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Irrigated Landscapes, Produced Scarcity, and Adaptive Social Institutions in Rajasthan, India

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This article employs an actor–network (ANT) and materialist approach to examine the changing relations among nature, society, and technology in dynamic groundwater-irrigated landscapes. Drawing on a case study from Rajasthan, India, it merges these frameworks to advance our understanding of the role that tubewell irrigation technologies play, through their associations with other objects, in altering existing social power relationships, environmental practices, and socioecologies, paying attention to the directedness of these relationships. This article demonstrates, first, that tubewell adoption is made possible through the creation of tubewell partnerships, a new social institution. Second, although tubewell adoption initially enhances production, significant groundwater withdrawal negatively alters groundwater and soil chemistry. This undermines farmers' abilities to grow high-yielding seed varieties, prompting a return to traditional crops, and exacerbates existing social inequalities both within and between partnerships. Third, irrigation practices and daily production activities follow from the demands and constraints of the tubewell, enabling and constraining human and nonhuman action. The adoption of the technology, therefore, sets in motion a recursive process of technological adaptation, social institution formation, and ecological change. Although this is presently leading to socioecological differentiation, the results suggest that these social institutions formed around the tubewell are very durable. The conclusion offers suggestions for encouraging them toward more equitable outcomes. *Key Words: agrarian technology, India, nonhuman agency, scarcity, social institution.*

本文运用了行动网络理论（ANT）和唯物主义方法，对在动态的地下水灌溉景观背景下，自然，社会和技术之间的变化关系进行了分析研究。通过对印度拉贾斯坦邦的个例研究，本文结合了这些框架，以推进我们对管井灌溉技术的了解。经由这些要素与其它事物的联系，有助我们关注现存社会力量关系，环境实践，和社会生态的导向。本文表明，首先，一种新的社会制度，管井合作制度使得管井的采用成为可能。其次，虽然管井的使用在最初提高了生产能力，但是大量使用地下水对地下水和土壤化学造成了负面影响。这种负面影响损害了农民种植高产品种的能力，导致农民恢复种植传统作物，并加剧了已经存在的管井合作伙伴相互之间和内部的社会不平等现象。第三，管井所需要和限制的灌溉实践和每日生产活动，有利于建立和制约有人和无人的行动规范。对技术的采用和适应由此引发了一个技术采用，社会制度形成，社会生态变化的递归过程。尽管这一切目前导致了社会生态的分化，结果表明，围绕管井产生的相应社会制度是非常持久的，结论建议鼓励他们走向更公平的结果。关键词： 耕地技术，印度，无人代办处，缺乏，社会制度。

Este artículo utiliza un enfoque materialista y de actor-red (ANT, acrónimo inglés de “actor-network”) para examinar las cambiantes relaciones entre naturaleza, sociedad y tecnología que ocurren en paisajes dinámicos irrigados con agua subterránea. A partir de un estudio de caso de Rajasthan, India, se combinan estos esquemas para mejorar nuestra comprensión del papel que cumplen las tecnologías de irrigación *tubewell* (con agua subterránea entubada), a través de su asociación con otros objetos, para alterar las actuales relaciones sociales de poder, prácticas ambientales y socioecologías, dedicándole atención a lo directo de estas relaciones. El artículo demuestra, primero que la adopción de la tecnología *tubewell* fue posible gracias a la creación de asociaciones para su construcción y manejo, una nueva institución social. Segundo, que si bien la adopción de la *tubewell* inicialmente incrementa la producción, la extracción significativa de agua subterránea altera negativamente la química del agua y del suelo. Esto debilita las habilidades de los agricultores para cultivar semillas de variedades de alto rendimiento, lo cual induce al regreso a cultivos tradicionales, al tiempo que agrava las desigualdades sociales

existentes dentro y entre las asociaciones. Tercero, que las prácticas de irrigación y las actividades productivas diarias están en íntima dependencia de las demandas y apremios del tubewell, habilitando y restringiendo la acción humana o de otro tipo. Por esto, la adopción de la tecnología pone en marcha todo un proceso recursivo de adaptación tecnológica, formación de instituciones sociales, y cambio ecológico. Aunque actualmente todo ello está conduciendo a la diferenciación socioecológica, los resultados sugieren que las instituciones sociales formadas alrededor del tubewell pueden ser muy duraderas. La conclusión ofrece sugerencias para promoverlas hacia diseños más equitativos. *Palabras clave:* tecnología agraria; India; agencia no humana; escasez; institución social.

In the twentieth century, agriculture experienced radical technological transformation. High-yielding seed varieties (HYVs), chemical fertilizers, pesticides, and genetically modified organisms (GMOs) have spread across the global landscape. They have been developed by state planners and firms to enhance agricultural productivity within capitalist production systems and adopted by farmers at the household level. This should lead to increased agricultural production, and indeed this has been the case worldwide. Their proliferation also has led to many unpredictable outcomes, however, particularly in the Global South. For instance, agricultural technologies often spread unevenly, aggravating local power relations (Brown 1981; Turner and Brush 1987). At times they may undermine subsistence production and weaken social institutions (Mustafa and Qazi 2007), while leading to new market-based innovations at others (Harriss 1993; Dubash 2002). They may undermine biodiversity in some instances (Shiva 1993), while benefiting local ecology in others (Grossman 1993). At times they tend to exacerbate existing tensions between farmers and the state (Birkenholtz 2008a), while empowering local people at others (Bebbington 1993). Thus, technology adoption in support of a particular production regime often leads to unintended social and ecological change. The emergent relationship among agricultural technology adoption, social formation, and ecological change continues to be unclear.

Take the case of tubewells. As a scarcity-reducing technology, tubewell-driven groundwater irrigation systems have proliferated globally. For millennia, however, global irrigation has been primarily a surface water phenomenon. So, too, distinct practices and social institutions have been formed by and for the particular demands and constraints of surface water irrigation (Wittfogel 1957; Ostrom 1992; Wescoat, Halvorson, and Mustafa 2000; Trawick 2001a; Meinzen-Dick, Raju, and Gulati 2002; Mosse 2003). Over the last half-century, however, groundwater-based irrigation has become increasingly prominent,¹ resulting in a highly transformed groundwater landscape (Moench 2002; Shah et al. 2003). In the United States, for example, groundwater withdrawals, as a percentage of total water

withdrawals for irrigation, climbed from 23 percent in 1950 to 42 percent in 2000 (Hutson et al. 2005). Moreover, in India, groundwater-based irrigated area rose from 7.4 million hectares (ha) in 1962 to nearly 30 million in 1997 (Narayanamoorthy and Deshpande 2005, 70), currently accounting for 70 percent of total irrigated area (World Bank 2005). Therefore, it appears that tubewell adoption leads to the expansion of production in a linear relationship, where its adoption supports the adoption of other technologies, and to an increase in commercial crops. Moreover, it would not be surprising to see market-based irrigation management institutions evolve under these circumstances (Dubash 2002).

But tubewell adoption could also lead to the production of scarcity, new social institutions for cooperation (Emel and Roberts 1995), or the decline of commercial crops. Therefore, we must ask this question: What is the emergent relationship among the proliferation of agrarian technologies and social, political, and ecological change? In what ways does tubewell adoption recursively manipulate land use patterns, water scarcity, and adaptation of water use for different communities at both the individual and social-institutional levels? How do technologies (in this case tubewells) by virtue of their particular requirements discipline the subject (farmers) and to what effect for nature-society-technology processes, including social institution formation?

This article examines these questions using a case study from semiarid northern India. Since the 1960s, tubewell irrigation systems have proliferated across India, transforming the landscape and production relations, as agrarian practices and institutions (standardized practices, rules, and conventions) have been reworked around them. As one example of a resource scarcity-reducing technology, it is not clear in what ways the tubewell has impacted social, political, and ecological relations or how it has influenced the development of social institutions. This research utilizes household production information and interviews with land managers, tubewell drilling firms, and local Hindu groundwater experts to examine these processes in the Jaipur District of Rajasthan near its capital, Jaipur (see Figure 1). Given that similar technologies

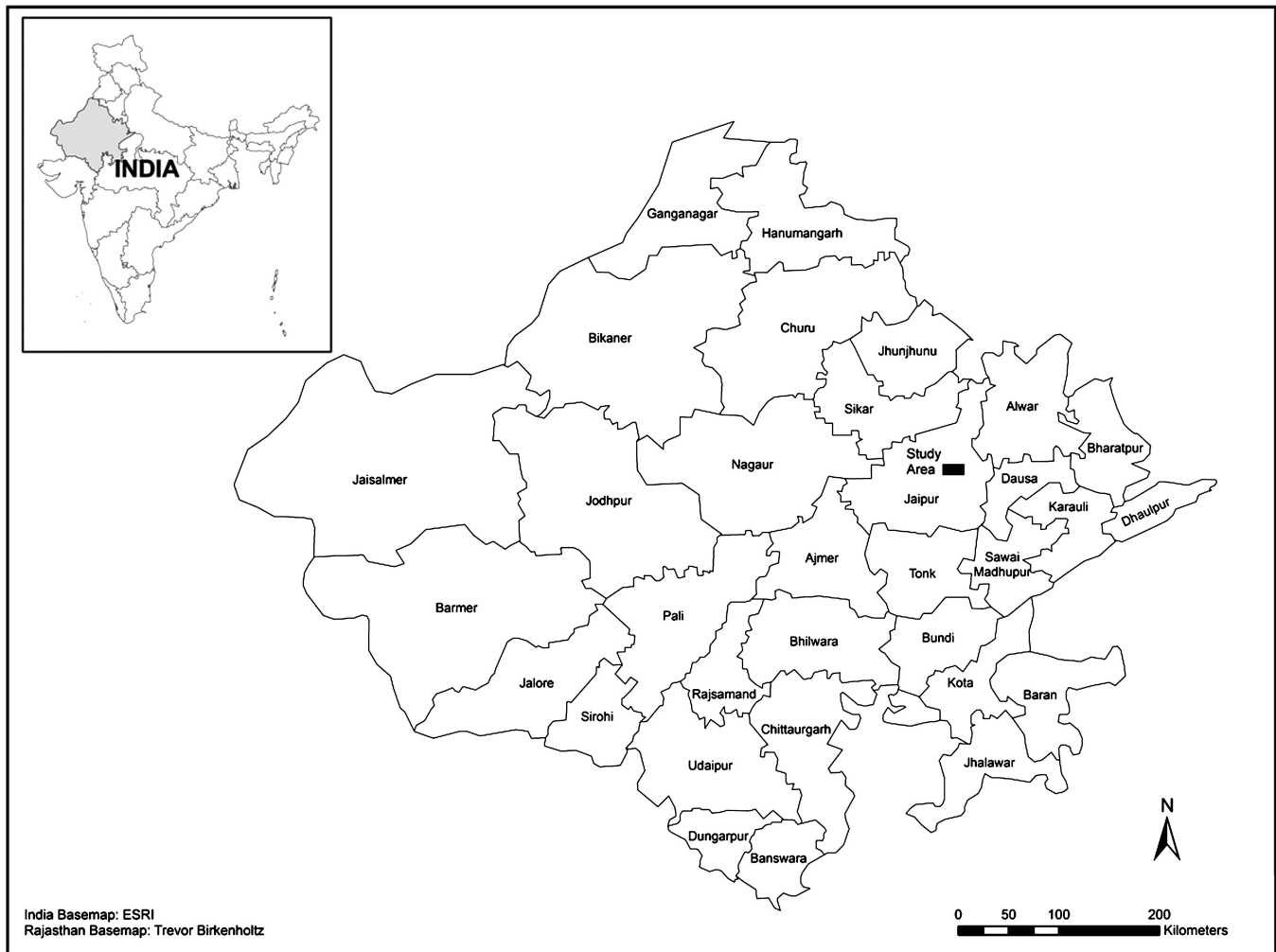


Figure 1. Rajasthan district borders and the study area.

(such as GMO crops) have proliferated in recent years, their effects on political ecological relationships are of particular concern.

I draw on research into irrigated socioecological systems and on work concerned with the momentum that technologies have, once adopted, on shaping the production of social institutions (Winner 1977; Robbins 2001a) to understand the impacts of the adoption of tubewell technology and associated irrigation systems on political ecological change. This work follows recent scholarship in geography (Swyngedouw 1999; Zimmerer 2000; Castree and Braun 2001; Robbins 2001a, 2001b; Whatmore 2002; Mansfield 2003; Kaika 2005; Perkins 2007), cognate fields (Escobar 1999; Mitchell 2002; Klingensmith 2003; Agrawal 2005), and science and technology studies (STS; Latour 1993, 2005) that has sought to understand the capacity that nonhuman nature and technologies have to shape the direction and character of socioecological change.

Ultimately, this research is about how we account for the nonhuman in geography, which is an active and growing area of inquiry unlikely to be resolved in the conventional sense (Harvey 1996; Castree 2002, 2005; Kirsch and Mitchell 2004; Bakker and Bridge 2006).

The article proceeds in four sections. In the first, I evaluate past and recent literature that has engaged the issue of technology adoption, including traditional theories of technology adoption and approaches to the study of irrigation, with more recent work on the intersections of technology with nature–society relations. Then I describe the study area, focusing on recent irrigation-driven changes in both the character and the amount of area devoted to agriculture. In the third section, I present the findings of research into the formation of hybrid practices and institutions and landscape change around tubewell technology adoption through a presentation of three case studies. I discuss these findings in the fourth section in terms of their relation

to the prevailing theories on technology adoption presented previously. At the same time, I advance these theories and our understanding of irrigation systems by rethinking the ways that political-ecological processes are shaped around technologies and what this might mean for the future of groundwater governance strategies within dynamic socioecologies.

Rethinking Nature–Society–Technology Relations

In the 1980s Brown and others showed that tubewells diffused unevenly and aggravated social power relations when introduced into areas where landholdings and income were unequal (Gotsch 1972; Biggs and Clay 1981; Brown 1981; Herath 1985).² Boyce (1987) built on this work to conclude that stagnation in Bengali agriculture, specifically the lack of diffusion of innovation in irrigation technology, was the result of not only an unequal agrarian structure (landholdings) but also institutional barriers (caste) and lack of public-sector investment. West Bengal experienced tremendous agricultural growth in the 1990s, however, displacing Boyce's original thesis (see Rogaly, Harriss-White, and Bose 1999). In contrast, Harriss (1993) found, rather than public institutions, that market-based innovations, such as entrepreneurial investment in irrigation, resulted in expanded irrigation and agricultural production. Related research has linked technology adoption rates to land manager perceptions of it and to those diffusing it (Glendinning, Mahapatra, and Mitchell 2001; for a review see Mercer 2004), to participatory agricultural extension techniques (Fagerberg and Verspagen 2002), and to perceptions of social or environmental marginal utility (Feder and Umali 1993; Caviglia and Kahn 2001; Upadhyay et al. 2003). This research has been important in illuminating the uneven motivations for and effects of technology adoption. Moreover, it leads to the question of coevolving socioecological and technological change. Research specifically into irrigation systems has attempted to address the lacuna in our understanding of complex socioecologies.

Trawick (2001b), for example, showed that Andean farmers created cooperative irrigation management institutions to mediate unpredictability in water availability. These institutions were adapted to specific surface water technologies and were grounded in preexisting cultural traditions of sharing. These farmers, however, were isolated from capitalist production relations and markets, which would impact the operation of the institutions as in this case. Alternatively, Mosse (2003) has

shown the ways that complex systems of social organization in surface water irrigation in Tamil Nadu, India, resulted from the interaction of precolonial, colonial, and postindependence political, economic, and technological efforts by the state to expand production. These accounts demonstrate that social institutions of coordination in surface water irrigation are the product of both preexisting socioecological relationships and complex political economies.

The recent proliferation of groundwater irrigation systems has led to an increased focus on groundwater socioecologies. Following Shah et al. (2003), "a more nuanced understanding of the peculiarities of Asia's groundwater socio-ecology is needed" (130). They inventoried a number of techno-institutional approaches to the groundwater question but concluded that these may not be compatible due to local environmental and social heterogeneity. Moreover, Moench (2002) illuminated the connection among groundwater scarcity, social instability, and agrarian livelihoods. In doing so, he also called for "institutions capable of adapting to change, while still maintaining the cultural and social continuity that grounds populations" (203). This work points to the great unevenness in institutional form and ecological change following technology adoption.

Dubash (2002), for instance, found in Gujarat, India, that the need for irrigation sparked both entrepreneurial investment by local nonfarming "capitalists" and the creation of informal market institutions for the buying and selling of groundwater across caste and class. Caste and class were not barriers to cooperation as argued by Boyce. More recently, Mustafa and Qazi (2007) demonstrated that in Balochistan, Pakistan, state-supported adoption of tubewells altered existing social power relations and resulted in the decline of traditional *karez* irrigation systems and the "complex systems of social organization" supporting them (see also van Steenberg 1995; van Steenberg and Oliemans 2002). In arguing for a return to traditional irrigation systems, they held that "particular types of resource use regimes and technologies become the locus and *raison d'être* for social capital formation and mobilization," whereas others (i.e., tubewells) do not (Mustafa and Qazi 2007, 1797). They also showed that preexisting *karez* social systems were transferred onto collectively owned tubewells, but they did not explicitly examine the ways that new rules and institutions coevolved and hybridized with new irrigation technologies (A. Gupta 1998; Mitchell 2002; Mosse 2003; Birkenholtz 2008a). In the short term, new technologies may aggravate existing inequalities, yet these new relations

may be harnessed toward more equitable outcomes. To explicate these processes, we need to examine the emergent relationships among technologies and social and ecological systems at particular moments in the economic process. This will shed light on their evolving differential capacities to effect change and to bind social institutions within dynamic socioecologies, ultimately pointing to where positive interventions may be made.

Actor–network theory (ANT) is one, but not the first, theoretical framework to examine the way that human and nonhuman nature and technologies adapt and change each other. Most notably, Harvey (1996), adopting a relational perspective he termed the *new dialectics*, which showed that capitalist production relations bring together and are embodied within otherwise seemingly disparate objects. It is the relationships that things have with other things that make them unique. These processes are seen as ancillary to the central process, however, which is the capitalist mode of production. Swyngedouw (2004) drew on this approach and ANT to argue that “the urban transformation of water is a manifestation and expression of wider relations that clearly transcend the simple question as to who does and who does not have access to water” (175). For Swyngedouw, these “wider relations” are those defined by the process of capital accumulation, and the transformation of water (nonhuman nature) and technological patterns are “expressions” of the general logic of capital. This implies directedness in the transformation of nature–society–technology relations by the imperatives of capital accumulation. Any failures in this process, such as the uneven sociospatial distribution of water availability or new institutions of water use (e.g., usurious private water vendors), are the result of the reconfiguration of social power relations and nature under capitalism. These are outcomes or “particular moments [that] contradict the ‘demands’ being placed on them by the logic of the process” (Castree 2005, 234). Thus, the relationship between intentions, such as attempts to expand production through irrigation, and outcomes, such as a return to traditional cropping varieties, is unpredictable.

This mode of inquiry opens up the association between heterogeneous objects to displace the stabilities between them. It offers at least three advantages over previous approaches to the study of agrarian socioecological and technological change. First, it breaks down the analytical barriers between human and nonhuman actors by denying the distinction between the social and the natural (Latour 1993). It instead focuses on the emergent relations between them. Second, it redirects

our attention from individual actors toward their interrelationship or networks of connection, showing that the “competencies and capacities of ‘things’ are not intrinsic but derive from association” (Bakker and Bridge 2006, 16; see also Whatmore 2002). Power and agency are not held by individual actors, therefore, but are products of the emergent, historical relationship between them, such as that between farmers, ecologies, and agrarian technologies. So, too, their capacities to drive change in these relationships vary from moment to moment in the economic process. Third, the approach does not assume a hierarchical structure of causation, where “large-scale actors come to dominate or explain the localized effects experienced by smaller actors” (Robbins 2004, 154). Instead it allows for the possibility of localized processes, such as technology adoption, to build momentum by enrolling and transforming other actors to create large-scale effects (Latour 2004; Robbins 2004). Approaching agrarian socioecological and technological change in this way sheds light on the particular actors accountable for these transformations, which allows for the possibility of redirecting the most normatively positive of these toward more socially desirable ends.

The more constructivist approaches to this topic have been criticized for being apolitical and incapable of assigning causality or responsibility for understanding the natures we have (Kirsch and Mitchell 2004; Bakker and Bridge 2006). It is important from a normative standpoint, therefore, to engage the question of nonhuman agency within human geography by means of a framework that provides for the possibility of assigning “causality, accountability, and the directedness of social relations” without being deterministic (Kirsch and Mitchell 2004, 687). This means that specific drivers of the social process cannot be assumed a priori, lest they structure our analyses (Mitchell 2002). Therefore, rather than prioritizing the association of the hybrid (as in strict versions of ANT), we should focus on the process of hybridization or of emergence to understand both the associations between heterogeneous objects and the homogenization or differentiation that results from this hybridization (Swyngedouw 2004). What is the emergent relationship among agrarian technologies and social, political, and ecological change?

Further research in this strand of thought has sought to understand how resource scarcity reducing technologies, once adopted, affect the organization of human action and the making of social institutions (to adapt to them). In his work on Indian forests, Robbins (2001a) drew on Winner’s (1977) notion of reverse adaptation

to show how existing forester and forest-dependent peoples' practices were reworked to meet the demands and categories of land cover embedded in satellite imagery technology. Once adopted, these technologies had momentum in shaping social and political institutions and ecologies. The manner in which technology adoption disciplines existing social practices and institutions remains unclear. We need to examine the ways in which individual technologies, in specific contexts, transform existing practices, social power relationships, and ecologies.

Scarcity-Reducing Technologies in India: The Quintessential Tubewell

One such quintessential technology is the tubewell in India, originally introduced in the nineteenth century to reduce water scarcity and the incidence of famine, especially in drought years (Indian Irrigation Commission 1903; Scottish Mission in India 1905). Tubewells tap aquifers of varying depth, volume, and recharge capacity. In northern India they typically range from 20 to 100 m deep and utilize an electric submersible pump.³ The tubewell is exemplary for furthering our understanding of these relations for three primary reasons: (1) it operates within historical social processes such as caste and class but is not completely subservient to them; (2) its use alters but can also be adapted to meet changing social and ecological conditions; and (3) its adoption intersects with both the material (production and reproduction) and the discursive (representation and signification).

The tubewell is not by any means the first technology in India for lifting groundwater, however. The use of the Persian wheel is well documented in northern India since before AD 900 (Rosin 1993) and it is still in use in southwestern Rajasthan today. The technology to lift groundwater and a knowledge of the dynamics of groundwater-based irrigation have been in a process of development for centuries.⁴ Following Birkenholtz (2008a), the tubewell did not simply diffuse throughout India but became enmeshed in previously existing ways of knowing, in previous practices of groundwater use and irrigation, and in previous social relations (see also Mitchell 2002). Second, it does not merely provide water but is adopted and adapted by land managers, bureaucrats, and tubewell drilling firms and is therefore enmeshed synergistically within multiple changes in social relations.

Although tubewells were introduced to India in the late 1800s by the British (contra Shiva 2002), it was not until the nationalization of the banking system in 1969 and the simultaneous expansion of rural electricity that they began to proliferate (Narayanamoorthy and Deshpande 2005). This shifted irrigation from large-scale state-run projects, creating the conditions under which individual farmers could adopt private tubewells. The "hands-off" program of decentralizing irrigation to individuals has been very successful throughout India, where today there are over 20 million agricultural tubewells (Narayanamoorthy and Deshpande 2005).

Tubewells in Arid India: Rajasthan

Nowhere has this strategy been more successful than in the arid and semiarid northwestern state of Rajasthan. Between 1962 and 2001, farmers adopted over 1.4 million agricultural tubewells in the absence of formal regulations in a state that was already densely populated with dug wells (Government of Rajasthan Groundwater Board, personal communication 2003). Presently, tubewell construction is accelerating, with 33 percent growth between 1999 and 2001 (Government of Rajasthan Groundwater Board, personal communication 2003). Irrigated area has also risen from 3 to 3.8 million ha, including an increase in net tubewell irrigated area of over 1.27 million ha during the same period (Directorate of Economics and Statistics 2000, 2003). The growth in tubewell construction and the expansion of irrigation has resulted in groundwater overdraft of 410 million m³ per year (Government of Rajasthan Groundwater Board, personal communication 2006) and rapidly declining groundwater levels in some areas by over 60 m between 1981 and 2000 (Government of Rajasthan Groundwater Board, personal communication 2003). The severe state of groundwater overdraft is of serious concern, as groundwater irrigates 71 percent of total irrigated area and provides 80 percent of both rural and urban domestic supply (Directorate of Economics and Statistics 2003; World Bank 2005). The future, therefore, of groundwater-led agricultural (and urban) development is a matter of serious concern.

Irrigated Landscapes: The Jaipur District Region

In a number of respects, the study area near Jaipur, Rajasthan (see Figure 1), is well suited for this research. It has the following advantages: (1) a long history of

groundwater extraction and development, (2) a recent history of rapid technological change and adaptation to new technology, and (3) a high degree of ecological and socioeconomic variability, which allows for the investigation of the differential effects of technology adoption.

Rajasthan is divided into thirty-two districts and each district is divided into numerous blocks or *tehsils* (there are 236 in all). Research for this study took place during an eighteen-month period between 2002 and 2005. I surveyed 151 farmers in six villages of Bassi Tehsil, around 60 km east of Rajasthan’s capitol city, Jaipur. Then, over the next several months I followed up on these surveys with repeated in-depth interviews of more than seventy-eight farmers, Hindu groundwater experts, and several tubewell drilling firms. Chosen for their social and ecological diversity, the villages comprise a highly stratified social environment of low- and high-caste Hindus; small, medium, and large landholders; and moderately to rapidly declining groundwater levels in their respective vicinities. Even though we should not take social categories, such as caste and class, to assume difference (Agrawal 2005), they are still important considerations (Jeffrey 2001). For example, Table 1 shows that the relationship between caste and landholdings is significant and interdependent, $\chi^2(4, N= 151) = 17.556$, $p = 0.001$. These variables interact to influence tubewell adoption, institution formation, and capital accumulation.

Table 1. Landholdings size by caste in study area

Land category (hectares)	Scheduled caste (%)	General caste (%)
0.25–0.50	9.2	5.8
0.51–1.00	41.5	27.9
1.10–2.50	38.5	32.6
2.51–3.90	6.2	20.9
4.00–7.50	4.6	12.8

Notes: n = 151. Scheduled castes: 54 Meena, 8 Bairwa, 3 Yadav (65 total). General castes: 80 Sharma, 4 Jat, 2 Gujar (86 total).

Jaipur District is a semiarid region of productive agricultural land, with nitrogen-poor alluvial soils (Singhania and Somani 1992). Situated between the arid plains of the north and west, and the comparatively humid lowlands of the southeast, it has moderately good groundwater recharge in years of adequate monsoon rains. Summer temperatures commonly reach 44°C. There are two cropping seasons: *Khariph* (summer), which is mostly rain-fed, and *Rabi* (winter), which is dependent on intensive groundwater irrigation (see Figure 2). Like much of Rajasthan, the people in this area are dependent on groundwater for their irrigation and domestic needs. There is no government water supply, save sporadically functioning village hand pumps. All village residents, therefore, rely on tubewells for water. This reliance has led to adaptive social institutions for the use and maintenance of tubewells, while motivating new forms of



Figure 2. Winter crops on intensively irrigated land in the study area.

socioecological change. The next section addresses these questions.

Tubewell Processes: Ecological Change, Differential Scarcity, and Adaptive Institutions

Land Use, Soil, and Groundwater Recursive Change

The ecology of the area has changed through four recursive processes: (1) the proliferation of the tubewell increased groundwater-irrigated area dramatically; (2) this initially led to the production of irrigation-intensive, monocultural commercial crops; but (3) the increased prominence of groundwater use for irrigation has increased the salinity of groundwater, which caused other minerals to leach into the soil, requiring the application of expensive gypsum to reduce the alkalinity; and (4) these alterations of soil and groundwater chemistry, the result of irrigation-intensive crops, has resulted in a reduced ability to grow these crops and instead has encouraged a return to the production of traditional crop varieties that are less sensitive to these chemical changes in the soil and groundwater.

First, over the eight-year period between 1993–1994 and 2001–2002 (the longest period for which comparable district-wide data were available), total net irrigated area rose dramatically in Jaipur District from 302,428 ha to 330,569 ha, a 9.3 percent increase. During the same

period, total net irrigated area rose throughout the state from 4.6 million ha (3.6 million in 1989–1990) to 5.4 million ha, a 17 percent increase. With these increases in irrigated area, the tubewell became more prominent in irrigation with an increase in net tubewell-irrigated area in Jaipur District from 296,421 ha to 329,230 ha (an 11 percent increase) and in the state from 2.5 million ha to 3.8 million ha (a 52 percent increase) over the same period (with much of this growth occurring between 1999 and 2001).

This expansion has two meanings. First, the growth of tubewell-irrigated area outpaced the rate of growth in total net irrigated area (i.e., area not formerly irrigated) in Jaipur District and Rajasthan. Therefore, the tubewell has taken over irrigation on previously irrigated land as the percentage change in tubewell-irrigated area of the growth in total irrigated area (of formerly nonirrigated area) is 116.5 percent in Jaipur District and over 165 percent in Rajasthan. Second, nearly four decades after the Green Revolution, the tubewell is still expanding. What is the character of this expansion in irrigated area and what does it mean for production?

As shown in Table 2, the character and productivity of the agricultural landscape changed dramatically in the district between 1993–1994 and 2001–2002. There was a decline in the production and area of commercial oil seeds (including total oilseed as well as rape or mustard and linseed) and a rise in sesame, groundnut, condiments and spices, and vegetables (the latter are limited to tomatoes and nonmaize vegetables: squash, eggplant, onion, pea, potato, and okra). Area and

Table 2. Percentage change in area and production of principal crops in Jaipur District, Rajasthan, between 1993–1994 and 2001–2002

Crop	Area Δ	Production Δ	Subsistence or commercial	Irrigation requirement
Linseed	–96.55	–90.91	Commercial	High
Rape/mustard	–60.12	–66.97	Commercial	High
Red chili	–36.82	–36.61	Commercial	High
Total oilseed	–38.97	–25.75	Commercial	High
Maize	–6.42	132.91	Subsistence	High
Pulses	–1.04	–6.41	Subsistence	None
Barley	6.69	71.17	Subsistence/commercial	Low–High
Total food grain	10.17	42.61	Commercial	—
Wheat	12.30	56.23	Subsistence/commercial	High
Pearl millet	13.73	37.15	Subsistence	Low
Sorghum	23.39	–60.97	Subsistence	Low
Total condiments and spices	32.10	–41.02	Commercial	—
Sesame	48.96	27.14	Commercial	Low
Groundnut	52.93	171.94	Commercial	Low
Total vegetables	53.58	11.01	Commercial	High

Notes: Table arranged by “area change” from most negative to most positive. Sources: Directorate of Economics and Statistics (1997, 2003).

production of subsistence crops such as wheat, pearl millet, and sorghum have also risen. Moreover, the area planted in barley, pulses, and maize has stayed steady but the production of barley and maize has increased exponentially. Therefore, the yields per unit area have greatly increased.

A shift in commodity prices over the time period could offer one explanation for these changes, but actually, prices overall moved downward (Barker and Molle 2005; Food and Agriculture Organization of the United Nations 2006). Therefore, this does not explain the rise in the production of some crops, such as sorghum, sesame, or groundnuts. So, too, the change in the type of crops being produced is not simply the result of irrigation (in the sense that the availability of irrigation leads directly to increases in irrigated area and to high-yielding or lucrative crop production) or political economic factors.

Consequently, the shift is due to the effects of tubewell adoption on the soil and groundwater. Of 151 farmers surveyed, 100 percent indicated that they had at least seasonal groundwater salinity, hardness (*talia*), or both, and 100 percent indicated that they had at some time added gypsum to their soil to “loosen” it up. S. L. Sharma and his brother irrigate more than 25 bighas (6.33 ha) near Kanota, about 25 km from Jaipur. They do not irrigate their summer crop, but in preparing their fields for the winter crop, they spread more than \$275 worth of gypsum yearly on the fields to break up the calcification of the soil:

The groundwater becomes more saline throughout the summer. It did not used to be like this; it [the salinity of the water and the calcification/sodic soil] happened with the irrigation. If we did not use gypsum to break up the soil and we had a good rainfall, it would not soak in for two months.

Groundwater extraction for the irrigation of water-intensive crops over the last four decades has indeed altered groundwater and soil chemistry. Jacks et al. (2005) showed that evapotranspiration of groundwater irrigation in Rajasthan led to sodic soils and changes in overall soil chemistry (e.g., increased alkalinity; see also Ramesam and Barua 1973). These changes caused the soil to release fluoride into the soil and groundwater, and the precipitation of calcite into the soil, producing conditions that can facilitate desertification (whether temporary or not; Rasmussen, Fog, and Madsen 2001; Davis 2005). The authors recommended remedial measures, such as the addition of gypsum to the soil to reduce alkalinity. These processes affect the kinds of crops that

can be grown, as well as irrigation and soil beneficiation practices.

The result is a situation where irrigation-intensive or less hardy crops cannot be grown because as groundwater is withdrawn throughout the season, with little or no rainwater recharge, the productive capacity (in terms of volume lifted) of the tubewell decreases, the groundwater's salinity increases, or both occur. This also happens due to mutual interference between tubewells in the regional aquifer or to the area's many perched aquifers, resulting in great unevenness in groundwater quality and recharge. Again quoting Sharma: “Formerly we could grow tomatoes, okra, chili peppers, and eggplant, but now we do not like to because we cannot produce much of it due to the salty water. So now we grow mostly sesame, groundnuts, fodder crops, and some lentils.” It is the shifting association among these objects (i.e., tubewells, crops, and ecology) that leads to particular recursive processes and outcomes: groundwater, soil chemistry, cropping pattern change, and adaptive social institutions. The result, therefore, is the production of crops that are require less water or are more saline tolerant. This situation is confirmed by others, who said, “We have increased our sesame production because it only requires one irrigation [per season].” The same is true with groundnuts. Farmers have increased their production of sesame and groundnuts throughout the district by nearly 49 percent and 53 percent, respectively. In other words, tubewells were adopted to grow HYVs in support of a capitalist production regime, but through their use the conditions under which those crops could be produced (adequate groundwater quality and quantity, and soil quality) were undermined. This has resulted in an unintended return to traditional cropping varieties (see Table 2).

The proliferation of the tubewell was aided by state intervention in loan and infrastructure provision in the 1960s. Coupled with the promise of lucrative and irrigation-intensive crops, tubewells enrolled farmers into associations with it. This process of enrollment reconfigured the existing associations between farmers and the land, leading to recursive ecological change and the production of new nature–society–technology hybrids, including an unforeseen production regime. What is the capacity of tubewell technology in driving shifting relations among producers, and producers and ecologies? It is not clear whether these technologies are alleviating or exacerbating natural resource scarcity and, once adopted, how they impact people's daily practices and the making of social institutions. The next two subsections address these issues.

Differential Scarcity in Irrigation

Tubewell irrigation has exacerbated social differentiation and natural resource scarcity. The research area is socially stratified, typical of Rajasthan, where scheduled or marginal castes have the smallest landholdings (see Table 1), which is a sound predictor of local power and wealth (Bernstein 1977, 1998; Ghimire 2002), as is the tubewell itself. According to one scheduled caste (SC) farmer, “A tubewell is like a moustache: having a tubewell is necessary to keep your moustache. If you have a moustache, nobody asks why you have it, but if you do not have it, then they ask—are you not man enough to have it?” Throughout rural India, moustaches are a symbol of agrarian masculine power, to which the tubewell is now akin. The tubewell is adopted, therefore, for more than its ability to produce water. Some farmers, such as this SC farmer, must adopt it to increase or maintain their social standing. Its absence opens them up to peer ridicule, undermining their authority, particularly for an SC. Like the farmer, the tubewell then acquires its capacity for change by enrolling other actors, where it transforms the existing stratified social network of associations. This differentiated social environment also bears itself out when looking at the discrepancies in income from various sources between Scheduled and General Castes.

General and Scheduled Caste households earn, on average, a total of 10,128 and 8,150 rupees (44 rupees = \$1) per month, respectively, and average landholdings are 2.16 ha and 1.38 ha. Off-farm income, however, is much higher for SCs, at 3,721 rupees versus 2,548 rupees for General Castes.⁵ On average, General Castes also irrigate higher proportions of their holdings in both summer and winter. SCs irrigate 62 percent of their land in the summer and 71 percent in the winter, whereas General Castes irrigated 79 percent and 83 percent, respectively.⁶ The difference in the percentage of irrigated area between castes is surprisingly small, at 17 percent in the summer and 12 percent in the winter. SCs are actually irrigating a lot of land, therefore. The question then becomes this: Under what conditions are they doing it?

Adapting Institutions to Solve Scarcity and Access Issues

Farmers are forming tubewell-owning partnerships, a novel social institution, to gain access to groundwater. Table 3 shows the average number of owners for their first tubewell adoption (some farms have had more than

Table 3. Number of tubewell partners on average by landholding category

Land category (hectares)	Tubewell partners, Tubewell No. 1
0.25–0.50	7.1
0.51–1.00	3.11
1.10–2.50	2.96
2.51–3.90	2.68
4.00–7.50	2.15

Note: $n = 141$.

one) based on landholding size. The smallest landholders, in the category of 0.25 to 0.50, have 7.1 partners on average, irrigating 7.1 farmsteads. The most marginal producers in landholding terms are SCs. Therefore, SCs should average the most tubewell partners per tubewell, and they do.

On average, SCs have 3.74 partners for their first tubewell, whereas General Castes have only 2.76. Moreover, as the water table declines, causing tubewell failures, farmers construct second, third, and even fourth tubewells. This is also disproportionate between the groups. Twelve SC partnerships had one failed tubewell, four had two, and two had three, as compared to General Caste partnerships that had twelve failures on their first tubewell and no second failures, which would force them into further adoptions. SCs also have twice the number of partners for their second tubewell at 4.08, compared to 2.0 for General Caste. SCs also dig deeper for groundwater (43 vs. 36 m on their first tubewell), which is partially the result of SCs being allotted the poorest land after land reforms (L. C. Gupta 1994). Therefore, there is a high degree of caste-based differentiation.

It could be argued that the high numbers of tubewell partners among the most marginal landholders are due in part to the indivisibility of the technology (Boyce 1987; Dubash 2002), where one tubewell is capable of irrigating more than 0.25 or even 0.50 ha. This is not the case, however. Tubewell sharing is due to the high risk of failure in installing a tubewell; high construction, electricity, and maintenance expenses; and barriers, in this area, to acquiring an electricity connection. According to one farmer, “We go in for the sharing because it is necessary due to the high cost of the equipment and operation costs. And if it [tubewell] goes bad, then we are not out so much.” It is also a cause and consequence of social institutional innovations making it possible to share tubewell use, in a context where farmers would prefer not to share technology. The constraints (see later) and requirements of

the tubewell, which mediate its adoption and operation, enroll farmers into partnerships, while transforming social power relationships and ecologies. According to farmers, they would much rather have their own tubewells:

Farmers that have partners are generally not happy because it is too difficult to coordinate. In the old times partnerships were okay. A dug well required partners to build, and also to irrigate required more than one person, but now it only requires one person to irrigate, but it does require more money. Now partnerships are not good because population has increased, groundwater has declined, pressures have increased—we need money now. It is also a problem because we only get six hours of electricity per day. Life is more complicated. (Brahmin farmer July 2005)

This indicates, first, that historical partnerships resulted from the constraints of dug-well irrigation, both technical and political-economic, not simply from a culture of sharing (Trawick 2001b). It also shows that contemporary partnerships are a necessity rather than an option and that they are a burden because of interrelated social and ecological factors. Moreover, the process of acquiring an electricity connection is an arduous, lengthy one, further compelling farmers to form partnerships:

[Electricity] connections applied for before 1990 have been completed. We are now working on connections applied for after 1990. It takes twelve to thirteen years to get a connection if you are in the general [caste] category. Currently there are two categories: SC and General. SCs normally get their connection immediately. General takes twelve to thirteen years. (Author interview, Jaipur Electrical Development Utility May 2005)

The process does not end with the application. The average bribe is between 10,000 and 25,000 rupees (\$227–\$568). Taken together, these factors favor sharing irrigation capacity through cooperative institutions. Why, though, as in the case of Dubash (2002), Rogaly, Harriss-White, and Bose (1999), and Harriss (1993), did private market-based institutions not develop? This study shows that it is due to the unpredictability of electricity supply, the scarcity of water, risk of tubewell failure, and an existing history of cooperative agrarian institutions.⁷

The significance of this finding merits elaboration. In particular, others have shown that natural resources scarcity, such as inadequate irrigation water, leads to conflict (Trawick 2001b, 2003). This study, by contrast, indicates that the scarcity of water for irrigation actually leads to new forms of cooperation. These new institutions are grounded in preexisting relationships of

trust and social power and form in a recursive process of social, ecological, and technological hybridization (Mitchell 2002; Birkenholtz 2008a), where the tubewell and the ecology are social actors (Latour 2005). Next, I turn to the operation of these institutional arrangements formed for the sharing of tubewells by first outlining their basic characteristics and then illustrating the functioning of the partnerships through three case studies.

Coordinating Irrigation

Tubewells are adopted to both intensify and extensify production, but once adopted, they demand the further creation of new social institutions. Farmers share tubewells for drinking water and irrigation, splitting associated operating and maintenance costs among them. They also coordinate their crops under changing ecological conditions, which are affected synergistically by their agricultural decisions. For instance, in this water-scarce region, cropping decisions must follow not only from the availability of water but also from the availability of the tubewell, which in turn affects the form of the cooperative institution.

In the survey, 83 percent of all tubewell owners had partners and 76.6 percent coordinated irrigation timing. All partnerships were formed on kinship lines.⁸ There are, minimally, seven steps in setting up a tubewell partnership: (1) form the partnership; (2) determine construction costs and arrange for the availability of funds; (3) determine a location for the tubewell; (4) acquire an electrical connection; (5) hire the construction firm and construct the tubewell; (6) decide seasonally on the crops to be grown and the rotation schedule; and (7) coordinate operation and maintenance costs.

In these patrilineal partnerships, the eldest is typically the main decision maker, although occasionally a more junior partner may assume this role. According to one farmer, “I am the eldest but I do not have the most authority. My brother has more control even though he is younger because he has more knowledge [of tubewell irrigation].” Existing social power relationships are reworked around tubewell adoption, therefore, which requires some technical knowledge. This farmer also makes his cropping decisions first, and the others follow. Cropping decisions must be coordinated because various crops have different resiliencies for not getting water at crucial times, which is always a possibility. Vegetables are very sensitive to the timing of irrigation, for example, whereas many local fodder crops are not. After the members of the partnership are determined, the

location is established. The location is based on proximity to an electrical connection, centrality to the partners, and technical consultations with tubewell drilling firms and local Hindu groundwater consultants as to the location of groundwater. Proximity to an existing three-phase electrical connection, capable of powering the tubewell pump set, is not inconsequential, as existing single- or dual-phase connections are inadequate. This is a carefully planned endeavor due to the long waitlists for an electrical connection and because farmers must pay a portion of the three-phase hookup cost, which is often significant. Once the tubewell is constructed, partners coordinate which crops they will grow and determine a rotation schedule. The more partners there are, the more difficult this becomes, because although each person is allocated an equal share, availability of electricity and the crop's sensitivity to the timing of irrigation play a crucial role.

Throughout the study area, electricity is only available for six hours per day with no set supply schedule. Electricity could be available one day from 12 p.m. to 6 p.m. and the next day from 2 a.m. to 8 a.m., commonly with interruptions in between. Moreover, the tubewell cannot be left in the "on" position for two reasons: it must be powered up through a manual sequence, and the practice of irrigation is not automated. Therefore, somebody in each partner's household must stay awake at night in the event that the electricity becomes operational, which affects other household production and reproduction activities (see Case Two). Tubewell adoption, therefore, not only creates opportunities for the production of new kinds of crops, but it imposes demands and constraints on the household, which could lead to further differentiation.

If the head partner plants an irrigation-intensive, timing-sensitive crop, he will exert pressure on the other

partners to allow him to irrigate his crop even if it is not his turn. At the end of the season, he then may be pressured by the others to redistribute some of his profits (either directly, in kind, or indirectly through wedding gifts, for example) from that successful crop or pay more of the operational costs, especially if others' crops fail. This transition from labor to cash liability has also been shown in the transition from *karez* to tubewell irrigation in Pakistan (Mustafa and Qazi 2007).

The partnerships are flexible and complex. They depend on constant negotiation. However, the research reported here documents no instances of failure. Therefore, these institutions form part of very durable networks, which are constantly being reconfigured or hybridized within dynamic socioecologies. They are networks that could be recombined, with rules that could be rearticulated to advance socioecological benefit, including governance reforms. The institutions of tubewell partnerships are best exemplified through the three empirical cases presented next. Table 4 presents the basic configuration of the partnerships. Small partnerships are clearly advantageous, as they reduce the constraints on the irrigation schedule and increase the variety of possible crops. All partnerships share electricity and maintenance costs equally.

Case One. Two upper caste Brahmins (General Caste) formed this partnership in 2002, when they constructed their first tubewell for 72,000 rupees (36,000 per partner). It is 75 m deep with a 7.5-horsepower pump, with a discharge of no more than 275 L per minute (Lpm). Their average annual agricultural income on 2.03 ha each was 125,000 rupees. They make their cropping decisions jointly and are equals in the decision-making process. Their incomes are distributed roughly equally. They have

Table 4. Three tubewell partnership cases

	Number of partners	Total cost	Average income per partner	Annual costs: Total	Winter crops	Summer crops	Rotation schedule
Case 1: ID 062	2	72,000 ^a	125,000	2,000 = maintenance 10,800 = electricity ^b	1, 2, 6	3, 4, 5	Every other day
Case 2: ID 126	7	56,000	8,000	3,500 = maintenance 10,800 = electricity	1	3	Once every seven days
Case 3: ID 013	9	90,000	22,700	10,800 = maintenance 10,800 = electricity	1, 6, 9	3, 4, 5, 7, 8, 9	Once every nine days

Notes: Crops: 1 = wheat; 2 = barley; 3 = pearl millet; 4 = sorghum; 5 = groundnut; 6 = vegetables; 7 = gram; 8 = til/guar; 9 = fodder.

^aPrices and costs are given in rupees (44 rupees = \$1).

^bCurrently there is a fixed agricultural electricity tariff in Rajasthan of 900 rupees per month. This is changing, however, as meters are being installed throughout the state.



Figure 3. The harvest of financially lucrative tomatoes by the partnership in Case Two.

good-quality groundwater and are, therefore, able to grow a highly lucrative tomato cash crop, which they sell to resellers from Delhi (see Figure 3). The women in these families do not work outside of the home except at harvest time and all of their children of age attend school.

To hedge against the possibility of failed electricity on an irrigation day, one partner built a 10×12 ft. ($1,131 \text{ ft}^3$ or $32,026 \text{ L}$) cement holding tank, an institutionalized adaptation.⁹ He attempts to keep this tank full so that if an electricity outage occurs, the water can be used to irrigate a small area of the more sensitive crops, such as tomatoes. If there were more farmers in the partnership, this would be an unaffordable luxury because each partner would have fewer days of tubewell access, limiting the amount of water that could be drawn off for the holding tank. It is also rare that the electricity would be off for more than twenty-four hours, decreasing the prospect of crop failure for the members of small partnerships.

With the adoption of the tubewell, the farmer becomes subject to both opportunities (the cultivation of lucrative vegetables) and constraints (the vegetables must be irrigated, which is sometimes problematic), leading to the holding tank adaptation. Having the financial capital to construct a large tank and few enough partners so that it can be filled permits the cultivation of more lucrative crops, which leads to further political ecological differentiation between partnerships.

Case Two. Seven Meenas (SC) formed this partnership in 2002, when they constructed their tubewell for 56,000 rupees (8,000 per partner). It is 57 m deep with a 7.5-horsepower pump and a discharge of no more than 300 Lpm. Their average agricultural income was 8,000 rupees on 1.39 ha, with the primary holder earning a little more. This income is much smaller than that in Case One due to poorer land and groundwater quality, which is the result of many partners (who place heavy demands on the tubewell and groundwater), poorer land quality, and smaller landholdings in the area, resulting in higher concentrations of tubewells that cause mutual interference. Each partner produces the same crops (but in varying combinations) due to poor groundwater quality. There is little negotiating of the crops to be grown or of the irrigation schedule, because poor groundwater quality limits the variety of potential crops. According to one partner, "We get along fine. The water is hard [*talia*] and we cannot grow much. So what is there to argue about?" It also prevents them from producing lucrative vegetables, as in Case One, which drastically limits their profits. Each partner is allocated one day of the week on which to irrigate and each partner follows consecutively. If on one day, there is no electricity or there is a maintenance problem with the tubewell and it is not possible to irrigate, that partner loses a turn. This farmer may buy tubewell time from one of the other partners, but this is rare as each partner's allocation is already maximized. According to one partner, "We have

become dependent on groundwater and electricity. But we do not know when they will come. So somebody must wait [day and night]. It is even more important because we have many partners." Access is limited by sporadic electricity and the number of partners, which increases the importance of waiting for electricity. This responsibility is often borne by females. The females in these families work in the fields and for other farmers. Daughters do not attend school beyond the fifth grade, limiting their future prospects and exacerbating inter-partnership, gendered social differentiation.

This partnership has very little ability to weather sporadic electricity supply and tubewell availability. Vegetable production is impossible because seasonal and daily groundwater drawdown in the area makes their water rich in saline and minerals. Instead they focus on grain crops (wheat and pearl millet), which are more drought tolerant, less sensitive to seasonal irrigation timing, and can be used as animal fodder whether or not they produce a seed crop. Finally, they are irrigating nearly 10 ha ($1.39 \text{ ha} \times 7 = 9.73 \text{ ha}$) with one tubewell, as compared to Case One, which is irrigating only 4.06 ha. The result is more irrigated area, but with a greatly reduced quantity and quality of irrigation water. This limits them to the cultivation of fodder crops and negatively impacts soil quality over time, again exemplifying the recursive process of exacerbated political ecological differentiation from tubewell adoption.

Case Three. Nine SC Meenas formed this partnership in 2001, when they constructed their tubewell for 90,000 rupees (10,000 per partner). It is 66 m deep with a 7.5-horsepower pump and a maximum discharge of 275 Lpm. As opposed to a typical tubewell construction, which is located at the ground surface, this one is constructed in a dug well 20 m deep. Near the bottom of the dug well, they constructed five 10-m, horizontal feeder tubes (with considerable time and effort) that emanate like spokes from the center to increase the efficiency in drawing in surrounding groundwater. This is a very common adaptation for two reasons. First, utilizing the depth of the existing dug well reduces the cost of digging a tubewell. Second, the horizontal feeder tubes use the cavity of the dug well to create a sink for groundwater.¹⁰

The average agricultural income of a member of this partnership was 22,700 rupees, with the eldest holder earning 35,000 rupees on 1 ha. Each partner is allocated one day every nine days in which to irrigate and each partner follows consecutively. Negotiating which crops to produce is less contentious in this partnership, as the groundwater quality is better than in Case Two but not

as good as in Case One. Even though they are irrigating over 9 ha with one tubewell, they are able to grow some vegetables; however, one tubewell cannot provide enough irrigation water to irrigate 9 ha of tomatoes or other water-intensive crops. This accounts for their diversity of crop production. Groundnuts, a cash crop, require more water than pearl millet but not as much as tomatoes. Members could split the partnership or construct a new tubewell, but the combination of the long wait for an electrical connection, and the cost and the fear of overpumping in a small area (indicating hydrogeological knowledge), are factors in not constructing an additional tubewell and limiting this institutional innovation. The combination of groundwater quality, the high number of partners, and the desire to produce cash crops results in an intensively irrigated landscape but one that is socioecologically uneven.

In sum, Cases One and Three coordinated irrigation timing to produce lucrative vegetables, which enhances their economic position. In contrast, Case Two, even though it had fewer partners than Case Three, grew fewer types of crops (pearl millet and wheat) that were less water intensive and would also grow with poorer quality irrigation water. Although the partners in Case Two were located in the same proximity as the other cases, the high degree of ecological variation in groundwater—where Case Two had poor-quality groundwater with low recharge—made it difficult to irrigate sensitive crops. Their lower agricultural incomes reflect this ecological reality. Moreover, Case Two illustrates the complex interaction of the constraints imposed by tubewell adoption with household reproduction activities, social stratification, and gender inequality. Case Three shows how farmers adapted tubewell technology to meet changing ecological demands. The method of placing a tubewell within an existing dug well ("dug-cum-bore well") is both cheaper and more productive, even though the process is labor intensive. Finally, the cases all illustrate intrapartnership struggles over production, but there are also interpartnership struggles. For example, according to one upper caste Brahmin:

The Meenas [low castes] are using too much water with their poor farming practices. The [ground] water doesn't come to us anymore. They are excavating their land to sell it to the brick kilns. This causes the rain to settle into their land and not into ours.

Sentiments such as these are widely held, whether or not the beliefs on which they are based actually reflect irrigation practices.

These adaptive institutions are very dynamic. Trawick (2001a, 2003) demonstrated six principles in Andean irrigation that were critical to the cohesiveness of cooperative irrigation and that, in his study, were never compromised. Three of these included “transparency” in rule making and allocation, “proportionality” in irrigation quantity, and “regularity” in irrigation timing. In this case, only the first, transparency, is practiced in an uncompromising way. The other two, proportionality and regularity, are constantly renegotiated within changing ecologies and attributable to sporadic irrigation availability, which is both due to irregular electricity supply and to short-term groundwater decline and salinity. Therefore, these institutions do not come into being because of their equitable character but form and persist due to the complex relationship among farmers, tubewells, ecology, and the political economy of production. This dynamism strengthens the institutions, rather than undermining them. Through these processes of mutual nature–society–technological transformation, ecologies and tubewells become socialized (Latour 2005).

Discussion: Recursive Ecological Change and Adaptive Social Institutions

The present situation and direction of ecological change, technology adoption, and human adaptation cannot be properly understood without examining the emergent relationship between agrarian technologies and dynamic socioecologies. Specifically, human and nonhuman nature, tubewells and irrigation, cropping constraints, and changes in groundwater quality act synergistically as both cause and consequence in the processes of ecological (groundwater and land use) change and dynamic social institution formation. These come together because of the tubewell and they cannot be separated analytically, nor can the durability of what appears social—the social institutions of cooperation—be understood without looking to the nonhuman objects that give them their “steely” permanence. Objects are all social, where to be “social” is not a “domain of reality or some particular item, but rather is the name of a movement, a displacement, a transformation . . . an enrollment” (Latour 2005, 64). What we generally understand to be social relations are held together by nonhuman objects and their ability to assemble. The tubewell enrolls other actors into associations with it. Rather than looking at the associations themselves as strict ANT would have us do, however, we need to

focus on the actual production of hybrids, which illuminates causality and directedness in these processes (Swyngedouw 2004).

Tubewell groundwater-lifting technology has capacity, through its associations with other objects, to drive processes of social institution formation and political ecological change at different moments in the economic process. First, social power is a product of the emergent relationship between these heterogeneous actors. Second, local, social, groundwater, and cropping pattern changes have produced a complex regional landscape. This change is nonlinear and recursive, however, undermining the notion that these phenomena can be studied as separate domains of inquiry. Third, following the proliferation of the tubewell in the study area, new social institutions have formed around the demands and constraints of the technology, in a process of reverse adaptation.

First, adaptive social institution formation results from the historical relationship among technology, political economy, and ecology. Tubewell partnerships do reflect a general history of cooperation, as exemplified by previous partnerships in dug wells, but this history of cooperation is grounded in hybrid assemblages of political-economic, technological, and ecological relations, rather than in an independent “culture of cooperation” (Trawick 2001a) or from individual self-interest (Ostrom 1992; Putnam 1995). Tubewells, groundwater, soils, and crops are not passive in the productive process. They assemble to produce new crops, forcing social adaptation; they reassemble in groundwater decline and edaphic change, leading to yet further adaptations—the return to drought-tolerant crops.

Second, the initial rise in lucrative and irrigation-intensive HYVs, produced severe groundwater exploitation. This led to declining groundwater quality and to the creation of sodic soils in some instances, which prompted a return to local, more resilient crop varieties. Table 2 showed that the production of many commercial crops in Jaipur District has indeed declined dramatically in recent years, as the production of less water-demanding crops has risen. The changes in type and productivity of the crops being grown cannot be attributed solely to irrigation (character of the monsoon, availability and quality of groundwater, and availability of HYVs, fertilizer, and pesticides are also factors), yet these changes would not be possible without it. This recursive ecological change is the result of the most marginal producers’ ability to create new social institutions (tubewell partnerships) through particular linkages with technology and ecology.¹¹ The

ecological effects of coordinating tubewell use and ownership to bring more irrigated land under the plow are clear at the district level in regional-scale change. However, the major impacts are felt by users and between groups of users, as discussed in the previous section.

When looking beyond district-level change in crop production, a more complicated political ecology emerges. It is a political ecology of differential scarcity grounded in caste and class, as exemplified by the higher number of tubewell partners among SCs in the study. Scarcity does not follow directly from these categories of difference, however. In this case, the politics of groundwater scarcity play themselves out not only among partnerships but also within partnerships. Among partnerships, the association between the number of members in the partnership, the availability of groundwater and its quality, current land use, and the change in land use that results from transformations in water and soil quality via irrigation produced socioecological differentiation. Within partnerships, these processes are made material in the kinds of institutions and practices that farmers devise to overcome the hurdles of access to groundwater, including cost of the tubewell, risk of failure, and the lengthy wait for and high cost of an electrical connection. Therefore, rather than leading to conflict (Trawick 2001a; Meinzen-Dick 2007), scarcity also leads to new forms of cooperation and adaptation. These social institutions of cooperation are an unforeseen result and refutation of expanded, capital-intensive production. Increasing capitalization in agriculture should have led to increasingly individualized production, yet instead it has led to collective ownership of the means of production (tubewells and access to water) and cooperative management institutions.

The demands and opportunities of tubewell adoption, and concomitant ecological change, have led to, third, a process of reverse adaptation, where daily production activities are reverse adapted to meet the demands of the object. The tubewell is a social agent of ecological change (Robbins 2001a). Daily practices follow from these institutions, including waiting on electricity, waiting on water, negotiating among partners for tubewell access, and cropping constraints that follow from groundwater change (which impacts the negotiations). In this way the object (tubewell) disciplines the subject (farmers), but it does not determine socioecological change or outcomes.

The tubewell does not cause groundwater decline any more than it forces people to adopt it, but it does enroll other actors into a network of associations with it. These relationships are not equal. Even before the

tubewell is adopted it is active as a symbol of agrarian power. After it is adopted, it enables and constrains (it has demands such as electricity and maintenance) particular relationships, such as those between and within groups of adopters. It has the capacity to effect socioecological change that is a product of its associations with other objects (Whatmore 2002). This is an emergent property that is the result of the hybridization of human and nonhuman nature. So, too, the shifting relations of power amid users within and between tubewell partnerships emerge from this recursive socioecological change. Consequently, it is not only large-scale economic processes or human agency that drives socioecological change. The dynamic relationship among local, social, and ecological change has regional-scale effects. This change is driven by processes of nature–society–technology hybridization, where the tubewell currently takes center stage. With the introduction of new technologies and further socioecological change, however, the current relationships could be altered. For instance, more efficient irrigation systems could be fostered by building on the durability of the existing dynamic networks. The character of these hybrids could be renegotiated to be more socially even.

Conclusion: Hybrid Landscapes and Groundwater Governance Reforms

The case presented here informs a fundamental question about accounting for the nonhuman in political ecological explanation and what it means for adapting to social, ecological, and technological change. Understanding the complexity and directedness of these processes informs the creation of formal groundwater governance institutions, which are currently being proposed in Rajasthan and India more generally. Efforts that rely on social capital or tragedy of the commons approaches, whether cognizant of it or not, however, are based on a limited conception of agency (even toward humans, let alone nonhumans) and a “distinctly apolitical and localized analysis of social and political institutions” that neglects relations of power (Mosse 2003, 275).

Following Robbins (2001b), hybrid landscapes are inevitable, “but their rate of proliferation and trajectory of change are products of specific planning histories” (656). Although he was referring to forests, the same applies for dynamic groundwater-dependent socioecologies. This article shows the differentiating effects of tubewells, but the success of the partnerships in

mediating these processes illustrates their strength and potential for positive change. After Moench (2002), who calls for social institutions capable of adapting to change, these tubewell partnerships are such institutions. They are ever shifting within dynamic socioecologies, of which they are both cause and consequence, but they are durable and capable of mediating dramatic socioecological change. Again, the tubewell is what brought these various actors together. If, as in more traditional approaches to the study of irrigation socioecologies, we take technology and the nonhuman to be inanimate objects and socioecological change to follow from human action, we miss the true character and dynamic strength of these institutions.

Although the nonhuman has the capacity to effect change in humans through their various associations, humans ultimately have the ability to rearticulate their network of relations, shifting the associations along the way for their own benefit. These existing networks (institutions and technologies) should not be abandoned but embraced. For instance, they could be rearticulated and channeled to aid in the development of efficiency-enhancing technologies, such as locally engineered but state-supported drip irrigation systems. Drip irrigation systems have been shown in southern India to enhance irrigation efficiency by up to 60 percent (Narayanamoorthy and Deshpande 2005). Their introduction would alter the current configuration of the network but would not disband it. Instead, new, more socially beneficial forms of socioecological change could occur.

What does this mean for groundwater governance and the future of socioecological change? It means that land use, groundwater, and political ecological research need further integration to allow us to fully comprehend the recursive and nonlinear relationship among these socialized objects. These interrelated processes cannot be examined unless these barriers to our thinking in scientific research are dissolved (Mitchell 2002). In doing so, research will help create sound policy interventions that support local communities and ecologies rather than undermine them.

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Notes

1. It is estimated that of the 300 million ha irrigated globally, 85 million to 95 million depend on groundwater, and 85 percent of these areas are in India, Bangladesh, Pakistan, Iran, and the north China plains (Shah 2005).
2. See also Yapa (1977), Blaikie (1978), and Freeman (1985). Contemporary research continues to draw inspiration from innovation diffusion (see Miller and Hope 2000; Webber 2006).
3. Diesel pumps located at the ground surface are still in use, but their efficacy is waning as water tables fall and fuel prices rise.
4. The Arthashastra, for example, which sets out rules and regulations for the use and taxation of irrigation water, was written no later than AD 150.
5. The trend in higher off-farm income among the most marginal of peasant farmers has been shown by many (Bryceson 1997, 2002) as they are propelled into off-farm labor to supplement inadequate agricultural surplus.
6. These percentages, for the most part, are based on farmer responses. The author stepped off three fields to check for accuracy and found the farmers' estimates to be very precise, but the percentages should be taken as approximations.
7. What does this mean for the future of neoliberal reform that is based on individual property rights? See Birkenholtz (2008b).
8. I found little indication that there were any existing partnerships in the study area (or beyond, based on comments from seventy-eight respondents) not founded on kinship. There was one atypical partnership that cut across caste lines, but the members proclaimed that they were an exception.
9. Smaller tanks for drinking water (between 250 and 1,000 L) are common throughout South Asia, but these are not.
10. Partially or completely defunct dug wells are also increasingly being utilized for rainwater harvesting. Farmers drain their rooftops into them after running the rainwater through a small settling box, where the silt is allowed to drop (gravity drop-box) before the water enters the well.

11. Results of ordinary least squares regression comparing the change in marginal landholdings (a census category of landholdings less than 1.0 ha) and the change in tubewell-irrigated area show a strong, positive relationship between the two with $R^2 = 0.724$ at the 99 percent confidence level.

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