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SPECIAL FEATURE: ORIGINAL ARTICLE

Networks of Action Situations in Social-Ecological Systems Research

Irrigation modernization and the efficiency paradox: a meta-study through the lens of Networks of Action Situations

Patrick Hoffmann[1,2] · Sergio Villamayor-Tomas[1]

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Abstract

Infrastructure and technology investments that increase water-use efficiency (also called modernization investments) have become one of the most preferred solutions to cope with water scarcity in the context of climate change, increase productivity to satisfy growing demand, and save water to maintain ecosystems. In many cases, however, the higher efficiencies have led to more, instead of less, water consumption. This is generally known as the efficiency paradox or rebound effect. Understanding the processes behind the efficiency paradox remains a difficult task, given the variety of variables that either directly or indirectly factor into farmers' water-use decisions and the strategic nature of many of those. This is even more the case when water is managed collectively by water-user associations, as in many irrigation systems worldwide. In order to better understand this complexity, our study applies the Networks of Action Situations approach to 37 studies of irrigation modernization investments in collectively managed irrigation systems. Through a systematic case review method, we identify 12 different action situations and 192 institutional, physical, and informational linkages that connect them. Although some studies report linkages between the modernization-investment and water-saving decision situations, many others relate them to situations typically associated with the collective management of irrigation systems (like the water application or infrastructure maintenance situations). A number of these situations, also including the water-saving situation, involve collective action problems that need to be integrated in current analyses. The solution towards more water saving may indeed benefit from a more active involvement of irrigation associations, given their proven capacity to promote collective action among farmers vis-à-vis other irrigation management situations.

Keywords Networks of action situations · Social dilemmas · Irrigation · Modernization · Efficiency paradox · Rebound effect · Meta-study

Introduction

Despite repeated warnings, the climate and ecological crises have only deepened over the last decades (Ripple et al. 2021). With it, research and calls for the transformation of socio-ecological and -technical systems towards more sustainable modes of production and consumption have become increasingly salient (Markard et al. 2012; El Bilali 2019; Köhler et al. 2019). In the irrigation sector, the transformation of irrigation systems through the modernization of infrastructure and technology (e.g., via investments in water storage, or sprinkler/drip irrigation) has been portrayed as the main way to move to more sustainable water use. Modernization sets the goal to increase water-use efficiency, which, in turn, is expected to contribute to alleviating water scarcity by reducing agricultural water-use. However, a growing body of literature indicates that water consumption increases rather than decreases after the implementation of modernization measures (Perry et al. 2017; Sears et al. 2018; Grafton et al. 2018; Freire-González 2019; Pérez-Blanco et al. 2020; Wheeler et al. 2020; Wang et al. 2020;

Handled by Christian Kimmich, Institut fur Hohere Studien-Institute for Advanced Studies, Vienna

✉ Patrick Hoffmann
patrick.hoffmann@autonoma.cat

1 Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona, Carrer de les Columnes s/n, 08193 Cerdanyola del Vallès, Barcelona, Spain

2 School of Business and Economics, University of Marburg, Barfüssertor 2, 35037 Marburg, Germany

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McCarthy et al. 2020). This seemingly paradoxical effect, known as the *efficiency paradox* or *rebound effect*, reveals a conflict with the goal of conserving water-dependent ecosystems and demonstrates how well-intended interventions in socio-technical systems can produce unanticipated and undesirable consequences. That conflict is particularly important given the growing world population, the associated increase in demand for food, and climate change (FAO 2017; World Bank 2020). Scholars have tended to justify the efficiency paradox mostly based on economic theory, which predicts that an increase in irrigation efficiency results in an income effect, permitting farmers to increase production by expanding irrigated area or by switching to more valuable and water-consuming crops (Ward and Pulido-Velazquez 2008; Contor and Taylor 2013; Pfeiffer and Lin 2014). The income effect can also be the result of other processes, like decreases in operation and maintenance (Gómez and Pérez-Blanco 2014) or energy costs (Stambouli et al. 2014). Additionally, as we argue in this paper, the efficiency paradox may owe to collective action dynamics and strategic decision-making, just like other unattended effects of infrastructure investments in irrigation systems (Lam 1998; Sanchis-Ibor et al. 2017a).

To our knowledge, there is little systematic understanding on collective action dynamics and strategic decision-making as they relate to the efficiency paradox, particularly in the context of collectively managed irrigation systems, where said dynamics and decision-making are particularly salient among farmers. Considering this gap, our paper addresses the following research questions: which strategic decision situations and their linkages encompass the management of collective irrigation systems in modernization contexts? To which extent do those decisions allow us to understand the emergence of water-use rebound effects? To address these questions, we rely on the theory of Networks of Action Situations (McGinnis 2011a) which understands the management of irrigation systems as a series of strategic decision-making situations, the outcomes of which affect each other and social and ecological outcomes. The contribution of this paper is thus to start delving into the complex behavioral dynamics behind the efficiency paradox and to provide a basis to systematize the so far scattered knowledge about it in the irrigation sector.

Methodologically, we conduct a meta-analysis of 37 case studies of irrigation modernization in community-managed systems. In the coding process, we first identified and named key action situations. Furthermore, the same strategy was used for linkages among dyads of action situations. In the analysis, we unveil collective action problems potentially associated to the situations, with particular attention to what we name the water-saving situation.

The paper is structured as follows: "Background" introduces the literature on the institutional analysis lens that inspires the theory of Networks of Action Situations. "Methodology" explains the methodology. "Results" presents the results in three subsections. First, we provide a descriptive summary of the case studies used in the meta-analysis. Second, we describe the set of identified action situations that characterize the studied irrigation systems in modernization contexts. Finally, we explore institutional, physical, and informational linkages among dyads of action situations. "Discussion" discusses the implications of our findings, reconstructs the analytic narratives behind two of the Networks of Action Situations (NAS) coded, and highlights gaps for future research. In the conclusion, we recap on the main findings.

Background

Despite the growing literature on the *irrigation rebound effect* (Perry et al. 2017; Grafton et al. 2018; Berbel et al. 2019; Pérez-Blanco et al. 2020; Wang et al. 2020), few studies consider that irrigation systems are managed collectively by farmers via water-user associations (WUAs). This is not trivial, because user-managed irrigation systems are widespread in many rural areas of the world, and many of them have operated with remarkable success over decades and centuries (Wade 1987; Bardhan 1993; Ward et al. 2020). More importantly, the functioning and success of such collective systems is pervaded by collective action dynamics, the exploration of which can complement our knowledge on the drivers of the rebound effect. Irrigation systems are a typical example of a common-pool resource (CPR), the management of which faces collective action problems associated to its depletability and difficult excludability, as well as to the strategic decision-making of users (Ostrom et al. 1994). Decades of research have shown the capacity of farmers to overcome those collective action problems to manage irrigation systems, and adapt to scarcity situations (Ostrom 1993; Poteete et al. 2010; Villamayor-Tomas 2014; Lam and Chiu 2016; Ma'Mun et al. 2020). They have accomplished this via rules that comprise water allocation, financial contributions, or monitoring and sanctioning mechanisms, as well as the creation of WUAs with the power to design and modify said rules.

The increase in productivity associated with efficiency-enhancing modernizations is likely to affect farmers' water-use decisions, as well as the way WUAs manage the irrigation systems (i.e., the abovementioned rules) (Bandaragoda 1998; van der Kooij et al. 2015; Ortega-Reig et al. 2017). Yet, there is still little research that addresses modernization processes with an eye on the collective management dynamics within those systems. In an early study of small-scale irrigation systems in Nepal, Lam (1996) found that externally imposed infrastructure investments were unlikely to achieve irrigation efficiency levels if local conditions and institutions were not taken into account, an argument that was further supported in a follow-up study of the performance of irrigation modernization (Lam and Ostrom 2010). García-Mollá et al. (2014) illustrate how modernization in a collective irrigation scheme in Spain translated into water savings but also in an increase of water fees the association charged to its members (to finance the new infrastructure). Albizua and Zaga-Mendez (2020) assess in a Spanish irrigation system how collective management conditions changed before and after a modernization project. They find that the technological conversion led to a decrease in farmers' autonomy to self-organize but also to tighter monitoring due to the externalization of this task to an external company.

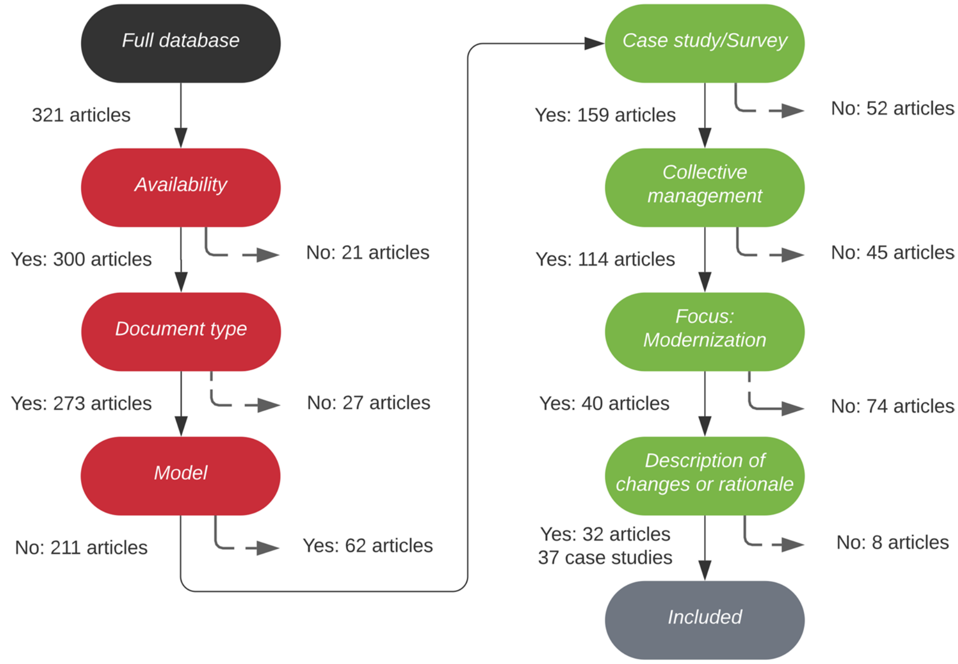
In this study, we rely on the Institutional Analysis and Development (IAD) framework (Kiser and Ostrom 1982; McGinnis 2011b). Its focal units of analysis are action situations which capture decision-making points for two or more individuals whose decisions jointly produce outcomes (Ostrom 2005). Irrigation scholars using the IAD lenses have tended to focus on two typical action situations: the water appropriation situation (whereby farmers decide how much water to use), and the infrastructure maintenance situation (how much to maintain the infrastructure) (Ostrom et al. 1994). Action situations are affected by contextual factors as well as biophysical, socioeconomic, and institutional conditions. Their outcomes can in turn feedback to the contextual factors of other action situations (see Fig. 9 in the Appendix). For example, how well the irrigation infrastructure is maintained will affect efficiency of water conveyance and the amount ultimately needed to satisfy farmers' needs and cope with scarcity (Tang 1992; Villamayor-Tomas and García-López 2017). To account for this interdependence, McGinnis (2011b) coined the approach of Networks of Action Situations (NAS). Linkages between action situations can be categorized into types depending on which of the contextual factors of one action situation (and therefore strategic decisions) are altered by the outcome of another. According to Kimmich (2013), linkages can be biophysical, institutional, actor-based, or informational. Physical linkages are, for example, changes in water availability or consumption; and institutional linkages are, for instance, water allocation rules. In sum, a linked set of action situations can be displayed as a network. The analysis can then be carried out by focusing on one action situation (the focal action situation) and exploring how it is affected by all others and their linkages.

Methodology

In the last years, a growing number of scholars have applied the NAS approach to single and comparative case studies (Kimmich et al. 2022), including irrigation management cases (Kimmich 2013; Villamayor-Tomas et al. 2015; Kimmich and Villamayor-Tomas 2019; Möck et al. 2019). We complement that literature by conducting a meta-analysis of case studies that cover irrigation modernization and its effects in the context of collective irrigation management systems. Our variables of interest are action situations and their respective linkages, but we also coded for geographical, biophysical, and technological variables (the complete list of variables can be found in Table 2 in the Appendix). Many irrigation studies do not explicitly mention NAS but contain information about linkages, nevertheless. After a first exploratory phase (see S1 for more details), we collected case studies from two complementary sources: a database from Pérez-Blanco et al. (2020)'s review on water conservation technologies, and a database resulting from a systematic literature search via Scopus. The first database provides a collection of 230 empirical studies analyzing the effect of water conservation technologies, which we narrowed down to a subset of cases with sufficient and relevant information, resulting in 152 studies reported in 139 articles. For the second database, we ran a document search with Scopus by applying the "related documents" algorithm based on four preselected papers which we considered exemplary applications of the NAS approach in the irrigation sector and/or modernization effects. We carried out one search per each of the 4 selected papers. For each search we selected the 50 most relevant results, mostly to guarantee a representative but still manageable size of articles. Aggregating the resulting 200 articles and deleting duplicates resulted in a second database of 182 documents, which, together with the first database, returned a database of 321 articles. These were then filtered by applying a set of exclusion and inclusion criteria related to availability (i.e., accessible), document type (e.g., not grey literature), methods (e.g., not modelling studies or theoretical papers), and substantive information (i.e., on collective irrigation management and modernization) (Fig. 1). More details on the Scopus search, the justification of the preselected papers, and the applied criteria are outlined in S1.

The goal of the coding process was to identify action situations and linkages between them. Several action situations in the context of irrigation management have already been identified by Kimmich (2013) and Kimmich and Villamayor-Tomas (2019). In our analysis, we built

Fig. 1 Selection process of studies according to the applied exclusion (red) and inclusion (green) criteria



on the set of action situations from the latter study and complemented it with new action situations based on the information found in the reviewed cases. The identification of linkage types was mostly inductive although inspired by Kimmich (2013)'s distinction between biophysical, institutional, actor-based, and informational linkages.

The exploratory phase revealed sufficient evidence in the studies to code for dyads of action situations, as expressed in causal effects between pairs of variables. For example, the statement "Energy tariff impacts timing of water pumped" indicated for us that the outcome of an energy allocation situation affects decisions in a water allocation situation (further examples for such statements are listed in Table 3 in the Appendix). Since connecting those dyads into a NAS for each of the studies would have required interpretation from our part (e.g., about the direction of effects throughout the network), we decided to stick to the coding of causal dyads.

Finally, although we sought for empirically supported statements, we also coded theory-informed statements that were relevant and directly connected to the cases (as when an author uses premises or interprets findings based on strong theory).

Results

Descriptive summary

Geographically, the 37 selected case studies cover a range of 11 countries. Most of the cases are based in Spain (24), while the remaining 13 are spread over 10 countries from all continents except Oceania.[1] Spain is the only European country featured in our analysis, and its overrepresentation can be explained by the fact that it is a country that has a long history and recognition for collective irrigation management (Lopez-Gunn 2003), and has experienced large-scale modernization processes in the last decades (Berbel et al. 2019). Also, three of the four articles used in the Scopus search were located in Spain, which could partially explain the overrepresentation of this country. The size of irrigation systems studied is heterogeneous, with the smallest irrigated acreage being 67 ha and the largest being 800,000 ha. The water source in most of the cases is surface water (e.g., water diverted from rivers) (Fig. 2).

The cases put forth various reasons for the engagement in a modernization process (Fig. 3). Saving water was by far the most frequently indicated goal, followed by increasing the system's productivity, saving water and increasing productivity simultaneously, as well as increasing the water supply in the system, among others.

Looking at the impacts of modernization, the information on whether modernizing the system leads to actual savings is only provided by 17 case studies, most of which negate water savings (Fig. 4). Also, less than half of the cases compare water use levels before and after the investment (Fig. 5). In 7 of them water use decreased, while in 10 water use increased.

[1] The remaining studies are based in Tanzania, Chile, USA, Ecuador, Philippines, Mexico, China, Algeria, and Morocco.

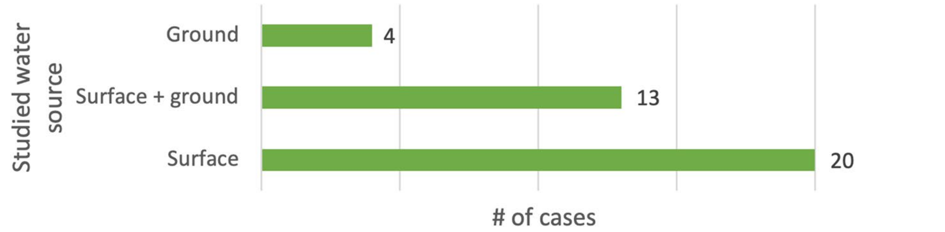


Fig. 2 Water source used for irrigation ($n = 37$)

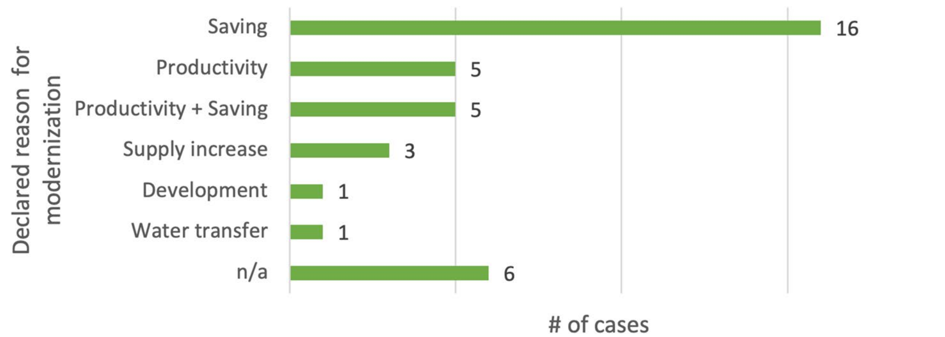


Fig. 3 Reasons for modernization ($n = 37$)

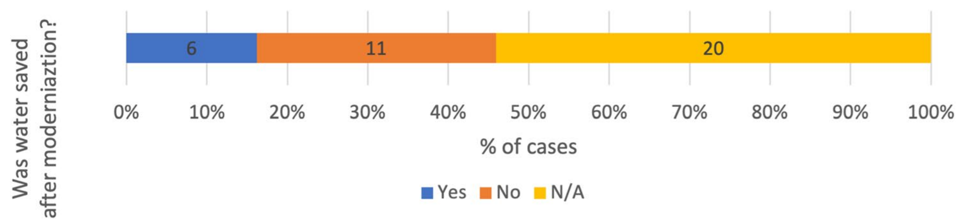


Fig. 4 Cases with reported actual water savings ($n = 37$)

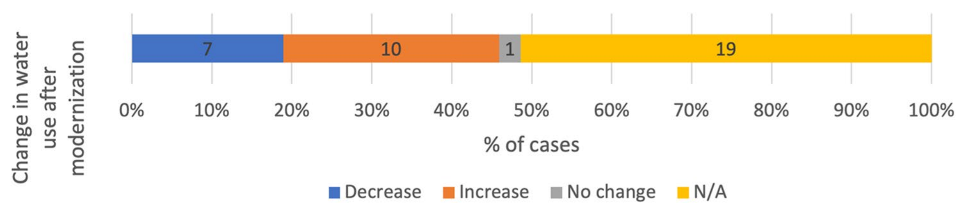


Fig. 5 Changes in water use after modernization ($n = 37$)

Action situations

Overall, our review resulted in the identification of 12 action situations relevant for irrigation modernization contexts. On average, we found 5 situations per case (standard deviation of 2.4). Below, we describe each of the action situations, i.e., the main decision involved and the stakes at hand.

Typical action situations

We start with the four basic action situations that are already known from the NAS literature in the irrigation context (Ostrom et al. 1994; Kimmich and Villamayor-Tomas 2019).

Water allocation (WAL) Even in contexts where water is abundant, infrastructure constraints (e.g., the limited carrying capacity of conveyance canals) can prevent individual demands to be met at all times across the irrigation system. This is particularly the case for surface irrigation systems and makes water allocation a central action situation in these systems. In this situation, farmers face a coordination problem, i.e., one that requires the ordering of irrigation. We identified the water allocation situation in 21 of the cases reviewed, for example when authors made statements like "water usage is regulated by water use turns and irrigation schedules" (Dessalegn and Merrey 2014: 13), or "water users smartly adapted to the rotational water distribution" (van der Kooij et al. 2017: 6). Typical water allocation rules in the reviewed papers include turns, irrigation schedules, or timed irrigation, the appropriateness of which depended on the dominant irrigation technology in the systems (Dinar et al. 1997; Ortega-Reig et al. 2017), biophysical aspects (van der Kooij et al. 2015), or the availability of groundwater (Cox and Ross 2011).

Water application[2] (WAP) More frequently than not, water is scarce, and farmers face the challenge of deciding how much of it they should use. Throughout the irrigation campaign, farmers seek to apply the optimal amount of water to satisfy their crop requirements. This decision confronts them with the typical CPR appropriation dilemma, especially if their water needs are higher than the water available. We coded for this action situation in 21 cases, i.e., whenever authors referred to changes in water withdrawals (e.g., Sanchis-Ibor et al. 2017b) or water use (e.g., Lopez-Gunn et al. 2012a). Additionally, we included cases informing about changes (frequently increases) in irrigated area (e.g., Sese-Minguez et al. 2017).

Infrastructure operation and maintenance (IMNT) In many irrigation communities, operation and maintenance of the system are carried out by farmers themselves via community work or collectively paid laborers (Lankford 2004; Communal et al. 2016; Kimmich and Villamayor-Tomas 2019). Yet, collective maintenance efforts are not trivial as the infrastructure itself is a local public good. To cope with free rider issues, water associations usually condition water application to compliance with maintenance rules and engagement in monitoring (Ostrom 1993). We identified this action situation in 23 of the cases whenever authors referred to "operation practices" or "maintenance of the system". As illustrated in some of these papers, ongoing technological advancements have led to operation and maintenance being outsourced in some occasions to private companies, and financed through fees collected from farmers (Sanchis-Ibor et al. 2017a; Molle and Sanchis-Ibor 2019).

Monitoring compliance (MON) As mentioned above, monitoring of rule compliance and/or resource conditions is an essential action situation for successful collective action in irrigation and other CPR contexts (Tang 1992; Cox et al. 2010). However, the provision of monitoring is also confronted with a public goods problem. Since the benefits from monitoring accrue to the community as a whole, individual farmers lack the incentive to contribute towards it. This action situation was coded from 8 cases, e.g., when studies pointed to the commissioning of guards or ditch riders by the WUAs (Lecina et al. 2005), collective investments in remote monitoring (Lecina et al. 2010a), or monitoring activities carried out by farmers themselves (van der Kooij et al. 2015). As was also illustrated in the papers, monitoring effort is highly contingent on the irrigation technology (e.g., metered water or water in open ditches is easier to track than otherwise) and water sources (e.g., aquifer conditions and extractions are less visible than surface water conditions and extractions) (Lopez-Gunn 2003; van der Kooij et al. 2015).

Focal action situations in the modernization context

Here, we introduce the two focal action situations relevant for an analysis of the modernization context.

Infrastructure investment (IINV) Investing in the improvement or construction of new infrastructure usually involves collective efforts (Lam and Ostrom 2010; Ostrom et al. 2011). The conversion of flood to sprinkler or drip irrigation, for example, typically involves investments at the system level, such as water storage works and equipment to pressurize water throughout the system, all of which would require collective action among irrigators (Blanke et al. 2007). Similar to in the infrastructure maintenance or the monitoring situations, system level investments benefit the community (to the extent that they, e.g., improve water efficiency or control), which is a disincentive for farmers to contribute to their financing or implementation.[3] We coded for this action situation whenever a study reported on a (collective) modernization decision, which was the case in almost all studies (note that our search strategy required the cases to involve some sort of modernization). Typical investments reviewed included headworks and in-system water storage works, the conversion from flood to sprinkler or drip irrigation, and the lining of canals (Lopez-Gunn et al. 2012b; Stambouli et al. 2014; Sese-Minguez et al. 2017).

Water-saving (SAV) This action situation sheds light on whether modernization investments lead to water savings or not. Water savings can remain within the boundaries of the system (which is mostly the case for groundwater), or flow to the outside environment or external water users (e.g., urban or industrial uses, or other water users), i.e., their value for the community depends on the systems' biophysical conditions. Everything being equal, an increase in irrigation efficiency reduces the amount of water applied per crop, hence freeing up a fraction of the water used before. Lankford (2013: 1) proposes labeling this freed-up fraction *paracommons*, i.e., "commons of the material gains from efficiency improvements". We follow this distinction to

[2] Although institutional analyses of irrigation management refer to water appropriation, most of the studies here reviewed refer to water application. Also, in those analyses, water appropriation has the connotation of water being consumed; however, as explained by recent irrigation studies, it is important to separate water used from water effectively consumed (see water-saving situation below).

[3] More precisely, the modernized system is an impure public good, as farmers enjoy also private benefits from an investment.

trace water savings analytically, finding sufficient evidence in the reviewed cases where water savings were mentioned apart from overall application rates.

The decision to distinguish the water-saving situation from the WAP situation is further supported by the theory of mental accounting (Thaler 1999). This concept suggests that individuals' decision-making on expenditures and savings depends on separate mental accounts that they hold for financial and material endowments. Applied to our context, we assume farmers to keep distinct mental accounts on the water they are endowed with and the water that is freed-up after an increase in efficiency.

Thus, the decision on how to allocate water savings confronts irrigators with a social dilemma, essentially like the dilemma in the WAP situation. Using the freed-up water benefits the water user directly given that they can effectively put that "extra" water to work and increase agricultural production (Berbel and Mateos 2014; van der Kooij et al. 2015). Alternatively, saving water could allow other irrigators within or outside the system to use it, or sustain the environment. Water does not only have an agronomic function but also contributes to sustaining freshwater ecosystems and the biophysical environment at large, both of which are public goods (Chiesura and de Groot 2003; Martin-Ortega et al. 2015). For the individual farmer, the benefit from increased crop production likely exceeds the benefit from contributing to the public good (Molle and Tanouti 2017). Thus, farmers may be more willing to use the freed-up water than to save it, even if the benefits of environmental conservation offset private ones overall. This aligns with the observation that farmers perceive modernization rather as a means to increase production and yield rather than as a means to save water (Benouniche et al. 2014; Ortega-Reig et al. 2017). Overall, we found evidence of this action situation in 15 cases, i.e., whenever authors referred to "water consumed" or "water saved".

Modernization-specific action situations

The following action situations are considered auxiliary as they were less frequently reported. However, they can be salient in the context of modernization.

Modernization policy (POL) In the context of self-governed irrigation systems, governments usually take responsibility for coordinating operations across said systems (Frey et al. 2016). Hence, governmental policies can also influence the incentives of farmers regarding other decisions, like those associated with infrastructure. A modernization-supporting policy was mentioned in 22 of the cases, most of which referred to governmental subsidies towards modernization (Renault 1998; Mollinga and Bolding 2004; Berbel et al. 2019). As pointed out by some of the studies, the stakes of government officials in releasing modernization subsidies can be high if these are understood to increase political clout or votes (Molle and Sanchis-Ibor 2019), especially if irrigators also lobby for them (Zeitoun et al. 2012; Kimmich 2016). Agricultural policies are more frequently than not shaped by the farm lobby in favor or against certain policies; however, we did not find evidence for action situations related to lobbying activities in the reviewed studies.

Cropping (CRO) This action situation captures farmers' cropping decisions at the beginning of the cultivation cycle. It was coded when the studies provided information about cropping patterns (Lecina et al. 2010b), cropping calendars (Delos Reyes and Schultz 2021), or other crop-related decisions. We found this action situation in 22 cases.

As is shown in the reviewed studies, cropping decisions are usually driven by changes in crop prices or input costs; however, changes in water availability (e.g., in the aftermath of modernization investments) can also motivate them (Soto-García et al. 2013; Graveline et al. 2014; Stambouli et al. 2014), which tightly links this action situation to the WAP situation. In dry environments, the availability of irrigation water may encourage farmers to water winter crops or switch to summer crops for their higher productivity or economic returns (Lecina et al. 2010b). Ultimately, if too many farmers within a system grow high water demand crops, issues of water availability and compliance with management rules may arise. Interestingly enough, irrigation associations usually do not have the authority to tell farmers what to grow, even though there are exceptions (Villamayor-Tomas and García-López 2017).

Energy application and allocation (EAL) This action situation was found in 12 cases, e.g., whenever energy or electricity costs were mentioned. As shown in the studies, in the context of transitions from flood to drip or sprinkler irrigation, many surface systems have become dependent on energy to pump water into pressurized pipes (e.g., in Spain see Molle and Sanchis-Ibor 2019). This can result in a rise in electricity costs, depending on the elevation of the system or the existence of a water storage facility (Jackson et al. 2010; Rodríguez-Díaz et al. 2011). In the context of collective irrigation, energy costs are shared to some degree, which makes energy a CPR and confronts farmers with a similar dilemma to that of the WAP situation. Also, there are infrastructure limitations (i.e., power limitations) that prevent the use of energy simultaneously by any number of farmers. This confronts farmers with a coordination problem that is very similar to that of the WAL situation. The energy application dilemma and coordination problem are evident when the irrigation association collectively owns an energy generation plant, as well as when WUAs sign collective contracts with electricity suppliers that provide

Table 1 Number of linkages per action situation

	WAL	WAP	CRO	IMNT	IINV	MON	POL	EAL	MKT	MIP	FER	SAV	Sum
WAL		2	3		1	1		1					8
WAP	1		3	2	1	1		3				1	12
CRO	2	5			1							3	11
IMNT	4												4
IINV	9	14	14	25		7		7	1	7	6	8	98
MON													0
POL	1	4	2	1	21					2		1	32
EAL	3	2	3	4									12
MKT	1												1
MIP	3		2	3	2								10
FER													0
SAV		2	2										4
Sum	24	29	29	35	26	9	0	11	1	9	6	13	192

Direction of a linkage: from *row* to *column*

WAL water allocation, *WAP* water application, *CRO* cropping, *IMNT* infrastructure maintenance and operation, *IINV* infrastructure investment, *MON* monitoring, *POL* policy, *EAL* energy allocation, *MKT* water market, *MIP* management improvement, *FER* fertigation, *SAV* water-saving

energy according to scheduled tariffs (Stambouli et al. 2014; Villamayor-Tomas 2018; Kimmich and Villamayor-Tomas 2019).

Water market (MKT) In some cases, users can exchange water concessions in formal or informal markets. Water markets are supposed to add flexibility to water-use concessions and allocate water to its most productive use (van der Kooij et al. 2015; Wheeler et al. 2020). This includes the possibility for farmers to sell concessions to the government, which can then allocate water towards other productive or environmental uses (Berbel et al. 2015). We found this action situation to be relevant only in one case study (van der Kooij et al. 2015).

Management improvement/adaptation (MIP) WUAs need to revise managerial practices and adjust them to changing conditions (Playán and Mateos 2006; van der Kooij et al. 2015). This can also be the case in the aftermath of modernization processes, as existing rules and practices need to be reviewed to adapt to the new technologies (Molle and Sanchis-Ibor 2019). Some authors argue that managerial improvements are as important as technical improvements to enable sustainable and efficient water management (Lecina et al. 2010a). Changes in management rules, however, are not smooth processes. They require cooperation among farmers, e.g., to diagnose problems and come up with amendments to existing practices (Ostrom 1990). Moreover, changes in rules usually create winners and losers. That is why some authors have pointed to the importance that said changes are better accomplished whenever stakes in water-use are low (Fernandez and Rainey 2006; Villamayor-Tomas et al. 2020a). This action situation was found in nine cases e.g., when authors included descriptions of institutional reforms associated with modernization projects, such as the establishment of new thematic committees within the WUAs (Lankford 2004) or the automation of administrative processes (Soto-García et al. 2013).

Fertigation (FER) The change of irrigation practices also affects the choice of fertigation. Fertigation is the injection of fertilizers into irrigation water to save the additional step of applying fertilizer at the field level. In collectively used infrastructures, members must agree on the amount of fertilizer to be injected into the water at the irrigation head, which bears potential for conflict (Ortega-Reig et al. 2017). We coded this action situation in five studies, i.e., whenever the possibility for collective fertigation management was mentioned.

Linking the action situations

Table 1 displays the count of links for each pair of action situations; the direction of the linkages is from the action situation in the row to the action situation in the column. The linkage matrix with all links characterized qualitatively is provided in S2.

Expectedly, we did not find links between all action situations (see blank cells in Table 1). Our focal action situation, the water-saving situation (SAV), was affected by four other action situations in 13 cases (see also Fig. 6). A direct link from the infrastructure modernization investment action situation (IINV) to SAV was reported in 8 cases. Out of these,

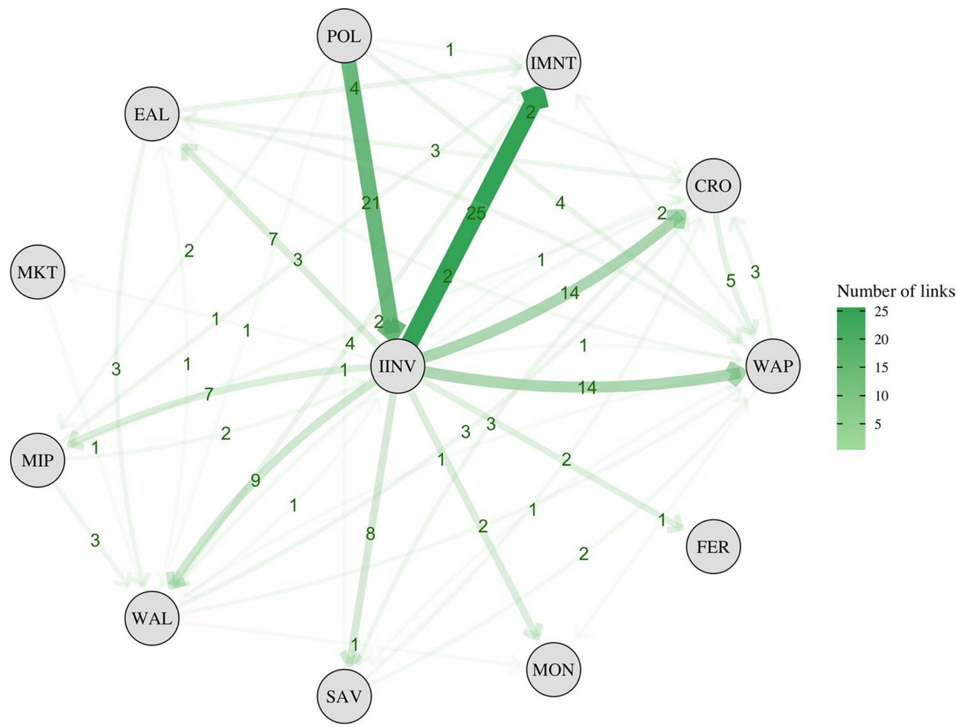


Fig. 6 Dyads of linked action situations represented as a network. The thickness of the arrows represents the number of studies reporting on that link. *WAL* water allocation, *WAP* water application, *CRO* Cropping, *IMNT* infrastructure maintenance and operation, *IINV* infrastructure investment, *MON* monitoring, *POL* policy, *EAL* energy allocation, *MKT* water market, *MIP* management improvement, *FER* fertigation, *SAV* water-saving

three connect water use efficiency increase to increases in water consumption or depletion, which provides evidence for the rebound effect. In contrast, two cases assert water savings, in one case helping to recharge an aquifer. The remaining three cases are ambiguous, as they acknowledge a fraction of freed-up water associated to modernization without making claims on whether it is allocated towards consumption or conservation. In another 5 cases, SAV was linked to the outcomes of other action situations, including the cropping (CRO), state policy (POL), and water application (WAP) situations.

The highest number of links identified (98) originate in the IINV situation. This can be attributed to our explicit focus on modernization studies. The link mentioned by the largest number of cases (25) is that between the IINV and the infrastructure maintenance (IMNT) action situations. In 8 of the 25 cases, the link speaks about an increase in operation and maintenance costs after modernization. Six other cases describe how irrigators had to employ technical staff or a private company for operation and maintenance due to the need for technical expertise, and 5 other cases mention a change in operation and maintenance practices for irrigators themselves. The remaining cases point towards changes in operation rules, improved working conditions, and the introduction of new communication devices such as remote control.

A relatively high number of studies also report links from IINV to the water allocation (WAL), cropping (CRO), and water application (WAP) situations. Links to the WAL situation are recognized in 9 cases. Six out of these report changes in the allocation procedure, mostly (4) from "turns" to "on-demand" allocation. The other three links are associated with cases where modernization led to improved compliance to distribution rules, the requirement for additional coordination effort, and an improved scheduling of water volumes, respectively. Links from the IINV to the cropping (CRO) situation are reported in 14 studies. Nine of them state changing cropping patterns in general or for specific crops, two cases estimate the crops after modernization to be of higher value, and another 2 cases describe the movement towards more intensive cropping or a more productive crop. We also found links from the IINV to the water application (WAP) situation in 14 cases. Eight of them point to the expansion of irrigated land, four remark on a reduction in water applied (without referring to water consumption), one case describes a reduction in quantities of water supplied, and another case states that the timing of extractions changed after modernization.

IINV was also linked to the monitoring (MON), energy allocation (EAL), and management improvement (MIP) situations in 7 cases each. Linkages typically report changes to automated monitoring or metering systems, increases in energy costs, and institutional and managerial reforms, respectively. The studies also provide linkages from the IINV to the fertigation (FER) situation, pointing to changes in fertilizer management (4 cases) and changes in fertigation costs (2 cases). IINV was linked to the market (MKT) situation in only one case study (van der Kooij et al. 2015):

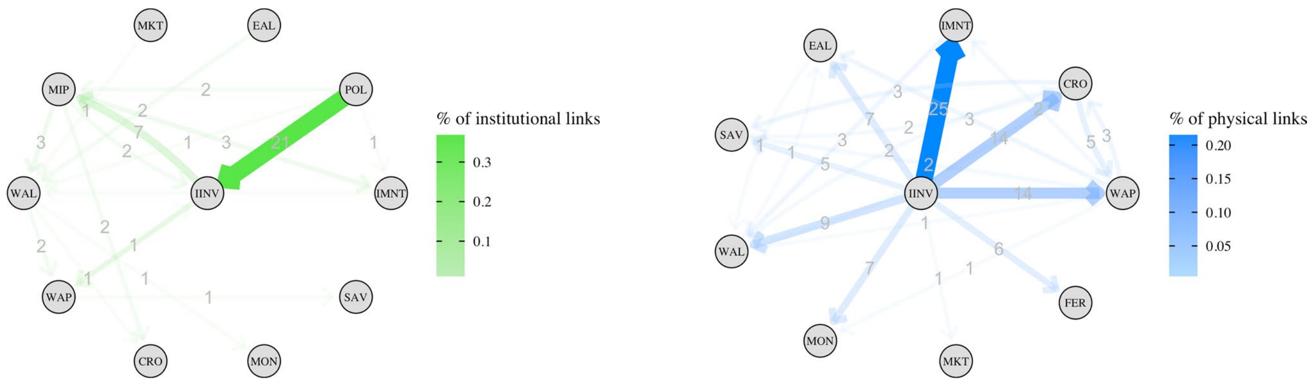


Fig. 7 Dyads of linked action situations categorized according to their institutional (left) and physical (right) nature. The number shows the count of each link while the thickness and opacity represent their relative occurrence within each category. The network of informational links is omitted here due to the low frequencies

modernization enabled a better control over water allocation and use and this facilitated water exchanges among farmers within the system.

Importantly, authors report an influence of the modernization policy action situation (POL) on the IINV situation in 21 cases. All the cases mentioned governmental (or, in one case, NGO) support for modernizing the irrigation system through subsidies. Conversely, we could not identify links directed at POL, although many authors acknowledge the role of influential groups and lobbying organizations in shaping agricultural policies (e.g., Dessalegn and Merrey 2014; van der Kooij et al. 2015; see also discussion).

The exploration of types of linkages reveals additional insights (see Fig. 7). Overall, out of the 192 links in the database, 29% and 62% are represented by institutional and physical linkages, respectively. The most salient linkages for each category are the subsidies that incentivize modernization investments (institutional; POL → IINV) and the infrastructural modifications that affect operation and maintenance aspects (physical; IINV → IMNT), including working conditions, remote control services, and the hiring of technical staff or the outsourcing of certain tasks.

Institutional links connect 11 out of the 12 action situations, showing the relevance of rules and property rights in collective irrigation governance. This is telling, given that most of the studies reviewed are not institutional analyses per se. Other than modernization subsidies that link POL to IINV (38% of the institutional linkages network), more than three linkages only exist between IINV and MIP (13%), which include mostly institutional reforms of practices.

Physical links are mainly the outcome of the infrastructural change and, therefore, depart most frequently from IINV to 9 other action situations. Other than the above-mentioned links between IINV and IMNT (22% of the physical linkages network) non-deniable links are also identified between IINV and WAP, as e.g., when the new technology allows increases in water application rates and/or irrigated acreage; or between IINV and CRO, as, e.g., when the new technology allows for cropping high-value crops.

Additionally, we found only 17 informational links (9% of all links). This may relate to the difficulties that we found in finding linkages that were purely informative and not institutional or physical (see S2 for examples). Finally, we did not find actor-based linkages; farmers were the main actors involved in all the action situations identified, except for the POL situation. None of the studies reported on, e.g., whether certain organizations or leaders played any role in connecting situations.

Discussion

Studies addressing the effects and consequences of modernization processes have grown in number over the last years. Much of this literature is based on modelling approaches which simulate the performance of infrastructural and technological reforms under different scenarios (Pérez-Blanco et al. 2020). In this study, we focus on actual evidence on water-use and consumption changes in an attempt to shed new light on the rebound effects associated to said reforms.

A diversity of action situations

Several of our findings illustrate strengths and deficits in the literature on irrigation rebound effects. Although a fair number of studies identify the reasons for modernization improvements, only half measure how water-use was affected by modernization, and only 17 report whether

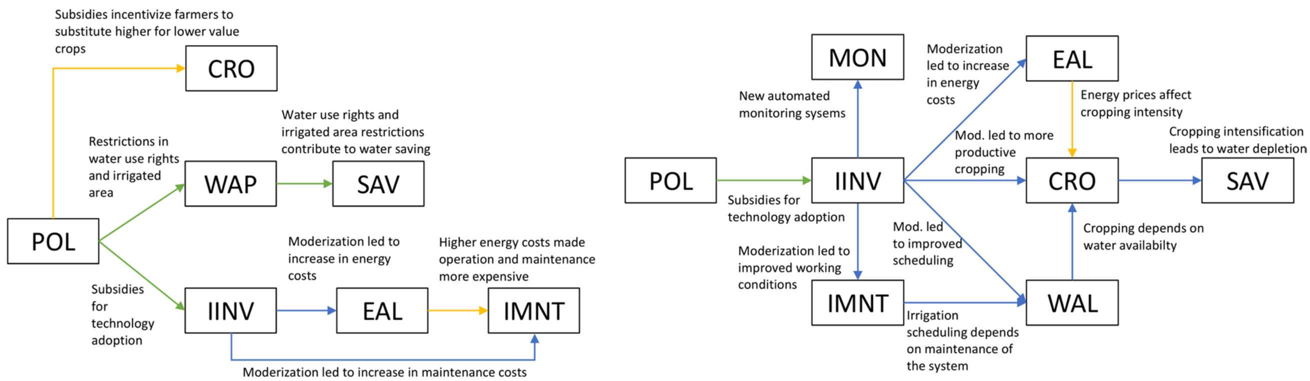


Fig. 8 Networks of Action Situations for Berbel et al. (2015), left, and Lecina et al. (2010a), right. Note: The networks have been reconstructed by "putting together" the dyads identified for the main analysis. Green arrows represent institutional linkages; blue arrows represent physical linkages; and yellow arrows represent informational linkages

water was saved. These variables need be considered more thoroughly in future research. Among the cases that assess water-use changes, most of them do consider changes in both water application rates and environmental returns, which is good news considering the tendency in the past to ignore the distinction between water use and consumption (Dumont et al. 2013). An important finding of the study is the relatively high and diverse number of action situations that we found per case, which illustrates the need to look at modernization effects from beyond a one to one relationship between the infrastructure investments and water savings (Perry et al. 2017; Sears et al. 2018). Two other findings we want to highlight in this section refer to the potential of pathways thinking and the distinctiveness of the water-saving situation.

The potential of NAS for pathway thinking

The process of linking dyads of action situations has proven itself useful to start uncovering the complexity of modernization investments and their effects on water savings. As explained in the methods, we did not code for networks of action situations due to the difficulties of doing it without much interpretation from our part.

Thus, although our data show how studies linked water saving to modernization and to other situations, it does not show whether and how all those situations were interrelated. Despite this, we can still make some speculations about those cross-situational pathways or networks. One example of such a pathway, and an illustration of achieved water savings (Fig. 8), builds on Berbel et al. (2015). Here, the government partially subsidized the investment costs for installing micro-irrigation (POL → IINV) in the Guadalquivir River basin, Spain. However, farmers needed to comply with certain conditions to receive the subsidies, including the reduction of their water rights and a proscription to increase the irrigated area (POL → WAP). As pointed out by the authors, these constraints contributed to actual water savings (POL→ WAP; WAP → SAV), which are used by the government to fulfill environmental flow standards. Additionally, the case also describes farmers changing cropping patterns (towards crops of higher value, as citrus and vegetable crops) as a result of the policy (POL → CRO), likely because of the reduction in water rights. Moreover, the increased electricity costs after modernization led to higher operation and maintenance costs (IINV→ EAL; EAL → IMNT). Nevertheless, no links connect these action situations to SAV.

On the contrary, Lecina et al. (2010a) illustrates how subsidized investments in sprinkler irrigation (POL → IINV) in the Ebro River basin, Spain, resulted in an increase in the proportion of high-value, high-water demand crops (IINV → CRO) like horticultural crops, orchards, and summer crops; and how these resulted in an increase in evapotranspiration (CRO → SAV) (Fig. 8). As the authors further illustrate, pressurized irrigation also comes with automated monitoring systems (IINV → MON); and allows for more fine-grained irrigation scheduling (IINV → WAL), which favors increases in crop productivity (WAL → CRO). That being said, the control over irrigation scheduling depends on system maintenance (IMNT → WAL), which is affected by improvements in labor conditions associated to the modernization (IINV → IMNT), and changes in energy prices (among other agricultural input prices) (IINV → EAL) affected the willingness of farmers to intensify cropping (EAL → CRO).

The two examples above demonstrate that our data allow to build analytic narratives in terms of networks of action situations (Kimmich 2016). As shown above, the networks can vary notably across case studies even if relying on a similar set of action situations. At the same time, it is likely that there are different pathways leading to similar outcomes and quite similar pathways that lead to different outcomes. Further research should identify and test those patterns (see Villamayor-Tomas et al. 2020b for a method that could be adapted for that purpose). This would inform not only better irrigation water-saving practices but also our knowledge on sustainability transitions of socio-technical systems more broadly (Markard et al. 2012). Water-saving policies are promising levers to transition towards more resilient and sustainable irrigation systems (Pérez-Blanco et al. 2020). As illustrated here, governmental policies in the form of infrastructure improvement subsidies can be quite effective at initiating said transitions and result not only in water savings but also in improvements in water allocation and infrastructure maintenance and management.

The distinctiveness of the water-savings situation

Our results also show that conceptualizing the water-saving situation as a distinctive situation offers analytical traction to further understand behavioral dynamics behind the rebound effect. Specifically, we posit that water users perceive water savings as a "separate" resource, which is in line with the concepts of the paracommons (Lankford 2013) and mental accounting (Thaler 1999). Inherently, the decision of how to allocate the freed-up fraction of water takes the form of a social dilemma. Modernization investments open the possibility to save water for environmental conservation or for other water users; however, farmers perceive modernization as a means to increase production and yield rather than to conserve water (Benouniche et al. 2014). This makes the dilemma of saving vs. using the water nontrivial and calls for policy interventions. Policymakers should consider redistributing the incentives between promoting higher efficiencies and encouraging water conservation, as it has been done, for example, through payment for ecosystem service schemes (Fisher et al. 2010; Lima et al. 2019). Furthermore, CPR theory suggests that social dilemmas in natural resource use can be overcome by collective action and strong institutions (Ostrom 1990; Poteete et al. 2010). Collective action in irrigation communities is realized by adherence to rules and norms, bottom-up participation in decision-making processes, and collaboration in collective tasks. Thus, water-saving as a goal might be easier to achieve if the community as a whole is persuaded to take ownership over the need to self-organize and to promote water-conserving behavior. The case of the Eastern La Mancha aquifer in Spain, for instance, shows that even in a context of severe overexploitation and mistrust, inducing cooperative behavior among farmers is possible through the promotion of self-regulation by the government, collective control of extractions (monitoring), and cultivation plans (Lopez-Gunn 2003; Esteban and Albiac 2012). Similar approaches may work when planning for modernization processes, even though the choice of the correct solution needs to be considered carefully depending on the situation at hand (Villamayor-Tomas et al. 2019).

An interesting point to consider regarding the water-saving situation is the role of biophysical conditions. Whether farmers appropriate water from a surface or groundwater pool might be a relevant biophysical factor influencing the efficiency paradox, as groundwater inherits the characteristics of a local common good and surface water those of a global common good (Stern 2011).

Our data are limited to explain this connection. Our review includes 20 surface irrigation cases and 4 groundwater cases. The number of cases where actual water savings were reported is 1 and 2, respectively. Although difficult to interpret, these results trigger some reflections about the role of resource system characteristics. By default, groundwater systems are less visible and, therefore, incentives for saving water might be lower; however, the incentives for water users in surface systems could also depend on their location along the basin. Further research shall thus explore this and other related conjectures and their influence on the water-saving situation.

Limitations and further research

The study also sheds light on data gaps that should be addressed in further research. First, the only action situation being influenced by IINV and not affecting any other action situations in our review is the monitoring situation MON. This was surprising for us, as monitoring is a key action situation in the management of CPRs at large (Slough et al. 2021). Further primary research shall explore whether our findings are an artifact of the empirical choices made by the authors of the reviewed studies or are indeed worth explaining.

Second, about half of the studies reviewed do not report water savings, which limits our ability to draw quantitative conclusions about the efficiency paradox. Qualitatively, however, the few studies that do report on water savings can provide interesting insights through the NAS lenses about pathways that would explain the complexities behind the rebound effect. As shown here, the modernization investments on water savings are mediated by what farmers do vis-à-vis water allocation, infrastructure maintenance, monitoring, or energy allocation, and would indeed be key to better understand the origins and potential solutions to the rebound effect.

Third, a blind spot in irrigation research are power dynamics and their influential role in (strategic) decisions. Our results show unidirectional linkages from modernization policies POL to other action situations, but not vice versa. Revisiting the case studies from our sample and conducting a keyword search for 'power' and 'lobby*', we found 6 cases that acknowledge power dynamics but fail to establish a direct link between them and modernization policies. Such linkages need to be recognized and incorporated more thoroughly into institutional analyses, as has already been proposed by other scholars (Clement 2010; Bennett et al. 2018).

Our own approach and choices are also subject to several limitations. First, 24 of the studies included in the review assess Spanish irrigations systems. This is mostly due to our search strategy, which partially relied on 4 preselected studies, 3 of which were based in Spain. Thus, our findings may not be entirely generalizable to a wide diversity of contexts. At the same time, they would apply quite well to the Spanish one. This is not ideal but neither that limiting. The fact that 3 out of the 4 preselected studies were located in Spain is telling of the quality (as per our selection criteria) and the momentum of irrigation modernization and rebound studies in this country. It also indirectly speaks about the cutting-edge work that Spanish practitioners and researchers have been carrying out on irrigation over the years.

Second, in this study, we focused on WUAs that have quite some managerial autonomy with regard to key irrigation management tasks (e.g., water allocation, maintenance, investments etc.); however, it is not unusual that WUAs share some of those tasks with public authorities or others (Hunt 1989; Frey et al. 2016). Further research shall explore more in detail whether the action situations and linkages identified here would still be relevant in co-managed systems or similar governance arrangements.

Third, although we excluded modelling studies from our study, we recognize the value of our analysis to conceptualize future models that formalize and explore different sets of the linkages presented here. Sensitivity analyses could be quite informative of the cascading effects of different water-saving interventions across action situations (see Kimmich and Villamayor-Tomas 2019 for a similar diagnostic approach).

Fourth, we only identified the existence of linkages from one action situation to another, but not whether the outcome of one action situation had a negative or positive effect on the outcome of the adjacent situation. As was shown, modernization investments affected energy allocation through increased energy costs in a fair number of cases but not in all of them (in one case the effect was the opposite). An explanation of the direction of outcomes needs to be addressed through more thorough analyses of the contextual factors that shape decisions within the action situations, and in particular the modernization and saving situations.

Fifth, finding evidence on informational links was challenging. We found it difficult to disentangle institutional and biophysical links from informational links (as information can refer to both institutions and biophysical conditions). In the end, only the evidence we could not categorize as institutional or biophysical was classified as informational links. Further research should better conceptualize and operationalize informational links as compared to the other types.

Sixth, based on data availability, we decided to include decisions associated with cultivated acreage into the water application situation, and collapsed the energy application and allocation situations into one. This rather inductive approach to draw the boundaries of action situations should, however, be tested and complemented with more deductive approaches, e.g., based on existing archetypes of games (Kimmich and Villamayor-Tomas 2019; Bruns and Kimmich 2021).

Finally, we have focused on identifying action situations and linkages. We have not featured the situations themselves (e.g., farmer's decisions and the factors that shape them within each situation) for lack of data. Identifying the situations was indeed already quite challenging because the authors barely get into behavioral dynamics and just focus on variables and outcomes. Thus, our results should be taken with caution: although we are positive about the linkages between the action situations, we cannot say much about the actual decisional dynamics within each, or even whether some of the non-typical action situations here identified (like the cropping, fertigation, or management improvement situations) are totally relevant with regard to strategic decision-making.

Conclusion

Rebound effects in water consumption in the aftermath of modernization investments in irrigation systems are part of complex processes that have yet to be fully understood. This is all the more important given current pressures around transitioning towards more sustainable agricultural practices (El Bilali 2019). In principle, the rebound effect can be explained according to the argument that a higher water use efficiency leads to higher productivity, which translates into farmers expanding their irrigated area, intensifying their production, or switching to higher value but also higher water-demand crops. To better frame and understand the behavioral dynamics involved in that process, we conducted a meta-analysis of 37 case studies describing irrigation modernization processes and their effects in collectively managed irrigation systems. We organized the coding around the idea of adjacent action situations in an attempt to shed light on the strategic decision-making situations that farmers are confronted with as they participate in modernization investments and adapt to the new infrastructure.

As shown in our results, it is possible to meaningfully understand relevant variables as either outcomes of or factors in strategic decision-making situations (action situations). Here, we identified 12 of those situations, and 192 institutional, physical, and informational links that connect them. Also, our findings illustrate that the connection between modernization and water savings is not as straight forward as frequently portrayed. First, although some studies report on linkages between the modernization investment and water-saving situations, many other studies also link those two situations to situations not strictly connected with modernization processes but to the collective management of irrigation systems (like the water application, infrastructure maintenance, or monitoring situations). Second, a number of those situations potentially involve social dilemmas and coordination problems that need to be integrated in analyses. Here, we pay special attention to the water-saving situation, which we frame as a public goods dilemma that confronts farmers with the decision of reusing the freed-up water (private benefits) or conserving it for reuse by others (common-pool benefits) or environmental purposes (public benefits). The evidence about increases of water-use in the aftermath of modernization processes aligns with economic predictions about the inability of farmers and governments to overcome the dilemma. By the same token, however, this understanding also calls for a more active involvement of farmers and irrigation associations in the management of the dilemma, as they have done already in the context of other collective irrigation management situations. Overall, it would be desirable to incorporate collective action dynamics and institutional analysis more systematically in the study of the manifold drivers of and potential solutions to the rebound effect. This should in turn contribute to more realistic water-saving policies in the sector.

As a final reflection, the collected data show that there is sufficient material in the literature to speculate about causal pathways that connect modernization investments and water savings. As illustrated here, it is possible to build networks of action situations after a first identification of dyads of them. In our view, advances in this direction will require expanding primary research on the behavioral dynamics within specific situations or pairs of them, as well as new meta-analyses that synthesize primary research.

Appendix

See Fig. 9 and Tables 2, 3.

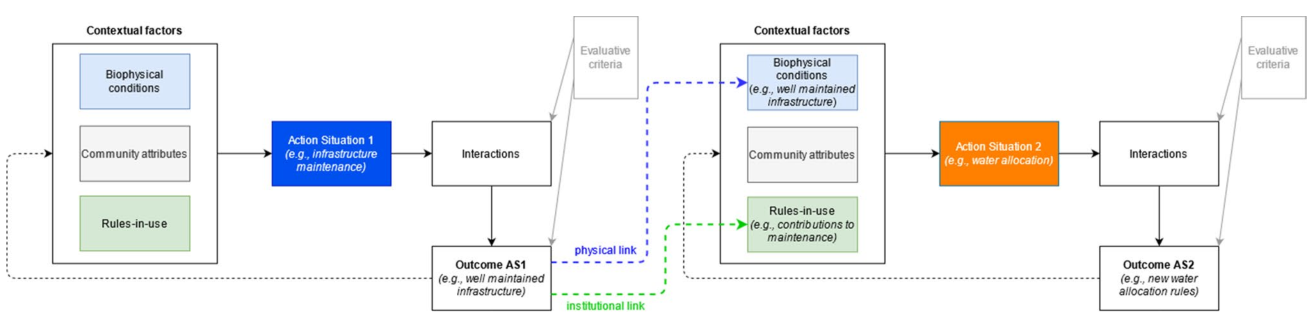


Fig. 9 Extended IAD framework. The thick arrows depict stylized examples for a connection between the outcome of Action Situation (AS) 1 and the contextual factors of Action Situation (AS) 2. Examples are presented in italic. Source: own elaboration

Table 2 List of variables

	Variable	Definition	Answer
General information			
	Country	Country where the study is located	Name of the country
	Country region	Country region/s where the study is located	Name of the country region/s
	Water basin	Name of the studied water basin/s	Name of the basin/s, n/a
	Irrigation district	Name of the studied irrigation district/s	Name of the district/s, n/a
Biophysical variables			
	Water source	Type of source of the water used in the agricultural production process	Surface water, groundwater, treated wastewater
	Water supply	Quantity of water supplied to the system (per year)	m^3/year, n/a
	Irrigated area	Area of land under irrigation	ha, n/a
Infrastructural and technological characterizations			
A	Technology0	Irrigation technology used before modernization	Furrow, sprinkler, drip
	Technology1	Irrigation technology used after modernization	Furrow, sprinkler, drip
B	Improvement	Type of infrastructural improvement of an existing technology that improves water use efficiency, and which parts of the system it concerns	Canal lining, Capacity increase
	Purpose	Stated purpose of the modernization	Water saving, productivity, supply increase, development
Outcomes			
	Water use	How did water use change after modernization?	Increase, deacrease, no change, n/a
	Water saving	Was water saved after modernization?	Yes, no, n/a
Action situations			
	WAL	Does the case inform about farmers engaged in interdependent water allocation decisions?	0, 1 (0 for no, 1 for yes)
	WAP	Does the case inform about farmers engaged in interdependent water application decisions?	0, 1
	CRO	Does the case inform about farmers engaged in interdependent cropping decisions?	0, 1
	IMNT	Does the case inform about farmers engaged in collective operation and maintenance decisions?	0, 1
	IINV	Does the case inform about farmers engaged in collective modernization investment decisions?	0, 1
	MON	Does the case inform about farmers engaged in collective monitoring decisions?	0, 1
	POL	Does the case inform about state policies that have a direct effect on decision-making processes?	0, 1
	EAL	Does the case inform about farmers engaged in interdependent energy allocation decisions?	0, 1
	MKT	Does the case inform about the existence of a water market?	0, 1
	MIP	Does the case inform about farmers engaged in interdependent management improvement decisions?	0, 1
	FER	Does the case inform about farmers engaged in collective fertigation decisions?	0, 1
	SAV	Does the case inform about farmers interdependently deciding upon allocating water savings due to efficiency gains?	0, 1

Table 3 Examples for coded linkages

Information found in article	Interpretation
The volume of water flows depends on the maintenance of the structures. (study id:14a, p. 273)	We can identify a link between the action situations WAL and IMNT, namely that the outcome of IMNT affects the WAL
Energy tariff impacts timing of water pumped. (16a, p. 71)	The choice of the energy tariff in a collective irrigation system is described by EAL, whose outcome changes the water allocation rule and therefore the WAL
This higher cost was due to new operating and maintenance costs, particularly because the cost of energy increased from an average of 25% of total water costs before the investment, to around 43% after the conversion. (1b, p. 666)	As a consequence of the technological conversion from furrow to drip (IINV), operation and maintenance (IMNT) was affected by higher costs. Furthermore, higher energy costs will affect the situation of choosing an energy tariff in EAL, which in turn affects IMNT

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