Design of policy intervention for collective irrigation reservoirs

M. Raggi[1]; M. Zavalloni[2]; D. Viaggi[2]

1: University of Bologna, Department of Statistical Sciences, Italy, 2: University of Bologna, Department of Agricultural and Food Sciences - DISTAL, Italy

Corresponding author email: matteo.zavalloni@unibo.it

Abstract:

Reservoirs are increasingly deemed to be important given their potential control of water availability across seasons - from wet to dry seasons, especially given the concerns on the effect of climate change. In this paper, we focus on the collective action aspect of investing in irrigation reservoirs and on the potential scope for policy intervention. We formulate a model in which farmers pool resources to construct a collective reservoir. We conceptualized the reservoir as a “blue” club that increases the potential water availability in dry season, thus improving water safety for the whole society. We determine the societal potential inefficiency in club size and the potential policy measures to correct it, focusing on two different club access rules (open vs closed membership). Results show that linear subsidy are ineffective in case of closed membership, and minimum participation rules are required.

Acknowledegment:

JEL Codes: Q25, Q28

#980

Design of policy intervention for collective irrigation reservoirs

Abstract

1 Introduction

Agriculture faces the double challenge of preserving food security for an increasing population and sustainably using key, finite, natural resources like biodiversity, soil and water. For obvious reasons, water is particularly of concern. For example, climate change affects both the supply of water, e.g. increasing temperature and rainfall variability (Karl et al. 1995), and the crop requirement of irrigation (Döll 2002). Moreover, the increasing water consumption from manufacturing and from urban population is expected to severely limit the future expansion of irrigation (OECD 2012) thus putting at risk food security.

The design of measures to improve water efficiency and to lessen the conflicts among the different allocations of water still appears to be high on the environmental agenda (OECD 2012). For example it has been suggested to reformulate subsidies to invest in technologies that increase the efficiency of irrigation (Medellín-Azuara et al. 2012; Wang et al. 2015). Water pricing is suggested to be adopted since it signals the scarcity of the resource and it is supposed to induce a virtuous behaviour in water consumption (Viaggi et al. 2010). Mandatory rules like the "minimum ecological flow" of the European Water Framework Directive restrict water abstraction to ensure the ecologically viability of rivers (Maia 2017).

Another set of technological measures focuses on the supply side by addressing one of the key challenges of climate change, namely the increase in the variability of rainfall. Reservoirs are increasingly deemed to be important given their potential control of water availability across seasons - from wet to dry seasons (Xie and Zilberman 2016). These projects can be rather different in scale, ranging from regional (Fisher and Rubio 1997) to individual farm (Bhaduri and Manna 2014), but also in ownership since reservoirs can be either private or collectively owned (Zhang et al. 2018). Moreover, the destination of the stored water is not limited to irrigation, but it can also be for urban uses (Dallman et al. 2016). The importance of water storage is also shown by being the subject of actual policy measures (E-R 2015).

Since their main objective is to smooth the variability of water supply, much of the economic literature on reservoirs has focused on the effect of uncertainty on the investment decision. Fisher and Rubio (1997) model the reservoir construction as an investment under uncertainty with adjustment costs, considering the possibility or irreversible environmental damages. They show how reservoir capacity increases with higher uncertainty but that environmental damages increase the scope for inaction. Bhaduri and Manna (2014) observe how water storage increase the value of efficient irrigation technology thus increasing its adoption. Maas et al. (2017) focus on how the value of water storage infrastructure depends, also, on the institutions that allocate the resources across the users, finding that inefficient management decreases the value of water by roughly 4-13%. Financing of this project has not been explicitly addressed, since it is usually either assumed fully public spending or fully private investment, even though private/public partnership and subsidies are usually analysed for other technologies.

In this paper, we focus on the collective action aspect of investing in irrigation reservoirs and on the potential scope for policy intervention. We formulate a model in which farmers pool resources to construct a collective reservoir. We conceptualized the reservoir as a "blue" club that increases the potential water availability in dry season, thus improving water safety for the whole society. More specifically, we theoretically analyze what is the size of the reservoir that emerges given that farmers have two different water sources (groundwater and the reservoir) and the reservoir construction cost is characterized first by economies of scale, and then by increasing coordination costs. We thus determine the societal potential inefficiency in club[1] size and the potential policy measures to correct it. Moreover, we focus on two different club access rules (open vs closed membership) to address different social environment. Finally, we provide a numerical example with data from the Emilia-Romagna (E-R) region (Italy).

The term "blue club" draws from the framework of van't Veld and Kotchen (2011) who focuses on the emergence of "green" club, groups of producers that by adopting environmental friendly practices deliver positive externalities. We modify their framework to fit into the problem here at stake. The analysis is inspired by a number of agricultural policy measures in E-R that partially subsidize the construction of collective reservoirs in E-R with the objective of reducing the pressure on groundwater resource (E-R 2012, 2015)[2]. These measures include minimum participation rules: eligible projects must provide water for at least a minimum number of farmers. As we will show in the theoretical analysis, we provide some rationale to indeed include collective conditionality constraints to club subsidies in case of closed membership.

As we previously observed, the economic literature on the topic has neglected the players' interaction in the construction of the reservoir. On the other hand, the collective dimension in the investment in irrigation infrastructures has been extensively analysed by the socio-ecological system literature (Baggio et al. 2016) even though the interaction with the policy environment has been seldom addressed (Muneepeerakul and Anderies 2017). However, to focus on the collective action issue, we neglect the hydrological aspect of the reservoir functioning.

The paper is structured as follows. In section 2 we theoretically analyse the problem.

---

[1] We interchangeably use the terms "club" and "reservoir".
[2] These are the regional implementation of the Rural Development Program of the Common Agricultural policies.

2 Theoretical analysis

2.1 Setting

Imagine a set *N=(i…n)* of farmers, who are homogenous in terms of water productivity. Each farm has revenues as a function of water: *f(w)* where water can come from two sources: groundwater (*g*) or a reservoir (*r*): *w=g+r.* Assume that they can only use either groundwater or reservoir so that the revenue function for a reservoir user is *f(r)* and for a groundwater users is *f(g)*.

Denote with $S \subseteq N$ the subset of farmers (with cardinality *s*) that belongs to the club. Consequently, there are *n-s* groundwater users. The available groundwater before the irrigation season is *G*; assume that there is a societal minimum desired level of groundwater availability g^d (similar to a safety minimum standard).

The reservoir size, both in terms of number of users (n-size) and water stored (q-size) is endogenous. In what follows we analyse the club equilibrium in two cases that can be interpreted as social rule that govern the access to the club. The two cases are the "open membership" one (where, club member cannot exclude non-members from entering) and the "closed membership case" (where, club member can exclude non-members from entering). After having analysed these two equilibriums, we characterized the policy scheme that can be implemented to reach the societal desired level of groundwater extraction.

Profit for a single member of the club (the reservoir) is given by:

(1) $\pi_{i \in S} = f(r) - k \cdot r - t(s)$

where $k \cdot r$ is the cost related to the construction of the reservoir, and *t(s)* is the cost of managing the reservoir linked to the number of users, where: $t(s) = \frac{1}{s} T(s)$ with the minimum (the solution of $\frac{\partial t(s)}{\partial s} = 0$) at $\breve{s}$. The function is "U" shaped in *s*. We can interpret *t(s)* as the cost of coordinating the club. Taking first derivative of (1) WRT *r* shows that the individual rate of use of the reservoir is independent from the number of users: $\frac{\partial \pi}{\partial r} = f_r - k$. On the other hand, profit still depends on the n-size of the club through the coordination costs: $\frac{\partial \pi}{\partial s} = -t_s(s)$.

To formulate the profit for non-users, we assume that the reservoirs delivers positive spillovers on non-members, namely that $\frac{\partial \pi_{i \notin S}}{\partial s} \geq 0$. One possibility is to assume that costs for groundwater users depend on the share of the total number of groundwater users $\left(\frac{n-s}{n}\right)\alpha$:

(2) $\pi_{i\notin s} = f(g) - cg - \left(\frac{n-s}{n}\right)\alpha \Rightarrow f(g) - cg - \alpha + \frac{s}{n}\alpha$

We further assume that the abstraction costs c are lower than k, the respectively cost for the club users. First derivative of (2) WRT to g shows that the spillovers do not affect the consumption of groundwater ($\frac{\pi_{i\notin s}}{\partial g} = f_g - c$) but only profits $\frac{\pi_{i\notin s}}{\partial s} = \frac{\alpha}{n}$.

2.2 Equilibria

2.2.1 Open membership equilibrium

If the club is open (users cannot effectively exclude outsiders from entering), the equilibrium is given by the point where profit for members is equal to profit for non-members (van't Veld and Kotchen 2011). To find such equilibrium first we find the optimal quantity of water consumed for any level of club size, and then we substitute such a value into equations (1) and (2) to have:

(3.a) $\pi_{i\in S}(r^*) = \pi_{i\notin S}(g^*)$

As we observed, for both club members and non-members, the optimal quantity of water (respectively from the reservoir and from groundwater) does not depend on s. Thus r^* is given at the point where $\frac{\partial \pi_{i\in s}}{\partial r} = f_r - k = 0$ and g^* is the solution of $\frac{\pi_{i\notin s}}{\partial g} = f_g - c = 0$.

So the equilibrium condition are given by:

Substituting equation (1) and (2) into (3.a) we obtain:

(3.b) $f(r^*) - k \cdot r^* - t(s) - f(g^*) + c \cdot g^* + \alpha - \frac{s}{n} \cdot \alpha = 0$

The number of reservoir users in open access s^O is the solution to (3).

Several hints can be obtained by analysing 3.b. Implicitly deriving s^O with respect to k yields: $\frac{\partial s^O}{\partial k} = -\frac{r^*}{t_s(s) + \alpha/n}$. Note that $r^*>0$ and $\frac{\alpha}{n} > 0$ so $\frac{\partial s^O}{\partial k} < 0$ if $t_s(s) > 0$ which is sure if $s^O > \breve{s}$ but it depends if $s^O < \breve{s}$. That in turn it implies that an increase in the profit for club member (due for example to a lower costs k) leads to an increase in the open access equilibrium club size. Moreover, if we define a quadratic function for *t(s)*, as for instance in (Sorenson et al. 1978), it is clear that the condition defined in (3.b) yields two solutions. The lowest one (characterized by $s^O < \breve{s}$) defines the minimum size below which the club size does not emerge. That also implies that if $s^{O} < \breve{s}$, then $\frac{\partial s^{O}}{\partial k}$ might become positive, ultimately entailing that an increase in the profit for club members induces a decrease in the minimum club size. The overall logic is depicted in Figure 1.

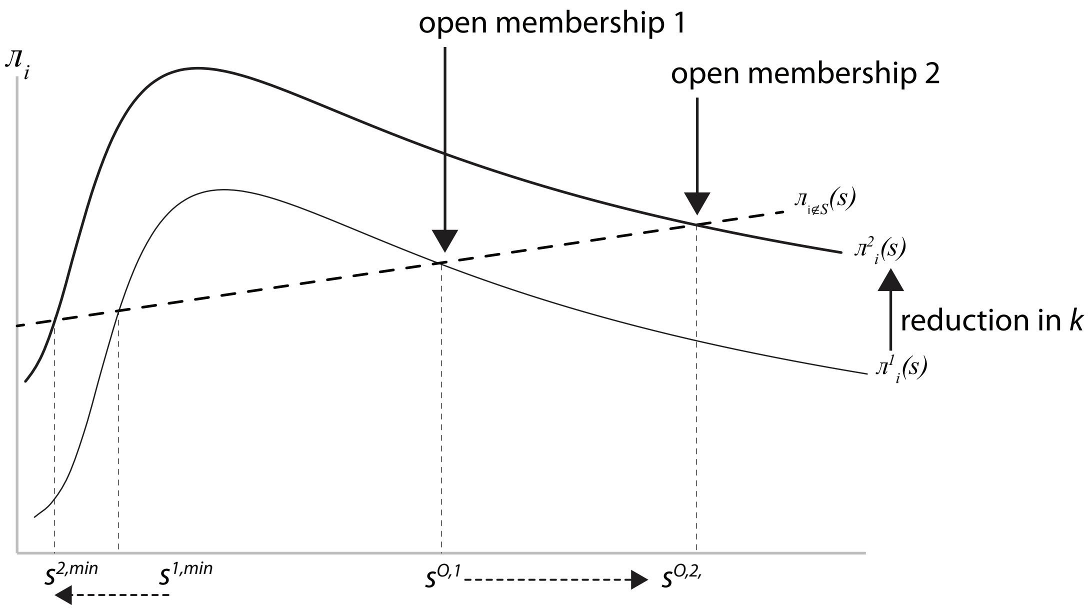

Figure 1. Change in open membership equilibrium due to a reduction in the water abstraction costs for club members (parameter k).

2.2.2 Closed membership equilibrium

Closed membership implies that club members can effectively exclude non-members from entering the club. This equilibrium concept represents the "within club" point of view that was first conceptualized by Buchanan (1965). In this prospect, the emerging club is the one that maximizes the average profits for club members. If the average profits for a club member would decrease, in case of closed membership, those farmers that are members of the club would close the access. Thus:

(4) $\max_{r,s} \pi_{i \in S} = f(r) - k \cdot r - t(s)$

The two FOCs are:

FOC 1: $\frac{\partial \pi}{\partial q} = 0 \rightarrow f_q - k = 0$

FOC 2: $\frac{\partial \pi}{\partial s} = 0 \rightarrow t_s(s) = 0$

From the FOC we get the individual amount of water used by each reservoir user, which is the solution of FOC 1: q^{*}. Note that q^{*} is independent from the number of users (FOC

2). The number of reservoir users (n-size) is the number of users that minimize the average costs for member $s^C = \breve{s}$. All together we have the q-size of the reservoir: $s^C \cdot q^*$. In figure 2 below a graphical comparison of closed vs open membership:

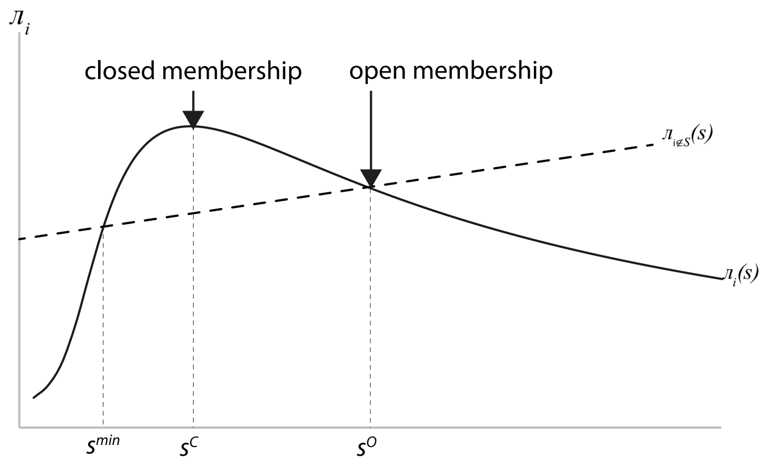

Figure 2. graphical comparison between open and closed membership.

2.3 Subsidy design

2.3.1 Policy in open membership

Recall from section 2.1 that we assume that there is a desired level of groundwater availability. The available groundwater, after irrigation use, is given by:

(5) $g^d = G - n \cdot g^* + s \cdot g^*$.

From (5) is obvious that g^d can either be reached by designing policy that affect g^* (either by using tax or a quota $\bar{g} < g^*$) or by subsidizing the club. Here in this paper we focus on this latter option, namely we design a subsidy for club members in the simplest form. In this latter option, the desired level of groundwater is translated in the desired level of club member s^d.

By subsidizing club members, equation (1) becomes:

(6) $\pi^P_{i \in S} = f(r) - k \cdot r - t(s) + p^O$

where p^O is the level of the payment in the case of the open membership case.

Given equation (6), equation (3) becomes:

(7) $f(r^*) - k \cdot r^* - t(s^d) + p^O - f(g^*) + c \cdot g^* + \alpha - \frac{s^d}{n} \cdot \alpha = 0$

comparing equation (7) with equation (3) we can derive the subsidy required to reach a level s^d:

$$p^O = t(s^d) - t(s^O) + (s^d - s^O) \cdot \frac{\alpha}{n}$$

Note that the higher the spillovers of the club on the non-club members ($\frac{\alpha}{n}$), the higher the payment level required to reach the desired club size. The logic of the policy intervention is depicted in Figure 3.

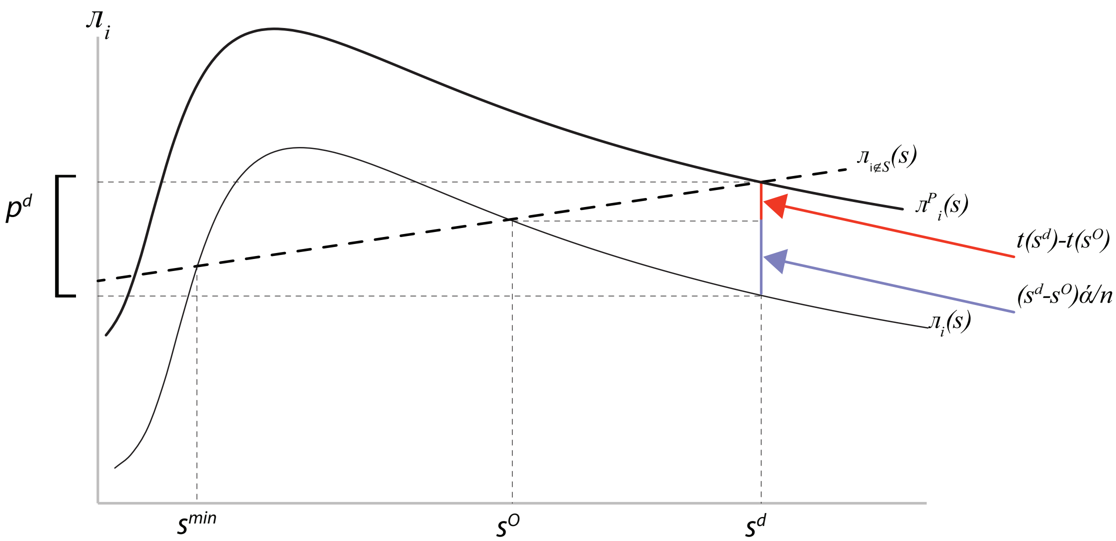

Figure 3. Graphical depiction of the policy intervention to reach the n-size s^d

2.3.2 Policy in closed membership

Recall equation (6), namely profits for club members in case of the policy:

$$\pi^P_{i\in S} = f(r) - k \cdot r - t(s) + p^C$$

where p^C is the level of the payment in the case of the closed membership. Again, in a closed membership, the club that emerges is the one that maximizes profits for the average club member:

Thus the club member program is:

$$\max \pi^P_{i\in S} = f(r) - k \cdot r - t(s) + p^C$$

The FOCs are:

FOC 1: $\frac{\partial \pi}{\partial q} = 0 \rightarrow f_q - k = 0$

FOC 2: $\frac{\partial \pi}{\partial s} = 0 \rightarrow -t_s(s) = 0$

The club member and the use rate of reservoir are not affected by the policy parameters. Consider instead a policy that subsidizes water consumption from a reservoir:

$$\max \pi^P_{i\in S} = f(r) - k \cdot r - t(s) + p^C \cdot r$$

In this case, the water use of reservoir users increase:

$$\frac{\partial \pi}{\partial q} = 0 \rightarrow f_q - k + p^C = 0$$

but not even this type of policy scheme affects the n-size of the club and hence it is ineffective in reaching the societal desired level of groundwater availability. One possibility to affect the size of the emerging club in case of closed membership is to formulate a policy scheme where the subsidy is attached to a minimum participation rule set at s^d. In other words, given s^d, the subsidy level is the one that equalizes the profit for a club member at $s^C = \breve{s}$ with the profit for s^d. Mathematically:

$$\pi^*_{i\in S} = \pi^*_{i\in S}\left(p^C, s^d\right)$$

or:

$$f\left(r^*\right) - k\cdot r^* - t\left(\breve{s}\right) = f\left(r^*\right) - k\cdot r^* - t\left(s^d\right) + p^C$$

which entails:

$$p^C = t\left(s^d\right) - t\left(\breve{s}\right)$$

The policy scheme thus needs to cover the higher costs that an increase in the club above the optimal one entails. Note that spillovers do not affect this payment level. Comparing p^C with p^O shows that the relative level of the payment in the two club membership rules depend on the difference between the coordination costs of the two club size equilbria, and on the spillovers:

$$p^C - p^O = t\left(s^O\right) - t\left(\breve{s}\right) - \left(s^d - s^O\right)\cdot\frac{\alpha}{n}$$

Note, that in case there are no spillovers (*α=0*), p^C is surely greater than p^O, since $t\left(s^O\right) > t\left(\breve{s}\right)$ by definition. Figure depicts the comparison between the subsidy in the open and in the closed membership cases.

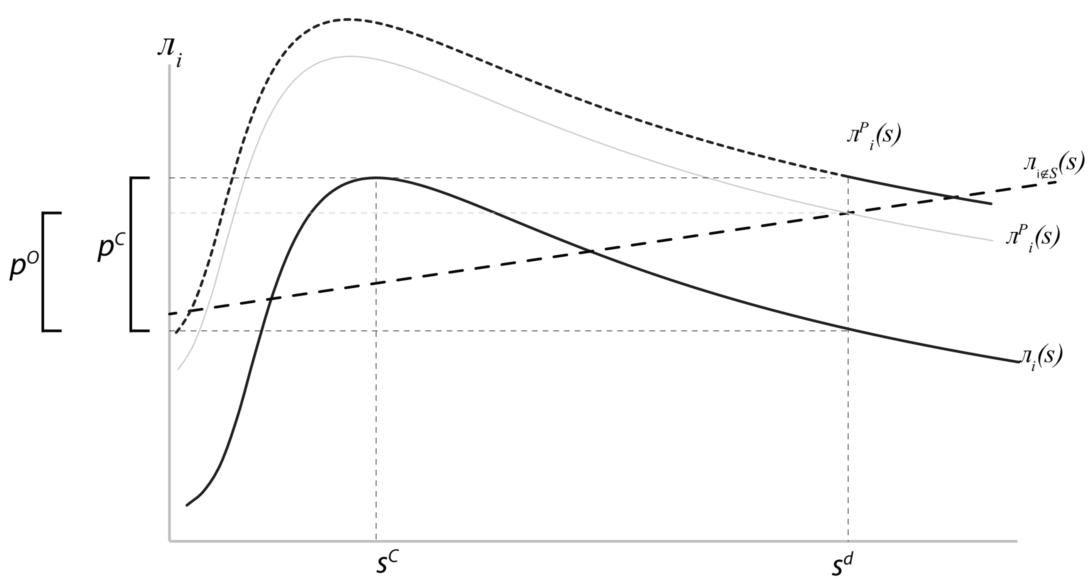

Figure 4. Graphical depiction of the comparison between the subsidies in the open and in the closed membership cases.

3 Numerical example

3.1 Data and scenarios

To build a simple numerical example we use secondary data on profit as a function of water from Viaggi et al. (2010). A mathematical programming model with data from the Ravenna province in E-R (Italy) is run for different level of water availability. Results of gross margins are then plotted against water consumption to have the required water revenue function in accordance with the theoretical analysis. The profit functions are the following:

$$\pi_{i\in s} = -ar^2 + br - kr - \left(ds^2 - es + fs\right)$$

and

$$\pi_{i\notin s} = -ag^2 + bg - cg - \alpha + \frac{s}{n}\alpha$$

We used two farm types, which are differentiated by the value of the water profit function:

	a	*b*	*c*
Cl2	-0.00008	1.2748	2548.8
Cl3	-0.00001	0.5031	11283

Table 1. profit function parameter for the two farm types that are considered.

The cost of construction/management of the reservoirs is $k=0.05$ *€/m*^{3}. The cost of groundwater extraction is: $c= 0.1$ *€/m*^{3}. The coordination costs are assumed to be the following: $d= 2.5$; $e= 100$; $f=1750$. The value of the spillover is assumed to be $\alpha=1500$.
For the club analysis, we consider four scenarios that are differentiated by the composition of the homogenous farm population, but are characterized by the same population size: $n=100$.

3.2 Results

The following table shows results for water consumed for members and non-members, and profits without considering coordination costs for club members and without considering the positive spillovers for non-members (using the mathematical notation previously described: $f\left(r^*\right) - k\cdot r^*$ and $f\left(g^*\right) - c\cdot g^*$).

water use		profits	
Groundwater (*g*)	Reservoir (*r*)	$\pi_{i\notin s}$	$\pi_{i\in s}$

Cl2	7342.5	7655	4313	4688
Cl3	20155	22655	4062	5133

Table 2. Water consumption and profits without considering coordination costs and spillovers for members and non-members for two farm types.

In Figure 5 and 6 we respectively depict the entire club analysis of respectively a scenario composed by 100 CL2 farms and by 100 CL3 farms. We assumed that in both cases, the desired level of club member is s^d*=50*. Despite the relatively small differences in the profits (Table 2), the equilibria are rather different. The most important results are listed in Table 3. As the theoretical analysis showed, the closed membership equilibrium is only affected by the transaction cost function parameters, and thus it is not affected by the composition of the farm population. The same is true for the payment required to reaching a given n-size of the club. However, the difference between the payment in the closed versus open access equilibria is more pronounced in the CL3 case, since this farm type is characterized by a relatively ampler water production function.

	Cl2	Cl3
s^{min}	5	0
Closed Membership equilibria	20	20
Closed Membership Payment (€/s)	2250	2250
Open Access equilibria	31	39
Open Access Payment (€/s)	2137	1458

Table 3. Results of equilibria analysis

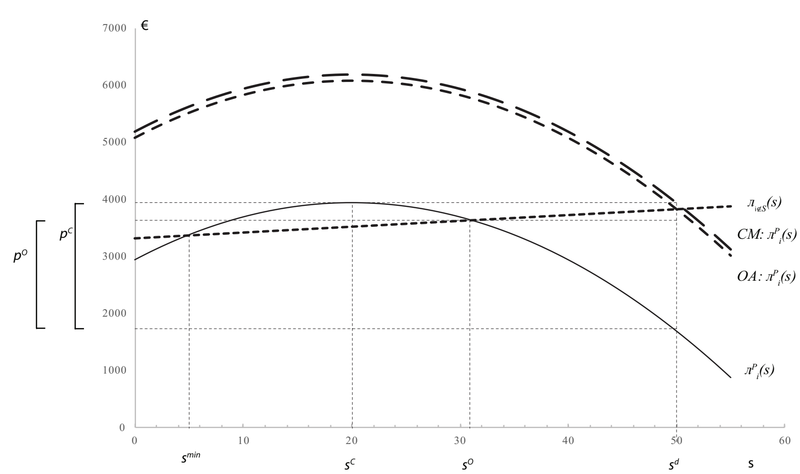

Figure 5. Equilibrium analysis for farm type CL2

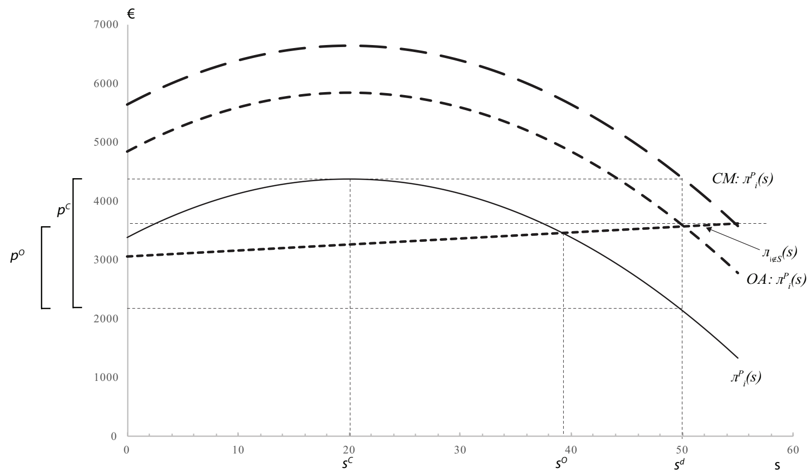

Figure 6. Equilibrium analysis for farm type CL3

4 Discussion and conclusions

In this paper we theoretical analyse the emergence of collective irrigation reservoirs. Conceptualizing the reservoir construction as the contribution to a “blue club”, we focus on the aspect of the coordination among farmers on such an investment. In such a way, we are able to address in what circumstances policy measures are necessary to reach the desired level of the reservoir size, so that the pressure on groundwater resource is reduced.

The theoretical analysis shows that payment levels and design must be differentiated according to the type of access to the club. A simple linear subsidy is sufficient to affect the reservoir size in case of open membership, even though potential positive feedbacks from the reservoir to the non-user increase the payment level required. However, this type of payment is ineffective in case of closed membership, since it affects the q-size of the reservoir, but not the n-size. In case of closed membership, minimum participation rules that explicitly link the subsidy to a desired n-size of the club are required. Indeed, in E-R, policy scheme that incentivizes the construction of collective reservoirs include such a collective conditionality constraints. This type of policy design seems hence appropriate in case the public intervention cannot affect the rule that determine the access to the club.

Several limitations apply. First, the separation between coordination costs and abstraction costs ease the interpretation of the results, but yields the funny result that individual water consumption does not depend on the n-size of the reservoir. The inclusion of a combined, non-linear, cost function of the type *t(s·r)* would solve this. Second, the model does not address the problem of the heterogeneity of farmers. While a detailed analysis is required for the open membership case, the inclusion of heterogeneous players would not affect the equilibrium in case of closed membership if the coordination costs only depend on the n-size of the club. However, different club compositions could emerge. Similar reasoning could apply to the introduction of spatially explicit analysis of farm distribution and its effect on the club emergence. Finally, abstraction from groundwater is often difficult to monitor and its limitation is difficult to enforce. The inclusion of a club perspective within a principal-agent framework seems promising.

Reference:

Baggio J, Barnett A, Perez-Ibarra I, et al (2016) Explaining success and failure in the commons: the configural nature of Ostrom's institutional design principles. International Journal of the Commons 10:

Bhaduri A, Manna U (2014) Impacts of water supply uncertainty and storage on efficient irrigation technology adoption. Natural Resource Modeling 27:1–24 . doi: 10.1111/nrm.12016

Buchanan JM (1965) An Economic Theory of Clubs. Economica 32:1–14

Dallman S, Chaudhry AM, Muleta MK, Lee J (2016) The Value of Rain: Benefit-Cost Analysis of Rainwater Harvesting Systems. Water Resources Management 30:4415–4428 . doi: 10.1007/s11269-016-1429-0

Döll P (2002) Impact of climate change and variability on irrigation requirements: A global perspective. Climatic Change 54:269–293 . doi: 10.1023/A:1016124032231

E-R E-R (2015) Italy - Rural Development Programme (regional) - Emilia-Romagna

E-R E-R (2012) Programma di sviluppo rurale 2007-2013 Reg (CE) n. 1698/2005

Fisher AC, Rubio SJ (1997) Adjusting to Climate Change: Implications of Increased Variability and Asymmetric Adjustment Costs for Investment in Water Reserves. Journal of Environmental Economics and Management 34:207–227 . doi: 10.1006/jeem.1997.1011

Karl TR, Knight RW, Plummer N (1995) Trends in high-frequency climate variability in the twentieth century. Nature 377:217–220

Maas A, Dozier A, Manning DT, Goemans C (2017) Water storage in a changing environment: The impact of allocation institutions on value. Water Resources Research 53:672–687 . doi: 10.1002/2016WR019239

Maia R (2017) The WFD Implementation in the European Member States. Water Resources Management 31:3043–3060 . doi: 10.1007/s11269-017-1723-5

Medellín-Azuara J, Howitt RE, Harou JJ (2012) Predicting farmer responses to water pricing, rationing and subsidies assuming profit maximizing investment in irrigation technology. Agricultural Water Management 108:73–82 . doi: 10.1016/j.agwat.2011.12.017

Muneepeerakul R, Anderies JM (2017) Strategic behaviors and governance challenges in social-ecological systems. Earth’s Future 5:865–876 . doi: 10.1002/2017EF000562

OECD (2012) OECD Environmental Outlook to 2050. Organisation for Economic Co-operation and Development

Sorenson JR, Tschirhart JT, Whinston AB (1978) Private good clubs and the core. Journal of Public Economics 10:77–95

van’t Veld K, Kotchen MJ (2011) Green clubs. Journal of Environmental Economics and Management 62:309–322 . doi: 10.1016/j.jeem.2011.03.009

Viaggi D, Raggi M, Bartolini F, Gallerani V (2010) Designing contracts for irrigation water under asymmetric information: Are simple pricing mechanisms enough? Agricultural Water Management 97:1326–1332 . doi: 10.1016/j.agwat.2010.03.014

Wang T, Park SC, Jin H (2015) Will farmers save water? A theoretical analysis of groundwater conservation policies. Water Resources and Economics 12:27–39 . doi: 10.1016/j.wre.2015.10.002

Xie Y, Zilberman D (2016) Theoretical implications of institutional, environmental, and technological changes for capacity choices of water projects. Water Resources and Economics 13:19–29 . doi: 10.1016/j.wre.2015.08.004

Zhang L, Hu J, Li Y, Pradhan NS (2018) Public-private partnership in enhancing farmers’ adaptation to drought: Insights from the Lujiang Flatland in the Nu River (Upper Salween) valley, China. Land Use Policy 71:138–145 . doi: 10.1016/j.landusepol.2017.11.034