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The Water-Energy-Food Security Nexus through the Lenses of the Value Chain and the Institutional Analysis and Development Frameworks

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ABSTRACT: A number of frameworks have been used to study the water-food-energy nexus; but few of these consider the role of institutions in mediating environmental outcomes. In this paper we aim to start filling that gap by combining insights from the Institutional Analysis and Development (IAD) framework and value chain analysis. Specifically we study food, energy and water value chains as networks of action situations (NAS) where actors' decisions depend not only on the institutional structure of a particular situation but also on the decisions made in related situations. Although the IAD framework has developed a solid reputation in the policy sciences, empirical applications of the related NAS concept are rare. Value-chain analysis can help drawing the empirical boundaries of NAS as embedded in production processes. In this paper we first use value-chain analysis to identify important input-output linkages among water, food and energy production processes, and then apply the IAD-NAS approach to better understand the effect of institutions within and across those processes. The resulting combined framework is then applied to four irrigation-related case studies including: the use of energy for water allocation and food production in an irrigation project in Spain; the production and allocation of treated water for food and bioenergy production in Germany; the allocation of water for food production and urban use in Kenya; and the production and allocation of energy for food production in Hyderabad, India. The case analyses reveal the value of the framework by demonstrating the importance of establishing linkages across energy, water and food-related situations and the ways in which institutions limit or facilitate synergies along the value chains.

KEYWORDS: Water-energy-food nexus, Institutional Analysis and Development framework, Socio-Ecological Systems Framework, value-chain analysis, irrigation cases

INTRODUCTION

The nexus approach is becoming increasingly popular among practitioners and scholars, as illustrated by the number of publications devoted to the topic in recent years (Hellegers et al., 2008; Waughray, 2011; Hussey and Pittock, 2012). A number of frameworks have been used to study the water-food-energy nexus, but few of these consider the role of institutions in mediating behavioural and environmental outcomes. This is not a trivial omission, as one of the central questions for nexus scholars is to assess the social and ecological effects of alternative policies (Scott et al., 2011). This paper aims to provide a tool to start addressing that institutional analysis gap. Specifically, the paper links the Institutional Analysis and Development framework (IAD) and the related network of action situations (NAS) concept to value-chain analysis, and illustrates its added value with a series of local water-food-energy management cases.

The nexus approach is a somewhat ambiguous, but nonetheless conceptually useful and increasingly popular perspective (Schnoor, 2011; Steduto, 2011). The emphasis of linkages among subsystems constitutes the theoretical core of the nexus approach which argues that although subsystems such as food, water and energy can be analysed independently, doing so would overlook the multiplicity of feedbacks and interdependencies that jointly affect the sustainability of the broader social-ecological system (Hellegers et al., 2008; Waughray, 2011; Ganter, 2011; Hussey and Pittock, 2012).

The nexus approach begins by identifying two or more resources that are often broadly defined in terms of food, water or energy within a particular geographic or sociopolitical boundary. It then continues by quantifying resource use and the ways in which the use of one resource affects the other to affect the sustainability of the interconnected social-ecological system. Stilwell et al. (2011), for example, consider the energy-water nexus in Texas, and focus their analysis on 'water used for energy and energy used for water'. They find that energy production in Texas consumes enough water to provide for the needs of approximately 3 million people, while the energy used for water treatment could provide enough power for about 100,000 people. Therefore they argue for greater attention on the linkages between energy and water subsystems, and for the design of policies that account for their fundamentally interconnected nature.

Much of the research has tended to focus on the existence of trade-offs (Ganter, 2011). As a representative example, Dalla Marta et al. (2011) consider the relationship between water use and energy crop production in Tuscany, Italy, and find that in most scenarios the total energy required to produce biofuel crops would exceed the total energy stored in those biofuels. Moreover, even in those scenarios where energy production exceeds inputs the water used for irrigating maize crops could have a significant impact on water availability for food production and domestic needs. In other words, biofuel production in Tuscany is unlikely to contribute to the sustainability of the interconnected water, energy and food social-ecological system. Similar assessments have been carried out in other contexts, including Spain (Hardy et al., 2012), Arizona-US (Perrone, et al., 2011), Australia (Newell et al., 2011), The Netherlands (Bonte et al., 2011), India and China (Malik, 2002; McCornick et al., 2008; Molle et al., 2008; Kahrl and Roland-Holst, 2008; De Fraiture et al., 2008; Rajagopal, 2008), Sri Lanka (Molle et al., 2008), as well as the Middle-East and South-Africa (Siddiqi and Anadon, 2011).

As mentioned earlier, a number of frameworks have been used to assess water-energy-food dynamics, including a life cycle analysis (LCA), material flows analysis, and value chains (Bazilian et al., 2011). All of these frameworks share a process-based approach to resource use and a preference for systems analysis and modelling over other empirical strategies. This can be useful to study water-food-energy inter-linkages (Hussey and Pittock, 2012), but is limited to a rather narrow and highly technical range of research questions; neglecting the very important role of institutionally mediated human agency. In what follows, we propose to address this deficiency by bringing insights from institutional analysis in an attempt "to move the water-nexus construct beyond an input-output relationship into the realm of resource governance" (Scott et al., 2011). Specifically, we combine the value chain framework (Kogut, 1985; Kaplinsky and Morris, 2001) with the Institutional Analysis and Development (IAD) Framework (Ostrom, 1994; Schlager, 1999), that has been used to great success in the study of socio-ecological systems (Ostrom, 1990, 2007, 2009; McGinnis, 2011a; McGinnis and Ostrom, 2014). From this combined perspective, policies are understood as amalgams of interacting institutions that shape either directly or indirectly the use and production of water, energy and food resources and thus potentially mediate the emergence of trade-offs and synergies across different production chains.

The value of a combined value chain-IAD approach is put to the test in a series of cases from the irrigation sector where there is a strong role of institutional dynamics and cross-resource interconnections. Interactions between water, food and energy use are highly prevalent in the irrigation sector. According to the UN World Water Development Report (Water, 2012), water used for irrigation and food production accounts for approximately 70% of global freshwater withdrawals and up to 90% in some fast-growing economies (Water, 2012). Moreover, 20% of cultivated land depends upon some form of irrigation which in turn accounts for about 40% of global food production (Water, 2012). Finally, 8% of global energy production is used to pump, distribute or treat water (Water, 2012), with irrigation accounting for up to 15-20% of energy use in some countries like India (Bazilian et al., 2011). But water can also be used to produce energy and, in fact, hydropower represents the largest renewable source of electricity generation (15% of global production in 2007), and it is estimated that two-thirds of the world's economically feasible hydropower potential remains to be exploited.

THEORETICAL FRAMEWORK

The IAD and SES frameworks

The approach developed for this analysis is based upon the IAD framework (Ostrom, et al., 1994). IAD is defined by its emphasis on the study of institutionally mediated action situations, wherein human actors interact with the environment and each other to make choices that ultimately affect joint outcomes in socio-ecological systems (SES). *Action situations* can be understood as spaces where actors make decisions and take actions where individual outcomes or pay-offs depend upon the actions of others (Ostrom, 1994). These spaces may be as formal as a legislative assembly passing laws, or as informal as a group of small-scale water users in a community deciding how to allocate a quantity of water or invest in maintenance of distribution canals. Although many action situations take place in a particular venue where actors physically come together to make joint decisions, the concept also applies to situations where individuals make choices independently that have resulting impacts on other actors. In the context of natural resources management, particularly salient action situations include rule-making, monitoring, sanctioning, information-sharing, and conflict resolution (McGinnis, 2011b; McGinnis and Ostrom, 2014). Successful resolution of an environmental problem typically requires that groups coordinate and cooperate around a particular institutional solution or strategy.[1]

Institutions are viewed as particularly important as they structure the incentives that actors face when they make choices from among a set of alternatives. These institutions are themselves the result of social processes and "consist of both informal constraints (sanctions, taboos, customs, traditions, codes of conduct), and formal rules (constitutions, laws, property rights)" (North, 1990).

As an extension for the study of SES, the framework looks at four main types of components, which include resource units, resource systems, actor groups and governance systems. A minimum of one

[1] The addition of sheep by herders in Hardin's (1968) pasture, for example, can be conceived as an 'appropriation' action situation where the addition of sheep by one herder reduces the quantity of grass available to the sheep of other herders. Although the actors never actually come together to make decisions (at least theoretically) their actions affect each other's pay-offs and can therefore be construed as if they had come together. In turn, institutions can thus be assessed with regard to their ability to promote cooperation among herders *vis a vis* their joint use of the pasture.

actor group and one resource system/unit can constitute an action situation. A simple example would be decisions by farmers about water appropriation from a shared water system. Action situations can, however, be more complex involving multiple actors, governance systems, resource systems and units. Resource allocation in a water system, for instance, can involve farmers, herders, drinking water and energy generation users, as well as the use of both surface water and groundwater resources, and different governance systems depending on the season or water availability.

Networks of action situations (NAS)

The essential point of the NAS approach is that the governance of social-ecological systems potentially involves many action situations that can be linked with each other via flows of resources, information or institutions which create networks of situations that jointly determine outcomes (McGinnis, 2011b). Archetypical examples of linked action situations in irrigation systems and similar common pool resources are appropriation and provision situations (Ostrom, 1994). Water withdrawals in irrigation systems, for example, depend upon choices made in appropriation situations; but also investment in infrastructure and maintenance that makes that water available for appropriation (Tang, 1991; Svendsen and Meinzen-Dick, 1997). More generally, linkages may occur horizontally, like in the previous example, or vertically, across different levels of choice. These include operational, collective-choice, and constitutional levels[2] (Kiser and Ostrom, 1982). Also, linkages can occur between resources, actors sharing resources and/or information, and governance interactions (Kimmich, 2013b).

Resource units and systems can be involved in multiple action situations; water in many irrigation systems around the world constitutes a critical resource to understand both cropping and energy use decisions. Also, institutions can shape outcomes in one action situation which, in turn, can affect adjacent action situations. Public regulations about land tillage, for example, can affect the efficiency of plot-level water applications, which, in turn, influences the allocation of water in plots. Institutions may also affect multiple action situations simultaneously. For example, water appropriation rules may be conditioned upon an individual's contributions to infrastructural maintenance, as is the case in many irrigation systems around the world (Tang, 1992; Lam, 1998).

Whereas analysis of single action situations can itself be a challenging task, analysis of multiple action situations is a significantly more difficult endeavour. To address this challenge, scholars have recommended focusing on outcomes from one or a small subset of action situations, i.e.; the focal action situations (McGinnis, 2011a). Once the focal action situation/s are defined, scholars can then begin to analyse a) how the situations are linked (e.g. via shared resources or institutions) and b) the direction of those linkages. In this process, the value-chain approach provides for an initial logic to identify physical linkages across the situations.

The value-chain approach

A value chain in its most basic form is "the full range of activities which are required to bring a product or service from conception, through to the different phases of production, delivery to final consumers, and final disposal after use" (Kogut, 1985; Kaplinsky and Morris, 2001). Every economic actor occupies a position in the value chain; upstream suppliers provide inputs before passing them downstream to the next link in the chain, the customer. Kaplinsky and Morris (2001) emphasise that production is only one

[2] Operational rules govern day-to-day activities of a set of participants; collective-choice rules govern the design and alteration of operational rules, and constitutional rules do the same for collective-choice rules. For example, farmers withdrawing water from an irrigation project on a daily basis make decisions in operational-level action situations, while the formal and informal rules that affect their choices are made in collective-choice action situations. Thus attempts to understand why farmers appropriate at a given level depend upon both decisions made in the focal appropriation situation and also the rules made in the more distal, but nonetheless influential, collective-choice situations.

of a number of value links in value chains, that there are a range of activities within each link and that these 'intra-chain linkages' are mostly bidirectional. For instance, activities in a particular link in a value chain are affected by the outputs of upstream activities; they must also take into account constraints in downstream links. Thus, using the value chain does not necessarily mean understanding action situations and their influence on each other in a sequential way; action situations at the end of the value chain can also influence action situations by the beginning or by any other sequence in the value chains.

The value-chain approach has been driven by a functional business view that evaluates costs and benefits and considers the added-value as a basis for competitive comparisons (Brown, 2009). But importantly for our purposes, the approach has been modified to analyse relationships between public policies and vertical integration processes, and to capture cross-sectorial and cross-spatial connections within production and distribution processes (Lenz, 1997; Raikes et al., 2000). This enhanced value chain approach allows us to identify resources, transactions and critical stages in the value chain, and to analyse the interactions of the varied participants (Kaplinsky and Morris, 2001; Kimmich and Grundmann, 2008).

Using the IAD framework and value chains to analyse the water-energy-food nexus

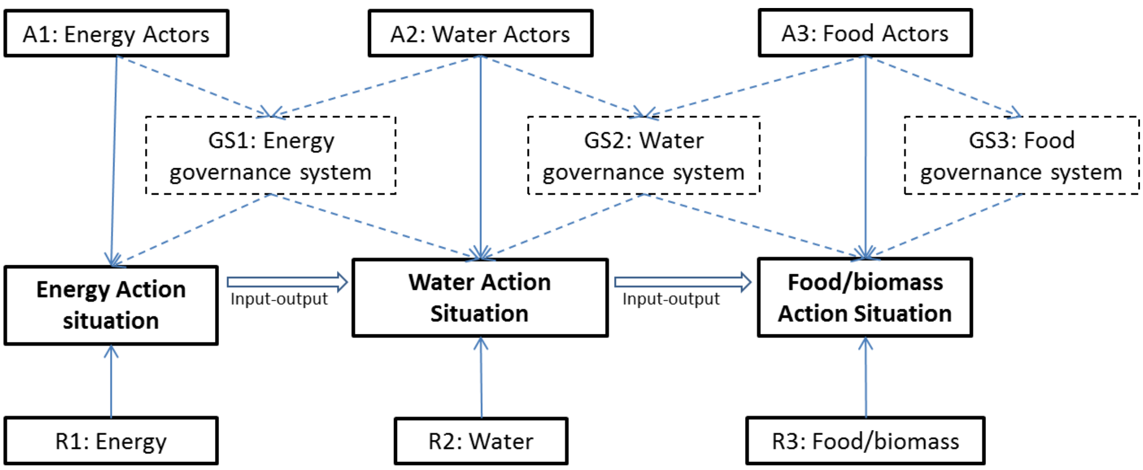
Although the IAD framework and value-chain approaches can individually illuminate interesting features of water, food and energy systems, we argue that a combined approach can help us to better understand system dynamics and therefore ways in which policies may affect sustainability outcomes at the water-food-energy nexus. First, the value-chain approach draws attention to the interface between processes of production and consumption for each resource and product, and the ways in which these processes are linked together as part of a system of input-output relationships. Specification of these mechanisms can be used to enhance the strength of causal claims by clarifying the direction of cause-effect relationships (Hedström and Ylikoski, 2010), and be used to evaluate the sustainability of the interlinked system and its component sectors. That said, value chains do little to explain how policies and other institutions influence behaviour leading to sustainable or unsustainable outcomes. Thus, the IAD framework complements the value-chain approach by focusing on the institutional structure of each link in the value chain and the ways in which this affects actors’ decisions in a variety of operational and collective-choice situations.

Participants in value chains have to deal with the hazard of opportunism and bounded rationality when they interact (Williamson, 2002). To reduce frictions, specific institutional arrangements are needed to manage the resource transactions and interactions of the actors (Williamson, 1985). Thus, empirical research on value chains can deliver insights to the question of "whether organisational relations (contracting practice; governance structures) line up with attributes of transactions" (Williamson, 1985). Maaß et al., (2014), for example, found that linkages and cooperation between actors of different value chains can increase resources use efficiency and reduce transaction cost trade-offs.

Through the combined IAD-value chain framework one could distinguish three interrelated situations – water appropriation, electricity appropriation and crop production – in the irrigation context. These interrelations can be conceptualised as a production chain where outputs from one situation affect the other, and jointly determine social and environmental outcomes. In effect, the choice to use energy as an input to withdraw and distribute water in a system (e.g. a system that depends on pumped water) may affect its availability in the water appropriation situation, offset some of the potential economic gains from water appropriation, and generate additional negative externalities (i.e. carbon emissions). By the same token, using water as an input to grow crops has important economic and ecological impacts in the food production process as compared to growing dry crops. Whereas the previous finding could be made using a value-chain analysis alone, the combined framework draws attention to the institutions at multiple levels (e.g. local rules and norms, agency regulations, national, national and European laws) that shape decisions both within and across the action situations. Thus, it allows us to evaluate how policies affect the production, distribution and/or appropriation of (1) energy in the energy sector (2) water in the water sector (3) energy in the water sector (4) water in the food production sector, and (5) biomass in the food production sector; and how these policies interact to affect the net sustainability of the interlinked system.

We begin by building the set of action situations and their respective institutional structures that drive decision-making in the system (see Figure 1). One potential, albeit unlikely, scenario is that there are no institutions regulating use of water, energy and food or their linkages. However, a more realistic scenario would involve at least one formal or informal institution and likely many more situations governing the use of each resource, and potentially their interactions (see dashed objects in Figure 1). As mentioned before, a particular advantage of the IAD value-chain approach for institutional analysts is that it allows us to consider transaction costs associated with multi-sector governance systems. Transaction costs are costs associated with gathering and sharing information as well as reaching and monitoring agreements. Transaction costs are also contingent on the characteristics that underlie the exchange of goods and services (Williamson, 1985) and collective-choice activities. In our running example of sprinkler irrigation, farmers might seek to address energy problems by generating their own energy (vertical integration) or purchasing it on the market. In both scenarios, specific institutions may be necessary to match the timing and quantity of energy supplies to water appropriation dynamics and/or vice-versa. However, efficient rules may fail to emerge if corresponding information-gathering, bargaining and monitoring costs, among other transaction costs, exceed the expected net benefits of a more sustainable system (Hagedorn, 2008).

Figure 1. Stylised flow chart representing potential input-output, actor and institutional linkages between resources.



Considering the components and linkages presented in Figure 1, we can begin to identify the situations in which the combined framework might apply, and the types of questions it might be used to address. First, it is designed explicitly for questions where outcomes depend upon interactions between two or more resources. Single resource problems would be far better and easier addressed using the aforementioned IAD framework. Second, it is appropriate for studies that aim to understand or evaluate policies and their effects on interlinked resources; rather than simply characterising the effects of the use of one type of resource on another, or the overall sustainability of combined resource use. With that in mind, we can begin to make some general propositions based on institutional theory and transaction costs economics, regarding the likelihood that policies will be able to successfully resolve complex water-food-energy problems.

The sustainability of water-food-energy nexus at local levels can be understood as a general equilibrium of cooperation and coordination pay-offs across water, energy and/or food-related situations (Kimmich, 2013b). More specifically, the institutional arrangements that successfully resolve cooperation and coordination problems are likely to depend upon the direction of input-output chains across water, energy and/or food situations. In other words, the effects of institutions are likely to vary depending upon their fit to the attributes of water-food-energy value chain. Second, when actors are involved in multiple action situations, they are more likely to recognise the structure of the situation they face, and devise institutions to account for the linkages across action situations than if they are not involved in those situations. Third, if resources in a value chain are truly linked, then policies affecting one resource are likely to affect the sustainability of the entire system. Fourth, and finally, transaction cost theory (Williamson, 1981) suggests that institutions that minimise transaction costs within and across situations would, ceteris paribus, be expected to be more efficient in facilitating the sustainability of water-energy-food systems than otherwise.

CASE SELECTION AND BACKGROUND

To illustrate the potential analytical value of the NAS and value-chain approaches to the water-energy-food nexus, we apply the framework to study four empirical case studies of irrigation water management at local levels in Spain, Germany, Kenya and India. The case studies are exploratory in nature, and are based upon data collected for other research projects. Thus, the analysis is not exhaustive but focused on the relevant components of each case. The cases share a similar irrigation context, which is particularly relevant to the water-energy-food nexus, as discussed in the introduction.

All the cases illustrate local manifestations of water-energy or water-food interactions in countries where water, energy and/or food security are of special concern. In Spain the energy-water nexus in the irrigation sector is of great importance due to current efforts to increase irrigation efficiency via pressurised pipes and sprinkler technologies, as well as the recent deregulation of the energy sector. This adds to historical concerns about water and energy scarcity and the priority given by the central government to encourage hydropower generation while accommodating the irrigation sector. In India, the energy-water nexus is also of great importance but for relatively different reasons. India is the world's largest groundwater user, with around 20 million wells, and growing. The groundwater boom has brought unparalleled economic growth but also important tensions in the energy sector, posing a dilemma to policy makers between preserving the benefits of water use and controlling its excesses (Scott and Shah, 2004). In Germany the energy-water-food nexus is of particular relevance given the increasing number of farmers using irrigation for energy crop production (Moss and Nolting, 2014; Bock und Polach et al., 2014) and the resulting competition between food and bioenergy production for scarce land resources. In Kenya, water-food nexus issues are particularly salient. There are many competing demands for water resources, and decision-makers face considerable challenges balancing these demands in the face of population growth and the prospect of climate-induced changes in water availability (Hogg, 1987; Davidson et al., 2003; FAO et al., 2012).

The cases were also chosen for important differences that allow us to explore the broad applicability of the framework. First, the cases illustrate varied combinations of the water-energy-food nexus, including two cases of energy-water (Spain and India) one case of water-food/energy (Germany) and one case of the water-food (Kenya) nexus. Second, the cases capture diverse institutional settings. Irrigation and drinking water management is carried out at the local level in all the cases. However, Germany, India and Spain have a longer tradition of decentralised management than Kenya, which devolved that authority at the local level only recently. The energy sector is liberalised in Spain, while in Germany and India it is regulated by the central government. Finally, food production in Germany and

Spain benefits from generous European income-support subsidies while, in Kenya, there are effectively no subsidies in place for most food production.

METHODS

Data collection strategies were contingent on the specifics of each case study. The Spanish case is part of the first authors' dissertation research. The governance structure and key actors in the water and energy sectors were characterised using secondary data (e.g. Lopez Galvez and Naredo, 1997; Nadal Reimat and Marquina, 1999; Iranzo, 2004). Evaluations of the dynamics involved water-food-energy interactions, and the mediating role of institutions in the local context was gained through focus groups with farmers as well as elite interviews with representatives of irrigation organisations and water authorities. The German case study is part of a joint research project funded by the Federal Ministry of Education and Research in Germany (BMBF). The characterisation of the institutional arrangements in the German case is based on primary information obtained from semi-structured in-depth interviews with the leaders of the communities and water boards, agricultural landowners and the operator of the energy production plant. The information basis for analysing the water-food/energy nexus was completed using secondary data (e.g. Ahlers and Eggers, 2004). The Kenya case was part of research associated with an NSF award through the Coupled Natural Human Systems program. Surveys with households and water project managers were used to construct a description of the governance arrangements in the watersheds and focus groups and informal interviews supplemented this information (McCord et al., in press). Surveys with caretakers of water infrastructure and managers were also conducted to document the rules related to maintenance of Water Resource User Association (WRUA) and water project networks (Dell'Angelo et al., 2014). Finally, information from monthly WRUA executive meetings provided insight into the decision of how and when to enact water rationing. The Indian case study was embedded in a large transdisciplinary research project funded by the BMBF on the water-energy-food nexus and involved an iterative combination of mixed methods and a pilot project with 800 farmers to test findings in practice.

The cases are analysed individually to (1) uncover the background and boundaries of each case, with a focus on a specific water-energy or water-food nexus; (2) identify the main actors involved; (3) the ways in which these actors manage linkages to address trade-offs and develop synergies; and (4) provide an assessment of the institutions that affect the development of linkages and outcomes.

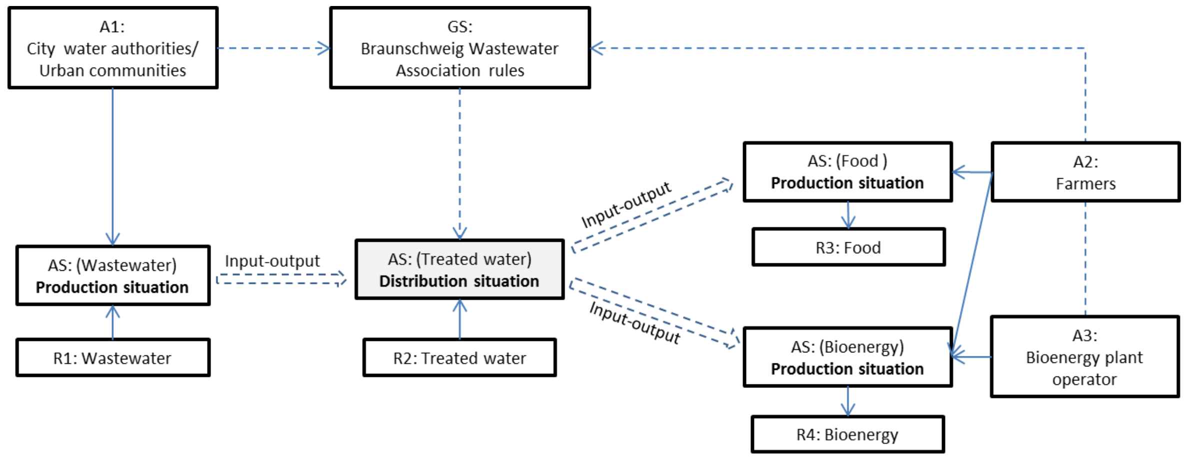
APPLICATION OF THE FRAMEWORK TO THE CASES

Germany: Braunschweig peri-urban area

The Braunschweig Wastewater Association (BWA) irrigation scheme is located in the State of Lower Saxony, Germany. Since 1954, it has managed the treatment of wastewater for the cities of Braunschweig and Gifhorn and distributes partially treated effluent to surrounding farms (~4300 ha). Braunschweig first used absorption fields (460 ha) for biological treatment in 1894, and can now process approximately 10,000 m^3 of wastewater per day. However, as population grew the absorption fields proved insufficient and resulted in the release of untreated run-off into the nearby Oker River.

Reorganisation of wastewater management was initiated by the city of Braunschweig according to federal and regional guidelines concerning water pollution control. Given the large quantity of wastewater requiring treatment it was immediately clear that absorption areas would have to be expanded. However, much of the surrounding landscape was already being used for agriculture which would have been expensive and difficult to acquire. Thus the city entered into negotiations with agricultural landowners, 550 of whom ultimately agreed to accept wastewater effluent on their fields for irrigation and treatment. This required the construction of a new pumping facility with mechanical primary clarification as well as a new organisational structure, the BWA, to manage conflicts and make operational decisions for wastewater treatment and distribution of irrigation water. As a result of various conflicts and technological developments, the BWA gradually increased treatment of wastewater prior to distribution by (i) introducing a 'meander system', and adding a (ii) sludge digester and biogas plant. Therefore, what began as a water treatment problem has now transformed into a complex interlinked water-food-energy system (Figure 2).

Figure 2. Water-food-energy nexus in Braunschweig.



Note: A: Actor, GS: Governance System, R: Resource; AS: Action Situation. Dashed single arrows represent institutional linkages across action situations. The numbering of the A, GS and R components does not follow any correspondence across the components (i.e. it follows an order from left to right). The same codes apply to the remaining figures.

The three main actor groups in this system are the communities and water boards (A1) that generate and treat wastewater, agricultural landowners (A2) who receive treated wastewater, and the operators of the biogas energy production plant (A3) (see Figure 2). The communities generate wastewater which is first treated by mechanical and biological methods and results in the production of sludge and purified water. One-third of the purified water is then distributed to infiltration fields while the rest is mixed with digested sludge and used as a nutrient-rich supply of water for agriculture during the growing season. The nutrient-rich irrigation water has allowed farmers to grow a wide variety of crops (sugar beets, maize, cereals and rape) that would otherwise be ill-suited to the sandy soils of the area, while the water is further treated by infiltration. In the winter, the sludge is dried and concentrated for sale in external markets. Finally, energy production is linked to both the treatment plant and farmers generating inputs in the form of sludge and energy crops (~38% of agricultural area), respectively. Thus the value chain in this case combines wastewater, energy and food.

The BWA case demonstrates how food, water and energy systems can individually and collectively benefit by developing synergies and linking production and other operational activities. The city benefits from the treatment of sewage water on agricultural fields; while also generating revenue from the distribution of solid and gaseous waste products to local markets. Farmers benefit from lower-cost fertiliser and irrigation water, and a local buyer for their energy crops. The energy-production plant benefits from locally sourced inputs that now serve the electricity and heating needs for approximately 6500 and 1250 households, respectively. However, important threats are now beginning to emerge threatening the viability of this system. First, the production of wastewater has been on the rise and, at times, the release of irrigation water exceeds the rate of soil infiltration leading to run-off. Second, during the critical summer months the supply of wastewater and rain has not always been sufficient and has required additional groundwater inputs. In this case, it is possible that the supply of cheap wastewater supplies has encouraged investment in crops that do not fit with the ecological context and have thus generated a negative externality in the form of increased water use. Finally, the use of sewage sludge as an input for agricultural production is threatened from several fronts. First, higher-level authorities have introduced legislation that prohibits the use of human sewage products on agricultural land. Second, although farmers benefit from the supply of nutrients and water, by choosing to irrigate with wastewater they are often forced to plant less-valuable crops due to consumer concerns. The BWA (GS) is reacting in close collaboration with the farmers to some of these threats, e.g. by coordinating the cropping plans of individual farmers, extending the irrigation period into the months of winter to respond to short-term rises of wastewater or storing water to compensate for water deficits during critical summer months.

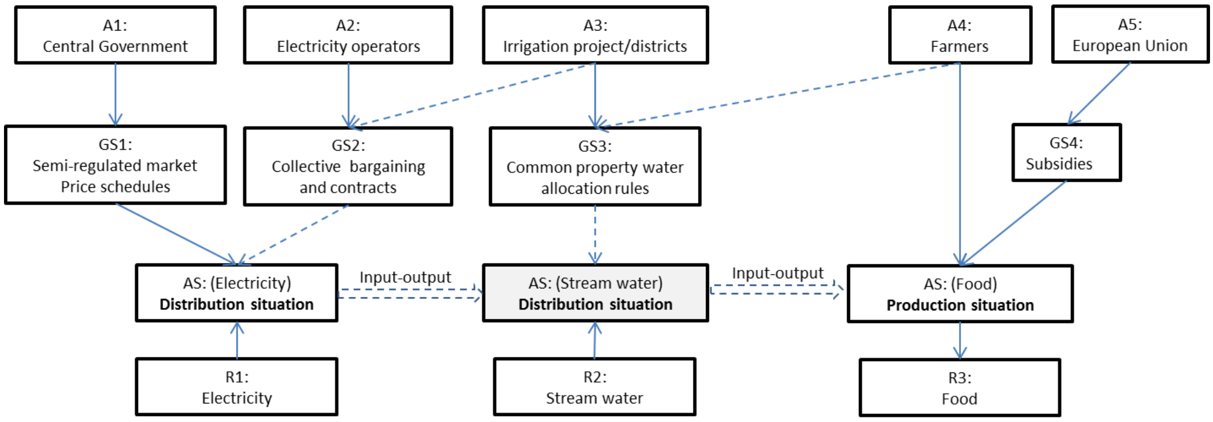
Spain: The Riegos del Alto Aragon (RAA) project

The RAA project is located in the Spanish region of Aragon, straddling the Gallego and Cinca river basins. A series of reservoirs and canals store and convey the water from the rivers to 50 irrigation districts, 100,000 irrigable hectares and more than 10,000 farmers. Water management in the RAA project is articulated at two levels of governance: Water User Associations (WUAs) operate at the irrigation district level and the General Community of RAA (GCRAA) operate at the project level. Ultimately, the water is served to farmers, each of whom is responsible for applying the water in their own plots.

The RAA project produces mostly wheat, barley, corn and alfalfa. Corn and alfalfa are grown from May to October and require considerable irrigation. The climate is semi-arid (average annual temperature 14 ^{o}C; average annual rainfall 300 mm) which makes water one of the main limiting factors in the food production chain. There are no rules preventing farmers from growing any crops they want in the land they own within the boundaries of the irrigation project. That is why a fit between water supply and water needs for food production should not be taken for granted (Subramanian et al., 1997; Lam, 1998; Villamayor-Tomas, 2014b). Over time, however, the RAA project and each of the districts within seem to have reached equilibrium between water supply and food production. This can be understood with regard to (1) a series of common property water allocation rules, which include, among others, the payment of water fees based on hectares irrigated and ad hoc use of water use quotas at the district level when there is water deficit (Villamayor-Tomas, 2014b); and (2) a European Union income-support system that relieves farmers from an excessive dependence on crop production (Villamayor-Tomas, 2014a).

A more interesting, and not fully solved trade-off is that occurring between water use and energy supply (see Figure 3). As a result of a heavy programme of governmental subsidies in irrigation technology improvements during the last decade, the average area per irrigation district devoted to sprinkler irrigation has increased from 22 to 44%, and the number of districts with some sprinkler irrigation increased from 17 to 28, most of which use electricity-fed pumping systems. This happened alongside the liberalisation of the electricity market in the late 1990s, which meant, among other measures, the suppression of preferential electricity tariffs for farmers (OMEL, 2012). The reform also meant a redesign of the regulated part of the price system, resulting in a schedule of peak and off-peak prices not well aligned with the timing of farmers' electricity demand. These changes put in jeopardy not only water allocation schedules in districts with electricity-fed irrigation but also the very economic viability of crop production in those districts.

Figure 3. Water-energy nexus in the RAA project (Spain).



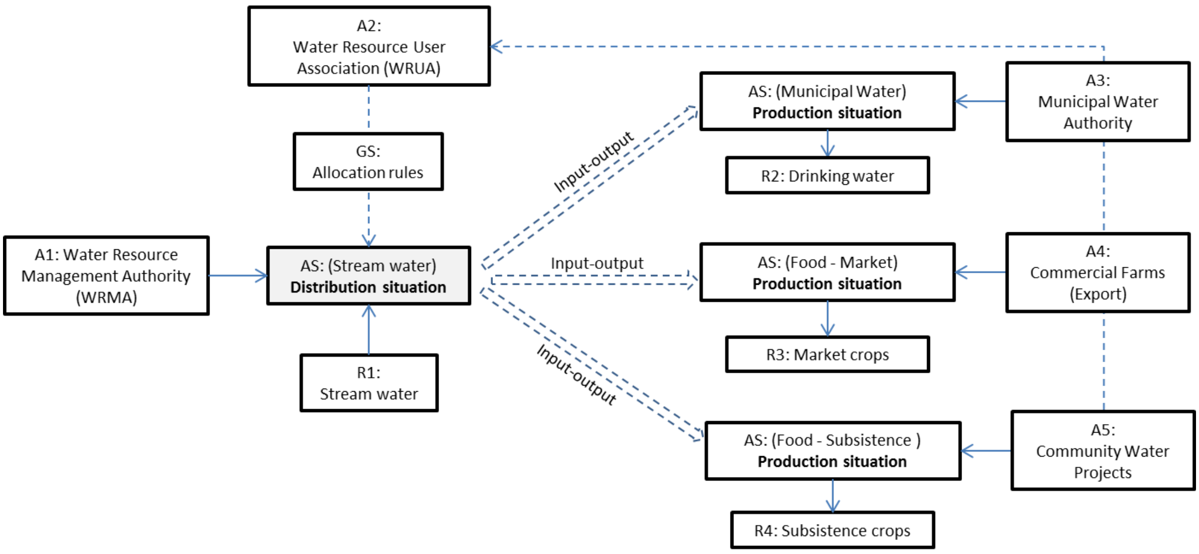
Some responses have emerged to accommodate energy supply and water appropriation situations (see Figure 3). At the district level irrigation schedules have been reorganised in an attempt to enjoy cheap electricity periods. At the project level, affected districts have started to get together and bargain collectively with electricity distribution companies to obtain better prices and year-long contracts. These are relatively straightforward and low transaction-cost responses as they build on the common property regime and long tradition of collective water management among farmers within each district. Collective bargaining is also favoured by the structure of the energy market, currently dominated by six operators, who rent the grid to a state-sponsored monopoly (Red Eléctrica Española). As a result of these measures, districts have partially buffered the upward trend of electricity prices and are less vulnerable to price shocks; however, there are still challenges to overcome. In some districts, farmers have opted for generating their own electricity via diesel generators, which is not necessarily a sustainable solution given the recent and expectedly future increase in diesel prices. Also, districts are free to opt out from the collective bargaining after each contract cycle, and this introduces uncertainty about their bargaining power as a group at the start of each new contract cycle. More generally, the project has developed some hydropower-generation capacity by taking advantage of elevation gaps along the canals; the energy generated, however, is sold to the general grid rather than redistributed internally among the irrigation districts with electricity deficits. The revenue generated by selling the energy is distributed in the form of infrastructural maintenance investments among the districts that need such investments and according to a principle of equity (i.e. all districts in need of infrastructural investments should be satisfied equally in the long term). Such equity principle would be undermined if the energy were directly distributed to districts that need it instead of being sold. Establishing an internal compensation mechanism across districts that balance the electricity needs of some districts and the principle of equity would require amending the current institutional arrangement and setting up a new energy monitoring mechanism at the project level. The potentially high transaction costs involved seem to have prevented such institutional response in the project.

Kenya: Nanyuki/Likii River catchments (Mount Kenya)

Mt. Kenya constitutes one of several 'water towers' in Kenya and the surface run-off from precipitation falling on the mountain travels many kilometres serving as a source of water for irrigated agricultural production, urban water demands, livestock and wildlife. The concept of WRUAs evolved from conflict resolution efforts between actors competing for water resources. Rainfall and snow accumulation in upstream locations flows downstream to areas that receive less rainfall (<200 mm/year) creating a classic structure where water withdrawals by upstream actors have dramatic impacts on downstream users.

The Nanyuki and Likii River catchments exemplify these competing demands for water. These include community water projects (CWPs) that use water for smallholder irrigated agricultural production and household needs, a municipal water service (Nanyuki town with a population exceeding 35,000 individuals) and large-scale commercial farms (see Figure 4).

Figure 4. Water-food/energy nexus in Nanyuki/Likii catchments.



The climatology of Kenya consists of distinct seasonal dry periods that require water withdrawals to be rationed and each actor within the WRUA has different capacities to cope with water shortages. CWPs are composed of small-scale farming households and when a water project's allocation is limited by rationing at the WRUA, the water project will in turn ration water within the water project. This means that in a drought year a household may receive less than 50% of flow compared to a normal year. Most households irrigate crops so that water rationing which reduces the amount of water available to households directly impacts crop production. The town of Nanyuki is a major economic hub and is home to a relatively affluent population compared to the agriculturists in the surrounding region. Given the influence of town business activities on the regional economy, the municipal water authority seeks to minimise water outages in town. Rationing decisions by the WRUA thus tend to favour Nanyuki town water demand at the expense of farmers.

In 2002, Kenya passed a national Water Act that increased the recognition of local-level water management. While ultimate decision-making authority is still semi-centralised through the Water Resource Management Authority (WRMA), the 2002 Water Act formally recognised the role of non-governmental entities in local-level water resources management. In particular, the Water Act formalised a model for local-level water management through WRUA organised around individual catchments. The central vision of the Water Act was to recognise the need to provide safe and affordable water to all Kenyan citizens with an emphasis on domestic needs (drinking and sanitation). At the core of this challenge is the need to meet food demands driven by an increasing population while at the same time understanding how urbanisation affects use and allocation of water resources across different types of actors.

WRUAs were designed to provide a formal mechanism for communication and conflict resolution between actors in a catchment. In the 1990s, there was significant, and in some cases violent conflict over water resources. Thus, the strongest mandate of WRUAs is to ensure water availability for domestic needs while at the same time requiring permitted water abstractors to leave at least 30% of water to flow downstream. The 2002 Water Act was designed to give weaker actors (those downstream) a mechanism to take legal action against upstream users. Within a WRUA each member is given a specific water allocation. In the Likii WRUA, the municipal water authority providing water to Nanyuki Town has the largest permitted water allocation and has a strong position within the WRUA to ensure municipal water needs are met.

Much of the monitoring and direct management of water is done by the WRUAs. Thus the WRUAs serve an important social construct where a downstream community that feels their water supply is unfairly low can use the conflict-resolution opportunity provided by the WRUA to address those concerns. While commercial farms and municipal water authority are in a position of power within the WRUA, since the development of the WRUAs there have been few cases where smallholder CWPs have resorted to legal action to address water-inequity issues. To a large extent, the WRUAs have served as an effective mechanism to voice and resolve concerns. A striking change since the 2002 Water Act recognised the authority of WRUAs is that the level of violent conflict over water has substantially declined.

India: Andhra Pradesh

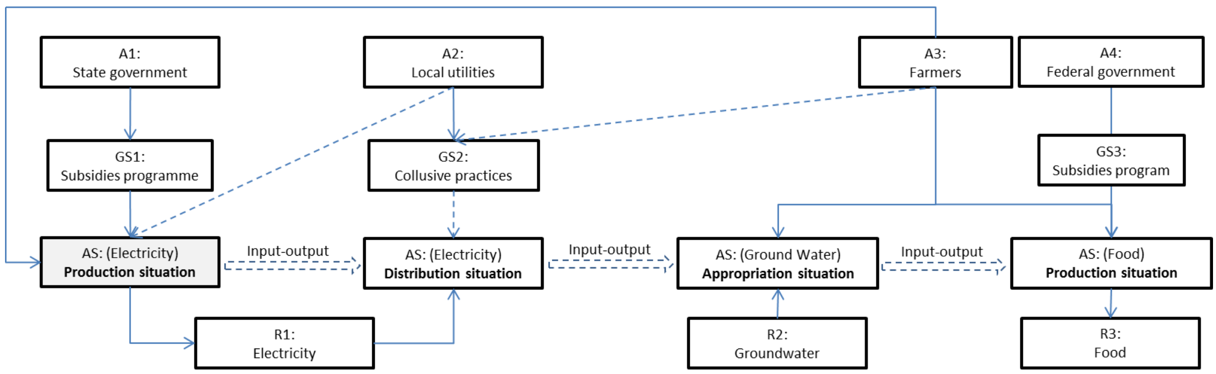
Electricity-driven groundwater pumping has become one of the most common sources of water supply in India, but especially in the Deccan Plateau with deeper dry rock aquifers (Shah, 2010). In the irrigation sector, both private and public wells have spread out enormously, even to regions where surface irrigation projects exist. The rapid expansion of private wells is the result of several factors, including the spread of cheap tube well drilling technology, subsidised electricity for agriculture, and an adaptive strategy to increasingly uncertain monsoonal precipitation. This expansion decisively contributed to the early success of the Green Revolution (Repetto, 1994). However, subsidised electricity has also led to several unintended consequences.

First, it required rapid investment in infrastructure for distribution, whose maintenance is often neglected by utilities. Second, partly due to flat rate pricing, inefficient, and often locally assembled pumping equipment is used, which puts heavy loads on the electricity grid.

In Andhra Pradesh there are nearly 3.3 million pump sets utilising 30% of all energy consumed in the state. Several studies have found that demand-side management (DSM) measures could drastically reduce peak and total energy loads by providing incentives for investment in energy-efficient technologies (Sant and Dixit, 1996; Reidhead, 2001). These include not only the use of more efficient sprinklers and friction-less foot valves by irrigators, but also improved capacitors and standardised pump sets. However, adoption of such measures has been very low, and both water and energy continue to be overexploited and inefficiently used.

The action situation of interest, at least with regard to the overall sustainability of the interlinked system is a coordination problem where collective DSM technology adoption improves shared power conditions (see Figure 5). However, coordination is undermined by a series of institutional factors linked to both energy and water use. On the one hand, patronage relations between the local electricity utilities and farmers limit revenue generation and maintenance investments by the former, which further discourages farmers from investing in DSM measures. Second, although dismantling the subsidies programme might force efficiency improvements the political costs of such a reform are considered too high and no government has been willing to take the risk. On the other hand, continued groundwater withdrawals have generated their own set of dilemmas. As the groundwater table fell, farmers have had to invest in new bore wells to access deeper aquifers. This has resulted in a competitive pumping process (e.g. Ostrom, 1990) that also demands greater electricity and pumping capacity. Higher pumping capacity, in turn, requires sufficient transformer capacity to cope with the increasing load. Institutions regulating groundwater use could therefore contribute to the efficiency of both water extraction and energy use; however, wells are managed privately by farmers and alternative institutional arrangements have proved to be difficult to implement. Groundwater use is, in turn, explained in part by cropping patterns in the area. Although dry rice varieties and semi-arid agricultural crops are viable in the area, water-intensive paddy cultivations are preferred by farmers due to the higher prices and government support (Kimmich, 2013a). More importantly, there are strong paddy-consumption habits that align with the current value chain. The nutritional value of paddy-rice in comparison to traditional dry crops is lower; thus the potential coordination of consumers around the consumption of those crops could result in an improved and more stable outcome both from a socio-economic and an ecologic perspective. As long as only a marginal number of consumers change food habits, however, no alternative value chain can become viable.

Figure 5. Energy-water nexus in Andhra Pradesh.



Discussion

The diverse irrigation cases presented in this paper demonstrate the potential value of the combined IAD and value-chain framework, while also uncovering how these frameworks can be used to provide insight into the dynamics in case studies with diverse social-ecological and institutional arrangements.

Through analysis of the case studies we have tried to demonstrate the utility of creating a conceptual bridge between value chains and the IAD framework. On the one hand, the value chain facilitates identification of relevant action situations, and the linkage among those situations. Linked action situations may be identified across resource sectors by considering whether the inputs to one situation are part of a larger value chain of water-food-energy interactions. This represents an important advance over the IAD framework which is often criticised for failing to adequately account for the roles of biophysical processes and linkages (Epstein et al., 2013). The important linkages between energy and water distribution situations in the Spanish case, for example, could easily be overlooked by an institutional approach which lacks a systematic way to account for the linkages across these two sectors. On the other hand, the IAD framework complements value chains by considering the social dilemmas that actors face and the ways in which governance systems are (or are not) used to resolve collective action problems. For instance, in the German case, farmers required or at least would benefit from low-cost water and nutrient inputs for their crops, while the city required additional absorption fields. Given these incentives it is perhaps unsurprising that they managed to successfully negotiate an agreement in which they both benefited. However, equally important is the fact that these actors have overcome barriers to institutional implementation and compliance, a condition which is lacking in the Indian and Kenyan cases.

Also, as illustrated throughout the cases, linkages across the water-food-energy sectors can be understood from an input-output, process-based approach. From this perspective the primary link of interest across the sectors is physical (see double arrows in graphs). The Spanish and Indian cases are similar in that both cases used energy as an input for water distribution and appropriation, respectively.

The Kenyan and German cases are also similar with respect to the use of water for food production. This focus on the physical aspects of a case is congruent with most nexus scholarship, which generally consists in a quantitative analysis of water and energy supply and demand dynamics. However, our approach suggests that additional linkages among actors and governance systems can help better understand the complexity of the cases (Kimmich, 2013b). For instance, some action situations involve different actor groups with different interests, all of which are potentially important to understand resource use and supply dynamics. The German case illustrates this point quite clearly, with four different actor groups involved in the treated water distribution situation, including the urban population and wastewater producers, municipalities and city water authorities, food and bioenergy production farmers and the Braunschweig water Association. In contrast, the Indian case is characterised by the active participation of only two actors (i.e. the local utilities and farmers) in the energy distribution situation. There are also actors involved in several action situations that could potentially play a pivotal role in the sustainability of the water-food-energy nexus. Indian local utilities, for example, are involved in both the energy generation and distribution situations; while Spanish irrigation districts participate in both the allocation of energy and water appropriation situations.

In addition to the linkages between physical systems and actors, there are important institutional linkages. Some of these linkages contribute to the regulation of resource use and supply dynamics across situations. In the Spanish case, the institutionalisation of collective bargaining over energy distribution prices and conditions provides for medium-term supply and demand equilibria, which are crucial to secure water appropriation during the irrigation campaigns. Similarly, the BWA's operational rules in the German case, contribute to the allocation of treated water for food and bioenergy production. Although in Spain and Germany institutional linkages appear to be supporting more sustainable outcomes, in other cases they may also generate perverse incentives across situations. The Indian case is paradigmatic in that regard. The cumulative effects of subsidised energy prices in the irrigation sector and informal arrangements between local utilities and farmers combine with an effectively open-access groundwater system, all of which result in a highly inefficient energy system and the risk of a depleted groundwater system.

Third, some of the cases illustrate the role of multi-level institutional fit and its contribution to the water-food-energy nexus (Scott et al., 2011). This is particularly evident in the Spanish case, which is characterised by the institutional accommodation of energy distribution and water use at the local level to a changing energy framework at the national level. More specifically national-level policies structure the incentives that actors face at the local level when deciding what types of crops to grow, what types of irrigation technologies to use, and how to power those technologies. Multi-level institutional coordination can add substantial complexity to the analysis of water-energy-food cases. The concept of focal action situation can be useful to limit the number of action situations, components and linkages observed in multi-level cases, as illustrated in the analysis of the Spanish case.

Fourth, the cases presented in this paper also help to refine our understanding of water-food-energy trade-offs. As highlighted throughout nexus scholarship, a number of trade-offs come in the form of supply and demand imbalances as well as a variety externalities of use (Scott et al., 2011). We observe this with the Kenyan case in the water sector, and in the combined water-energy sector in the Indian case. Further trade-offs arise in the cases related to the timing of resource use. As illustrated in the Spanish and German cases, the main issue and thus the main institutional challenge characterising the water-energy nexus is the coordination between energy supply and water use across irrigation seasons. Other types of trade-offs may exist, each of which might require different institutional solutions.

Finally, an aspect only observed in some of the cases but still important for future work is the potential for institutional path dependencies, i.e. resistances and/or choice limitations that are associated to an institutional status quo and prevent decision makers from choosing an institutional alternative despite the efficiency gains or social desirability of the alternative (Pierson, 2000). We see this in the Indian case in the persistence of the institutional framework for energy distribution, as well as in the Spanish case, where irrigators have ignored the possibility of generating energy within their own systems. The study of institutional path dependencies (DiMaggio and Powell, 1983; Pierson, 2000) is of particular relevance for the water-food-energy nexus scholarship. The coupling of water and energy use has increased over time (e.g. through the use of new irrigation technologies), and previously independent institutions need to adapt to take into account cross-sector linkages. However, as illustrated in the Indian and Spanish cases, vested interests and norms may prevent such adaptation.

One important aspect not addressed in this paper is the distinction between levels of action, and the ways in which institutions operate to affect outcomes across operational, collective choice and constitutional situations (Kiser and Ostrom, 1982). Institutions and linkages may operate at any of those levels, which implies the need to study institutional arrangements both horizontally and vertically.

Another element of these systems that is somewhat missing analytically is the role of power relations between and across actors. The actor linkages are highlighted but the importance of the relative power positions of actors is not fully described nor is there elaboration of how those power dynamics affect the system outcomes. Here a useful potential connection could be made to work in political ecology (Watts, 2011; Fabinyi et al., 2014), but we leave this for future work.

Also our application of the combined framework is limited in its focus on provisioning services[3] along the production chain. This, however, is not a fundamental limitation of the combined framework but rather an analytical choice made in this paper (Rodríguez et al., 2006).

Finally, the combined framework is better suited to test and build theories about institutional performance (Acheson, 2006) than it is to study how these institutions emerge and change (Van den Bergh and Gowdy, 2000; Vatn, 2005; Ostrom and Basurto, 2011). Thus as shown with the cases, the framework allows to assess the suitability of particular institutions and/or diagnose whether changes might be necessary; but it does not help explain how or whether such changes might occur.

CONCLUSIONS

In this paper we have sought to address the current institutional analysis gap in the study of water-food-energy nexus by developing a framework that combines a process-oriented heuristic (value chains) with a rigorous framework for the study of institutionally mediated choice (the IAD framework) (Ostrom, 1994; Ostrom, 2007, 2009; McGinnis, 2011b). More specifically, we adopt a value chain analysis perspective and complement it with the IAD-based concept of network of action situations to focus on the effects of institutions on collective behaviour and social and ecological outcomes. As illustrated with the analysis of four irrigation-related cases, the combined framework facilitates the identification of institutional linkages across water, energy and food supply along a value chain. Moreover, the framework can be used to evaluate the interactive effects of different institutions, as they affect one or multiple water, energy and/or food management situations at different stages of the value chain, as well as the role of physical and/or institutional feedback loops, the pivotal role of key actor groups and institutional path dependencies.

From a more substantive view, the paper also contributes to a better understanding of the complex water-energy and food interrelations for diverse types of irrigation contexts. In the German case, the analysis illustrates the feasibility of cross-sector coordination when there is a relatively reduced and homogeneous set of actors involved (city government, bioenergy production plant and neighbouring farmers) and the ability of each of them to contribute to the monitoring of the water-for-food and water-for-biomass allocation system. In the Kenyan case, the relative success of the WRUA to

[3] Water and energy are the source of important regulating and cultural services (De Groot et al., 2002) none of which were included here.

compensate for upstream-downstream asymmetries can be explained by looking at the varied interests and influence on decision making of users across different water-use value chains (municipal, subsistence farmers and export farmers). Finally, an interesting insight gained in the Spanish and Indian cases is the importance of cross-sector path dependencies when trying to reform water and energy institutions. In the Spanish case the robustness of cooperation and water management institutions has facilitated the emergence of some institutional solutions to cope with the volatility of energy market prices but also prevented alternatives that could lead to better social outcomes in the long term. In the Indian case, patronage relations between the local electricity utilities and farmers limit revenue generation and maintenance investments by the former, which further discourages farmers from investing in energy and water extraction efficiency measures.

Overall, the integration of value-chain analysis with IAD allowed us to gain helpful insight into the salient dynamics, actors and structures across a diversity of water-food-energy nexus cases. This conceptual bridge between value chains and institutional analysis would seem therefore well-suited to the challenge of understanding nexus research, given the importance of resource flows and governance dynamics in these coupled systems.

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