the best water right registry data, about 2100 agents immediately quit farming.

To demonstrate the interplay of non-attributed and legalized sources of irrigation water under inter-annual variation of water availability, results from the calibrated model are decomposed for two cropping cycles: the hydro-meteorologically normal or typical season 1997/8 and a moderate drought season 1998/9 (Figure 2(a)). During the latter year, extension services report intense and sometimes violent conflicts amongst farmers over access to water. In following years, official records show an increased investment into irrigation equipment [CNR data, internal]. Irrigation water availability is plotted over time, for the total legalized water supply and for the pool of non-attributed water that is available, and also the sum of both as a total (full line). Note that in off-season, when none of the available water is used, much of the legalized water is counted twice because it becomes available again as non-attributed surplus water. Furthermore, flow quantities that farmers expect during their crop planning decision is plotted (dotted line). In the normal year, expected modeled flows and ‘real’ modeled flows coincide closely. In a dry year, agents strongly overestimate supply. Finally, irrigation water demand for both seasons is fairly similar (slashed line), peaking in December. While this demand is easily covered in the normal year, the water shortage during the dry year is significant.

1 The original model also re-distributed inefficiencies, using a reuse factor that was applied to the legalized water endowments \( (T_i = L_i/u_j) \). Such factor-based approach levels out different inefficiencies within the sector, redistributing from the less efficient to the more efficient. However, this mechanism did not provide water to farmers without rights.
Figure 2: Model output depicts the total delivery of legalized water and the pool of non-attributed water over a normal and a dry cropping season. Furthermore, modeled ‘real’ water delivery is compared with the delivery that farm agents expect during crop planning.

The ratio of total actual flows to farmer’s expectations on total flows drops from 100% in a normal year to a meager 15%, which is even lower than the ratio of irrigation demand that can be satisfied (Figure 2(b)). Specifically, the ratio between non-attributed water and total water almost drops to zero, because farmers use up most of their entitlements and do not replenish the common pool. This highlights the increased vulnerability of those farmers who rely primarily on the spillover.

The impact of canal efficiency improvements is directly linked to the pool of non-attributed water and how users can access it. Canal improvements increase efficiency $\eta_c$ and thus always increase the supply of legalized water $L_i$. Water right owners can either use this additional supply to increase their irrigated area, irrigate more or abandon the additional water for the use of others. However, canal improvements also reduce the share of canal losses that provided spillover water.

For a use portion $\beta_c = 0.3$ and a moderate redistributive parameter $\lambda_c = 2.5$, individual impacts on farmers are evaluated. For illustrative purposes, farmers were assigned to 20 groups, according to their farm size stratum (sub figures in Figure 3) and according to the share of water they meet from water rights (lines). For each of the 3500 farmer agents, differences between the reference and the policy scenario were computed. Then a Gaussian distribution function was fitted for each group and its area was normalized to one for each stratum. This was done for two years, a normal one (solid lines) and a dry year (dotted lines). For most farms with significant water rights endowments, a 10% canal efficiency improvement increases water supply by about 5%, both in normal and in dry years. Farmers with no or a very low share of legalized water rights face more complex impacts: The small stratum that benefits overproportionally from using canal losses may even be impacted negatively by canal improvements, especially in dry years where surplus water generation is lower. Parameter sensitivity experiments show that this effect increases with smaller $\beta_c$ and also with larger $\lambda_c$.

The overall impact on water availability $\Delta T^i$ on an individual agent $i$ can thus be decomposed into three components, each of which fluctuates over time: (1) the increased delivery of river water $\Delta L^i$ because of improved conductive efficiency; (2) the increased overall availability of non-attributed water because those agents that already received excess water now leave even more surplus water $\Delta S^i$ in the canals once these are improved; (3) the decrease of non-attributed water because canal losses that originally produced non-attributed water $\Delta C^i$ are now eliminated.

$$\Delta T^i(t) = \Delta L^i(t) + \Delta S^i(t) - \Delta C^i(t)$$
Arnold et al. /Integrated Modeling of Access to Water

Figure 3: The effect of 10% canal efficiency improvements (x-axis), graphed as distribution functions for a population of farmers normalized to 1 (y-axis). Farmers are grouped by their farm stratum (box) and the share of irrigation water they receive through legalized water rights (lines). Full lines represent a moderately dry year, the dotted lines a hydrologically representative year.

4 DISCUSSION

Perhaps the most important result is that agricultural land use can only be simulated consistently if informal mechanisms such as the allocation of non-attributed water as a source for irrigation is taken into account. However, for such informal water management arrangements and practices, data scarcity exists and it may not be feasible to quantify these through measurements. Thus, all results presented here are merely a qualitative demonstration of how access to non-attributed water, as abandoned or informally shared water and canal losses, may impact farmers. Processes such as water endowments, canal infrastructure, the hydro-meteorological condition, the distribution of water rights across a sector, and the behaviour of others together form the environment in which less endowed farmers must make a living. These processes sometimes function counter-intuitively.

From the policy viewpoint, this model confirms that canal improvements are beneficial to most farmers, especially to those that own water rights and are thus represented in water user associations. However, it also shows that many other farmers may be negatively impacted by improved infrastructure. Furthermore, it offers a direct explanation of why user organizations with many small water rights holders are not eager to improve their infrastructure: it could jeopardize the informal arrangements that benefit many.

The proposed model also reproduces Donoso’s observation of spillover use [2006] quantitatively, using very simple assumptions. From the integrated modeling viewpoint, the existence and relevance of non-attributed water was never a research objective. However, with analysis of both the hydrological water availability and farm-level data, the hydrological model and the economic model could not be reconciled with empirical data. This necessitated the broadening of the scope of analysis and the assessment of every process along the cause-effect chain. With validated water rights registries and other strong empirical data, integration across disciplines pointed to the dominant relevance of this interaction. This interaction may also explain why farmers are willing to engage in canal efficiency projects, which feeds back on this interaction process.

This paper identified another knowledge gap: As production input, non-attributed water fluctuates even stronger than ‘legalized’ water supply. The existing adaptive learning model performed relatively poorly, and many farmers had negative outcomes as a result of severe planning mistakes –
particularly commercial farm agents that invested heavily, based on short-sighted expectations (Figure 2(a)). However it is during drought conditions when conflicts between farmers are severe and local extension workers pointed out to us that informal arrangements become the cause of litigation between neighbors.

5 CONCLUSION

Empirically, this paper underlines that the Chilean model of privatized water rights is complex and must be assessed within its local context, in this case the Maule region. Informal arrangements may be as important as the legally prescribed water rights and management regime, especially for small, traditional farmers as the rural poor. Water access related to these informal arrangements may be an important reason why farmers support the improvement of canal infrastructure, which can benefit those with legalized water more than those without.

Methodologically, the integrated analysis elucidated an agent-to-agent feedback mechanism by extending assessment across a long chain of causes and effects. The interactions ‘between disciplines’ were especially relevant for poorer segments of the population that benefit over proportionally from a niche of informal arrangements. This only became apparent with a disaggregated analysis, combining a multi-agent model with detailed data on water endowments.

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