Institutional Boundaries and Common-Pool Resource Management: A Comparative Analysis of Water Management Programs in California

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Abstract

Policymakers and academics often identify institutional boundaries as one of the factors that shape the capacity of jurisdictions to manage natural resources such as water, forests, and scenic lands. This article examines two key bodies of literature—common-pool resource management theory and local public economy theory—to explain how the boundaries of political jurisdictions affect natural resource management. Two empirical methods were used to test hypotheses from the literature, using a study of water management programs in California. The results demonstrate that institutional boundaries that coincide with natural resources are likely to be associated with the implementation of more effective resource management programs. At the same time, where jurisdictions can control through coordination, they can also facilitate more effective resource management where jurisdictions do not match resource boundaries. © 2004 by the Association for Public Policy Analysis and Management.

INTRODUCTION

Policymakers and public administrators face a host of problems in managing common-pool resources (CPRs)—such as water, forests, and fisheries—due to their physical characteristics. As with public goods, it is often difficult to exclude users from CPRs. Yet, unlike public goods, CPRs are highly subtractable, meaning that any one appropriator of a CPR can deplete the supply of that resource available to others. Because of these characteristics, CPR users often face problems of overconsumption or resource depletion. What, then, might facilitate more efficient and sustainable CPR management to maintain adequate resources for future generations? Many scholars recognize that institutions play a key role in shaping how CPR users coordinate their actions to solve supply and demand dilemmas (Ingram et al., 1984; Lam, 1998; Lord, 1984; E. Ostrom, 1990). Institutions are the laws, policies, and organizational arrangements that communities devise to permit, forbid, or require certain human behavior (Crawford and Ostrom, 1995; North, 1990; E. Ostrom, 1990). Institutional arrangements can include enforced formal laws governing individual behavior, public and private organizational arrangements, as well as informal norms and standards shared among communities.

This article examines one way formal institutions shape the management of CPRs by analyzing the relationship between the scale of water-governance institutions and

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the use of a promising water-management method known as conjunctive water management. Water is a considerably valuable CPR, as increased urbanization and higher intensity agriculture have created severe water supply and water quality dilemmas worldwide, particularly in arid regions such as the southwestern United States (Case and Alward, 1997; El-Ashry and Gibbons, 1986; Reisner and Bates, 1990).[1] The scale of institutional boundaries, or jurisdictions, has been considered particularly relevant in shaping water resource management. For instance, recent calls for "watershed level" institutions suggest that small or fragmented institutions governing water resources lack both the ability for comprehensive resource planning and the ability to address problems that cross state and local boundaries (Dzurik, 1990; Gottlieb and FitzSimmons, 1991; Kenney, 1997). While such studies acknowledge the importance of institutional boundaries for managing water resources, the relative effectiveness of different types of institutional boundaries in facilitating improved water resource use remains open to empirical analysis. Clarifying the relationship between water management choices and institutional boundaries not only informs studies of water management; it also provides insights to understanding how different governance arrangements are likely to affect other resource management choices.

CONJUNCTIVE WATER MANAGEMENT IN CALIFORNIA

One of the responses to the dilemma of ensuring adequate water supplies for human and environmental demands has been to coordinate the management of groundwater and surface water, or "conjunctive water management." In general, the goal of conjunctive water management is to provide water supply reliability by coordinating the timing of the use of ground and surface water supplies (Bookman-Edmonston, 1979; Thorson, 1978; Todd and Priestaf, 1997; Trelease, 1982; WSWC, 1990). For more than 50 years, conjunctive water management has been promoted as an effective alternative to expensive and ecologically damaging dams and reservoirs, which have become less palatable politically as water management options (Thorson, 1978; Trelease, 1982; U.S. ACIR, 1991).

Conjunctive water management can be accomplished in various ways. Many conjunctive management projects rely on the capacity of underground aquifers to store surface water supplies. When surface water is abundant during times of abundant precipitation, excess supplies can be stored underground through artificial recharge or seepage. Recharge can occur through constructed basins where surface water is delivered and then percolated through soils, through injection wells, or through streambeds (Bookman-Edmonston, 1979). Stored water can then be extracted by pumping groundwater in times of drought or increased demand. Conjunctive water management also occurs indirectly when surface water is imported to areas that rely on groundwater; this reduces groundwater pumping during peak times and allows basins to refill naturally. These basins can then be drawn down at times when surface supplies are low. To engage in conjunctive water management successfully, organizations require adequate groundwater storage capacity and surface water access, as well as assurances that they will be able to store and recover water in underground basins without other water users interfering with or consuming those supplies (Blomquist, Heikkila, and Schlager, 2001).

[1] For instance, U.S. census data show that between 1990 and 2000, populations across some western U.S. states increased more than 30 percent, the most rapid growth being concentrated in areas such as Las Vegas, Phoenix, Denver, and San Diego (U.S. Census Bureau, 2001). Meanwhile, the number of western farm acreage decreased slightly, but the average value of croplands across the West increased (USDA, 1999).

One of the benefits of this approach is the potential to economize on the costs of surface water storage and distribution facilities to meet peak demands (Bookman-Edmonston, 1979; Fisher et al, 1995; Trelease, 1982).[2] In addition to the dilemma of growing demands for limited water supplies, many water providers face the fact that surface water flows are least abundant during summer months when municipal and agricultural water demands usually are highest. Conversely, when flows are most abundant, demand is much lower.[3] When water providers have the capacity to change from surface water to groundwater supplies during peak demand, they can avoid the costs of adding higher increments of storage and delivery capacity to their surface supply systems. Similarly, when communities that rely on groundwater take advantage of surplus surface flows and allow groundwater basins to replenish naturally, they can avoid the costs of deepening wells to reach lowered water tables. The use of groundwater for consumptive use during peak demand also helps maintain instream flows that are often critical for meeting nonconsumptive needs during dry seasons. But conjunctive management is not a panacea. When pumping and extracting water from basins that are hydrologically connected to surface flows, drawing down the water table can damage the natural hydrologic connection between ground and surface flows (Glennon and Maddock, 1997; Matthews, 1991). Also, excessive pumping may reduce available flows for surface users or endanger species of wildlife. These problems, however, can be even more severe when groundwater supplies are pumped without the option of using surface water to replenish depleted flows, and vice versa. Thus, despite the potential downfalls, the benefits of conjunctive water management are still greater than managing ground and surface water supplies separately.

California offers a useful setting for evaluating the variation in conjunctive water management relative to institutional boundaries. California's water demands have been growing consistently over the past decades, particularly in relatively arid areas of the state (CDWR, 1998a). Due to the state's high water demands for agriculture and urbanization, the need for conjunctive management certainly exists, yet the use of conjunctive water management varies across California (Blomquist, Heikkila, and Schlager, 2001; Purkey et al., 1998). Another reason California is an appropriate setting for evaluating conjunctive management programs is that many areas of the state have the physical capacity to devise conjunctive management programs. Adequate underground storage is vital to developing conjunctive water management programs. Groundwater is relatively abundant in California, lying below nearly 40 percent of the state's lands, and surpassing the quantity of surface water available in the state nearly sixfold (CDWR, 1998a). Statewide, water users also have access to infrastructure and surface supplies often used in conjunctive management programs, since the state and the federal government have financed the construction of large north-south water diversion projects throughout California (U.S. ACIR, 1991).

In addition to the demand and physical capacity needed for conjunctive management, California is an appropriate setting for evaluating institutional boundaries because of its diverse institutional arrangements governing groundwater. Although

[2] For example, according to the California Department of Water Resources (CDWR, 1994), storing surface water in reservoirs costs about $800 per acre-foot of water, whereas storage through conjunctive management costs about $150 per acre-foot. (An acre-foot is equivalent to about 325,000 gallons of water.)

[3] The disparity between the timing of water availability and peak water demand causes municipal water providers—in California, for example—to invest more than a billion dollars a year to establish water supply systems and reservoirs that provide reliable flows for peak demand (Purkey et al., 1998).

surface water governance is relatively similar throughout California, groundwater governance is highly decentralized. The only statewide rule governing groundwater is that all land-owners have the right to pump groundwater underlying their land. Beyond this basic right; the state gives local institutions the authority to limit or manage groundwater use.[4] For example, some communities of groundwater users have undergone special court adjudications, which quantify and limit rights to all users overlying a geographically defined groundwater basin. Other institutional arrangements include city and county management ordinances that regulate basin activities, as well as special districts authorized by the state legislature (CDWR, 1998b). These institutions may be involved in determining groundwater rights, regulating groundwater pumping, or funding the storage of water underground (CDWR, 1998b). Although a number of local communities have established institutions to manage basins in California, not all have done so.[5] Since conjunctive management projects rely on basin-level storage and retrieval, the different locally defined institutional arrangements can clearly influence the feasibility of engaging in conjunctive management.

THEORY: JURISDICTIONS. BOUNDARIES AND RESOURCE MANAGEMENT

Self-Governance Institutions and Common-Pool Resources

One long-term research program that can help explain how and why the boundaries of institutions might affect the implementation of different operational resource management techniques, such as conjunctive management, is the study of CPR management, developed most notably by Elinor Ostrom and colleagues. CPR management theory evaluates how institutions influence the use of CPRs, such as water, fisheries, and forests (E. Ostrom, 1990, 1998, 1999). CPRs exhibit varying degrees of two key characteristics: difficulty in excluding users and subtractability of supplies, where each resource user reduces the supply available to others (E. Ostrom, Gardner, and Walker, 1994). The first characteristic can lead to problems of free-riding or insufficient maintenance of supplies. The second characteristic can create problems of over-appropriation or congestion. Conventional wisdom may presume that the use of CPRs leads to the "tragedy of the commons," or ultimate destruction of the resource, yet CPR management studies have shown that CPR users often devise institutional arrangements to resolve these dilemmas (Blomquist, 1992; E. Ostrom, 1990; E. Ostrom, Gardner, and Walker, 1994; Schlager, 1990; Tang, 1992).

CPR studies show that effective institutional arrangements for managing resource dilemmas vary depending on physical and community conditions (Lam, 1998). Effective institutional arrangements may diverge across settings, yet CPR studies have identified some general principles of long-enduring, self-governed CPR insti-

[4] Surface water in California, on the other hand, is governed largely by the prior appropriation doctrine. The prior appropriation doctrine establishes rights to surface water based on the timing of beneficial use. Those appropriators who use stream flows for beneficial purposes at the earliest point in time have superior rights to use their claimed water rights when flows are insufficient to supply all water lights claimants.

'California's system of groundwater governance differs from most states' where groundwater institutions are most often imposed at the state level. California's local-level institutions arguably may be better at addressing and solving problems that a group of shared groundwater users face. However the implementation of groundwater management institutions requires extensive coordination and pressure from policy entrepreneurs (Blomquist, 1992). This system can cause some uncertainty about the effectiveness of different institutional arrangements for facilitating sustainable groundwater management, as each basin may be governed by a unique set of rules tutions. The first design principle associated with sustainable CPR governance institutions is the establishment of clearly delineated boundaries around the resource and resource users (E. Ostrom, 1990, 1998). CPR studies have identified a number of other key design principles of successful institutional arrangements for managing CPRs. This article primarily focuses, however, on the first principle.

CPR theory's boundary principle implies that institutions whose boundaries are congruent with the scale of the physical boundaries of a CPR are more likely to be successful and sustainable. E. Ostrom notes (1990, p. 91): "Without defining the boundaries of the CPR and closing it to 'outsiders,' local appropriators face the risk that any benefits they produce by their efforts will be reaped by others who have not contributed to those efforts." Thus, the literature has shown a clear relationship between the successful resolution of CPR dilemmas and the organization of institutional arrangements that are clearly defined around CPR boundaries. According to the principle, one can assume that in managing water supplies using a method such as conjunctive management, then the institutions governing the basins where water is stored and recovered would be more effective when organized around the boundaries of the groundwater basin. Based on this assumption, the following hypothesis is proposed:

HI: Water management institutions that are organized around the physical boundaries of groundwater basins are likely to be positively associated with the use of conjunctive water management.

Considering the Boundary Criterion in Complex Settings

The institutional boundary principle coming out of CPR theory appears to present some limitations in its applicability to large-scale or complex water management situations. First, in some natural resource settings, the physical boundaries of the resource can be difficult to identify, particularly where resource flows are highly mobile, or where flows are interrelated with other resources. Even where it is possible to identify general physical boundaries of CPRs, such as with stationary groundwater basins, people constantly redefine institutional boundaries based on changing perceptions of their needs and problems. The boundaries that CPR users identify around a resource may depend more on the human problems associated with the use of the resource than on the physical location or flow of a CPR.

Another potential limitation is that CPR users usually live within complex and overlapping institutional settings that may not be conducive to devising management institutions that apply to some physical boundaries. The CPR literature, however, acknowledges that self-governing jurisdictions can function in concert with larger institutional arrangements within which they are embedded. For instance, it describes ways in which larger institutional arrangements, or "nested" institutional settings can provide information and support to help sustain local governance of a CPR (E. Ostrom, 1990, p. 90; E. Ostrom, Gardner, and Walker, 1994). The problem that remains with the literature is that it still does not specify how institutional boundaries matter within complex CPRs when boundaries are difficult to define or when CPRs are part of a larger institutional system.

Studies of local public economies and public service industries provide some key insights that can explain more accurately how boundaries matter within complex physical and institutional settings. CPR studies and local public economy studies both have developed out of a research framework, known as the Institutional Analysis and Development Framework, which emphasizes the importance of institutional arrangements in shaping solutions to collective action problems (E. Ostrom, 2000). Local public economy and industry studies consider the effective resolution of collective action problems among organizational level actors, while CPR studies emphasize the variables and incentives that shape collective choices among individual actors. Therefore, the two literatures offer related, yet distinct, solutions to resource management dilemmas.

In general, the literature on local public economies describes the potential advantages of overlapping political jurisdictions for meeting citizen demands for public goods and services adequately and cost-efficiently (Oakerson, 1999; Oakerson and Parks, 1988; Parks and Oakerson, 1993; U.S. ACIR, 1987, 1991). The term "local public economy" refers to the collection of overlapping jurisdictions that supply and produce various public goods and services in a community such as a metropolitan area (Oakerson, 1999; Oakerson and Parks, 1988; U.S. ACIR, 1987). This research also describes the collection of overlapping jurisdictions that coordinate to provide or produce specific goods or services within a particular sector of the public economy as a "public service industry" (V. Ostrom and E. Ostrom, 1991; U.S. ACIR, 1991).[6] The U.S. water industry, for example, acts as a collection of public, private, and quasi-governmental water providers, government regulators, and administrators that cross multiple political jurisdictions (Grigg, 1996; V. Ostrom, 1971; U.S. ACIR, 1991).

Given this description of overlapping jurisdictions that provide and produce goods and services, what does the public economy and industry literature offer in terms of understanding institutional boundary criteria for managing complex CPRs? In contrast to CPR theory, public service industry literature does not emphasize the physical boundaries of a resource or good as a criterion for identifying the appropriate scale of jurisdictions that provide or produce a sendee such as conjunctive management. The public service industry literature claims that efficient provision scales can be determined by considering which individuals share a common interest in, receive benefits from, and are affected by the provision of a good or service (V. Ostrom, Tiebout, and Warren, 1991; U.S. ACIR, 1987). This does not imply that physical boundaries are unimportant. Local public economy/industry literature has suggested that effective institutional boundaries take into account physical externalities when considering the effects that users of goods and services have on each other (Oakerson, 1999). Yet the theory considers these effects in terms of the common problems that users of a shared good or service face. Thus, when a group of citizens or a local jurisdiction decides to provide a water management service, the basis for that decision is likely to rest on the recognition of some common water supply or demand problem, such as insufficient surface water supplies for irrigators in dry seasons. These problems may or may not coincide with the physical boundaries of a specific stream or groundwater basin.

To solve shared problems and provide goods and services, according to the local public economy/industry literature, overlapping jurisdictions can take advantage of interjurisdictional coordination (Oakerson, 1999). Given that provision, production, and governance can be separated, jurisdictions have opportunities to address a shared problem related to the management or use of a resource by coordinating service production. In relation to conjunctive management, water industry juris-

[6] A public service industry, or a local public economy, has three components. They are jurisdictions and organizations that provide (fund) a good or service, jurisdictions and organizations that produce or supply a service or good, and jurisdictions and organizations that legislate and administer rules governing production and provision (Oakerson, 1999; V. Ostrom and E. Ostrom, 1991; U.S. ACIR, 1991).

dictions may be able to facilitate conjunctive water management by coordinating their efforts to acquire water, store water underground, and recover that water. Interjurisdictional coordination, in effect, can allow small-scale jurisdictions to engage in conjunctive water management in a way that eliminates the need for a large centralized authority to encompass a large watershed. From this discussion, the following hypothesis is derived:

H2: Interjurisdictional coordination is likely to be positively associated with the provision of conjunctive water management services.

EMPIRICAL MODELS

This section empirically tests the hypotheses regarding the relationship between the boundaries of groundwater management institutions and the use of conjunctive water management in California basins. A logistic regression model provides the first test. A method known as qualitative comparative analysis (QCA), developed by Charles Ragin (1987), supplements the logistic regression model.

The data used in these analyses came from a larger study funded by the National Science Foundation (NSF) and Environmental Protection Agency (EPA) that compared conjunctive management activities across Arizona, California, and Colorado.[7] Data collection began with the identification of conjunctive management programs in each state during 1997. Surveys of water providers in each state identified the existence of conjunctive management projects and types of projects operating. In California, the principle investigators conducted a 30 percent cluster sample of the population of California's 450 groundwater basins, as mapped by the California Department of Water Resources, to identify conjunctive management projects. The sampling frame was based on the state's seven major hydrologic regions, as identified by the Department of Water Resources. Before sampling the basins, two hydrologic regions were eliminated based on the physical conditions and low water demands, making the regions not conducive to conjunctive management. From the remaining five regions, the sample randomly selected 70 basins. Researchers used a list of California's water providers by zip code to identify water providers operating in the sample basins. The study team then surveyed water providers to determine the type and number of conjunctive water management activities operating in the sample basins. For the logit and QCA models, if the surveys identified any conjunctive management projects in a basin, then the basin is coded as a 1 for the dependent variable. If no conjunctive management projects are active in a given sample basin, then the case is coded as a 0 for the dependent variable.[8]

Variables and Indicators

The dependent variable for the analytical models is the presence of conjunctive water management projects in a groundwater basin. To evaluate how the bound-

[7] See NSF/EPA Water and Watersheds Grant, number R824731.

[8] This analysis does not consider the number of conjunctive management projects in a basin, thus potentially losing magnitudes of difference. However, the purpose of this paper is to assess the factors that can facilitate conjunctive management, not to compare the volume or quality of conjunctive management across basins. In most basins very few projects occur, and measuring the number of projects provides little additional information on the extent of conjunctive management programs, as the size and capacity of these projects can vary extensively. Thus, a measure of number of projects may provide a false sense of quality of conjunctive management in basins.

aries of groundwater management institutions relate to conjunctive management activities, the independent variables for the models include the four primary types of groundwater management institutions whose scope of authority and jurisdictional boundaries differ. Among the population of California basins, some may have multiple groundwater institutions, a single institution, or none of the groundwater management institutions. The first two institutional forms used in the models have boundaries that are congruent roughly with the groundwater basins they overlie.[9] The third form covers the boundaries of multiple jurisdictions that overlie a common basin. The fourth institutional form does not have boundaries that match the physical boundaries of basins. Using data from the California Department of Water Resources, each basin is coded for the presence or absence of the four institutional variables.

The first type of local groundwater institution is a special groundwater management district. The California legislature has authorized a number of special districts to engage specifically in groundwater management. The state has created 12 groundwater management districts with the authority to regulate groundwater pumping. Additionally, 22 existing water districts also have special statutory authority to engage in various forms of groundwater management, but not all are acting on their authority (CDWR, 1998b). Most of these districts have taxing authority for basin replenishment and recharge.

The second type of local groundwater institution is the adjudicated groundwater basin. In 16 of California's groundwater basins, state courts have adjudicated the quantity of rights available to appropriators and have designated basin "watermasters," who ensure that appropriators comply with assigned rights. Adjudicated basins often are subject to high water demands and the need for comprehensive management is critical. The amount of water a well owner can extract from an adjudicated basin is based on the amount of groundwater available in the basin each year (CDWR, 1994).

The third form of local groundwater institution in this analysis is a legislatively authorized institutional arrangement called an AB3030 Plan. The state legislature changed the California Water Code in 1992 to provide local agencies with a clearly defined procedure for developing a groundwater management plan and the authority to raise money for groundwater management (California Water Code, Sections 10750-10756). Approximately 150 local agencies have begun the process of implementing AB3030 Plans, but these efforts are relatively recent and compliance with AB3030 Plans is voluntary (CDWR, 1998b). The boundaries of this institutional arrangement are limited to the existing scales of local political jurisdictions, which are not devised around basin boundaries. A number of agencies using AB3030 Plans have adopted coordinated management plans across basins using joint powers agreements or memorandums of understanding. Therefore, in many cases the institutional boundaries of AB3030 Plans can cover large areas of basin boundaries.[10]

County ordinances are included as the final form of local groundwater institution. California law does not preclude cities and counties from implementing ground-

[9] Since the boundaries of groundwater basins are less mobile than many resources, the California Department of Water Resources has been able to map the boundaries of major basins. Thus, the estimates of these boundaries, even if not completely accurate or subject to change over time, have been used for the purposes of devising the boundaries of groundwater management institutions in California.

[10] Existing agencies have long held the authority to coordinate the provision of services through joint-powers agreements under the California Government Code Title 1, although the development of AB3030 Plan provides specific processes for setting up a groundwater management plan in a basin. Thus, AB3030 Plans offer institutional design and structure specifically for groundwater management that was not available under California legislation prior to 1992.

water management ordinances, but currently only seven counties have established local management ordinances (CDWR, 1998b). Through such ordinances, counties may create funding and regulatory powers that could potentially encourage conjunctive management in a basin. These institutional arrangements are not devised around groundwater basin boundaries. Table 1 summarizes the boundaries and regulatory powers of the four local groundwater institutions.

In analyzing the relationship between institutional boundaries and conjunctive water management, the models also incorporate variables that control for certain physical and human conditions in a basin that impact conjunctive water management practices. The first two control variables represent demand for water. As stated earlier, one of the main goals of conjunctive management is to stabilize water supplies and to protect water users from drought conditions. Growing water demand by municipalities, agriculture, and industry facilitates the need for various forms of comprehensive water management. Therefore, conjunctive management presumably would be more likely to occur where urban or agricultural demands are high. While many areas of California have excessive water demands relative to supplies, it still has substantial rural and undeveloped regions with low water demand (CDWR, 1994).[11] The measures for water demand come from 1997 U.S. Census data on population density and irrigated acres of land in counties that surround or overlap the sample basins (U.S. Census Bureau, 2001).[12]

The third control variable takes into account the physical capacity of groundwater basins to store surface water. Deciding where conjunctive management is feasible, through underground storage depends on hydrogeologic conditions of a basin, including the storage and production capacity of groundwater basins and the movement of groundwater within basins (Bookman-Edmonston, 1979). Specific sites within basins that are best suited to conjunctive management are found where the

Table 1. Institutional forms governing groundwater use in California.

Institutional Type	Boundary Scale	Local Powers
Special groundwater districts	Groundwater basin	General: may regulate extraction and provide basin management
Adjudicated basins	Groundwater basin	Court decrees quantified rights and watermaster monitors
AB3030 / multiagency	Existing cities, counties, irrigation districts	Revenue raising powers for basin replenishment/ management
County ordinances	Counties	General: may regulate groundwater use under police powers

[11] Based on 1995 estimates of urban, agricultural, and environmental water uses, overall water shortages in the state approach 1.6 million acre-feet in years when water supplies are normal, and 5.2 million acre-feet in drought years (CDWR, 1998a).
[12] Where more than one county overlaps a basin, the county with the majority of overlying land in the basin serves as the basin-level indicator. If the basin area is roughly equal across county boundaries, then the population and agricultural indicators for the counties are averaged.

soils and clay layers in a basin allow for high rates of infiltration and high well yields (Hauge, 1992). These hydrogeologic characteristics, however, can vary substantially across groundwater basins, and can vary within a basin or even a sub-basin. The analysis presented here focuses on basin-level factors and not sub-basin conditions, so the third control variable is the storage capacity of basins, which can be measured at the basin-level. Basins with low natural storage capacity are less likely to be used for conjunctive use projects (Hauge, 1992). The California Department of Water Resources Bulletin 118 provides measures of the storage capacity of individual groundwater basins (CDWR, 1994).

Conjunctive water management projects are not likely to be feasible without sufficient access to surface water supplies at some time during the year. Given the scarcity of native surface water supplies in many parts of California and the fact that where substantial native supplies exist they have been dammed and diverted, constructed water projects have become an important component in the development of conjunctive management activities (MWDSC, 1996; Purkey et al., 1998). The fourth control variable, therefore, is project water access in a basin. Project water is defined as surface flows imported to an area via California's three major projects: the State Water Project, the Central Valley Project, and the Colorado River aqueduct. The indicator for the quantity of project water available in a basin is based on California Department of Water Resources measures of acre-feet of project water imported to each hydrologic region of the state (CDWR, 1998a). A second indicator of adequate surface water flows or supplemental water available for conjunctive use, and the fifth control variable, is average yearly rainfall in each hydrologic region. The measures of average annual rainfall across California come from 1997 California Department of Water Resources data (CDWR, 1998a).

Table 2 summarizes the expected relationships between each of the independent variables and the presence of conjunctive management in a California groundwater basin. The control variables are indicators of physical and demand conditions that facilitate the use of conjunctive management. Thus, all of these variables are expected to have a positive effect on the likelihood of conjunctive management occurring in a sample basin. The four types of local groundwater institutions provide indicators of institutions whose boundaries differ. Hypothesis 1 claims that institutional boundaries that match resource boundaries are likely to be positively associated with conjunctive management. Therefore, if only adjudicated basins or special districts, which have boundaries that match groundwater basins, have a

Table 2. Summary of model variables and expected impact.

Dependent Variable = Conjunctive Water Management Projects		
Independent Variables	Indicator of	Expected Impact
Population density	Urban water demand	+
Irrigated acres	Agricultural water demand	+
Basin storage capacity	Physical capacity for CWM	+
Project water availability	Surface water access	+
Av. annual rainfall	Surface or storm water access	+
AB3030 plans	Coordinated jurisdictions	+ Supports H2
County ordinance	Non-basin level jurisdiction	- Supports HI
Special GW district	Basin-level jurisdiction	+ Supports H1
Adjudicated basin	Basin-level jurisdiction	+ Supports H1

positive effect on conjunctive management outcomes, this would support Hypothesis 1. Hypothesis 2 claims that interjurisdictional coordination can facilitate conjunctive management, rather than a single jurisdiction devised around basin boundaries. Thus, if AB3030 Plans have a positive relationship with conjunctive management outcomes, this would support Hypothesis 2.

Logit Analysis

A logit regression model provides the primary test of the effects of the independent and control variables on the likelihood of conjunctive water management occurring in the sample of California groundwater basins. Table 3 presents the results from the logit regression analysis. The logit model appears to be a strong estimator of the probability of conjunctive water management. As a whole, the variables used in this model are significant (x^2 = 62.56) and the likelihood of correctly predicting the presence of the dependent variable using this model is 97 percent. To calculate the magnitudes of the effects of the independent variables on the probability of conjunctive management using the logit model, the following formula is used:

$$P(Y) = l/(l+exp(-(a+B_1X_1+B2X2+B_3X_3....))) \quad \text{(Eq. 1)}$$

Table 3. Logit regression analysis of effect of groundwater institutions on conjunctive water management.

Variable	*B* (s.e.)	*Wald*x^2	ExpCB)
Population density	-0.002 (0.002)	1.92	0.998
Irrigated acres**	0.021 (0.009)	5.09	1.02
Basin storage capacity (maf)**	-0.047 (0.022)	4.64	0.954
Project water available (taf)**	0.011 (0.034)	4.49	1.01
Average annual rainfall*	0.365 (0.207)	3.12	1.44
AB3030/multiagency plans**	10.78 (4.63)	5.44	48982
County ordinance**	-16.17 (7.27)	4.95	0.000
Special GW district*	7.18 (3.74)	3.69	1309
Adjudicated basin	23.97 (92.99)	.066	25754956319
Constant**	-18.11 (8.04)	5.07	0.000

* = significant at a= 0.10
** = significant at *a*= 0.05 *B* = the effect of variable on log-likelihood of *Y*.
Exp(S) = the effect of variable on probability of *Y*.
Overall % of Correctly Predicted Cases = 97%.
Model Chi-Square = 62.56.

The logit results show that conjunctive water management is likely to be implemented under institutional settings that control the boundaries of the groundwater resource in California. For example, the presence of a special groundwater district in a basin, holding all other variables constant, significantly raises the probability of correctly predicting the presence of conjunctive management in a given basin. On the other hand, the county ordinance variable has a significant negative effect on the dependent variable. The presence of county ordinances, holding all other variables constant, reduces the probability of conjunctive water management occurring in a basin to nearly zero. These results appear to support the CPR theory hypothesis that institutional boundaries that are devised around resource boundaries can facilitate improved resource use.[13]

The AB3030 variable provides support for Hypothesis 2, showing a significant and positive relationship with the likelihood of conjunctive management occurring. As stated earlier, these plans provide legislative approval for local jurisdictions, such as cities and irrigation districts, to manage shared groundwater with other providers in the basins.[14] In other words, AB3030 Plans do not create a single jurisdiction that is co-extensive with a single basin, but they allow for interjurisdictional coordination that may correspond to the boundaries of a single basin. Thus, the logit model supports the Hypothesis 2 without rejecting Hypothesis 1.

The control variables in this model also offer some notable results. The coefficients for the variables representing irrigated acres, project water, and rainfall are all positive, and significant, as expected. The logit results show that a one-percent change in each of these variables would have a relatively small, but positive, impact on the likelihood of conjunctive management in a basin. The basin storage variable has a relatively small, but negative, effect on the dependent variable. This result could indicate that within basins with the largest storage capacities, conjunctive water management is not occurring in California. Practical evidence, in fact, has shown that in some of the largest capacity basins of California's Central Valley, conjunctive management has not been used, even though it is a viable supply management tool (Purkey et al., 1998). From an institutional perspective, these results could represent a different issue: in larger basins, it can be more difficult to coordinate water users to engage in conjunctive water management.

Equation 1 can also be used to evaluate how changing values of any independent variable can alter the effects of other independent variables. When no groundwater institution is present in a basin and all other control variables are at mean values, the probability of conjunctive water management is 0.003, or less than 1 percent. When county ordinances are the only institution in place and all other control variables are at mean values, the probability of conjunctive management is even lower, at 0.00006. When all control variables are at maximum values and county ordinances are the only institution present, the probability of conjunctive

[13] Given the large standard errors and coefficients for some of the institutional variables in this model, an alternative model, suggested by an anonymous reviewer, was also run using a four-value multichotomy for the institutional variables. This involved folding cases with multiple institutional arrangements into a single category, using the "county" variable as the reference. This model produced only slightly lower standard errors on the variables of interest, and was deemed inappropriate theoretically because of the loss of mixed institutional settings. Data and results are available from the author.

[14] Arguably, AB3030 Plans present some problems in determining their causality of conjunctive management projects, given that these plans only have been in existence since 1992. Conjunctive management has been present in California for nearly 60 years in some areas of the state. Without time series data on the development of conjunctive management relative to groundwater institutions, however, this relationship cannot be clarified.

management is still less than 1 percent (0.004). However, when special districts are present, with no other institutional variables in place, and all of the control variables are held at their mean values, the probability of conjunctive water management increases to 81 percent. If, for example, special districts are present, but the variable for irrigated acres is reduced to its minimum value (0.78) (all other controls are at mean values), the probability of conjunctive management decreases to 8 percent.

Calculating the probability of conjunctive management occurring with AB3030 Plans in place, instead of special districts, results in similar, but stronger, effects on the likelihood of conjunctive management. When all control variables are at their mean levels, the likelihood of conjunctive management increases to 99 percent with AB3030 Plans present. Even if the variable for irrigated acres is reduced to its minimum value (0.78), while other controls are at their mean values and AB3030 Plans are present, the probability of conjunctive management is still 76 percent. On the other hand, if all control variables are at minimum values, and AB3030 Plans are present, the probability of conjunctive management is only about 1 percent.

QCA Model

To supplement the results of the logit analysis, this section introduces results from a method known as qualitative comparative analysis (QCA), which is based on Boolean comparative logic (Ragin, 1987). This method compares different combinations of independent variables in relation to a dependent variable, and then simplifies the causal conditions using a bottom-up data reduction process. (See the appendix for a more detailed description of this method.)

The benefit of a Boolean analysis for this study is that it addresses the problem of limited observations in this data, which can reduce the explanatory power of quantitative statistical control models (Ragin, 1987). In many instances, 70 observations are sufficient for quantitative statistical control methods. However, in this study, the number of basins with conjunctive management occurring in the sample of 70 basins is relatively small (15/70). Also, the four types of institutional arrangements in the sample basins occur even less frequently. For example, only five instances of adjudicated basins and eight instances of special districts exist in the sample basins. Though the total number of observations is sufficient for statistical control methods, the number of observations representing the variables of interest is small. Using QCA as a supplemental method therefore offers greater validity to the results of this analysis. Another benefit of using QCA is that it shows qualitatively how different types of interactions among many independent variables are related to an outcome of interest (Ragin, 1987). QCA identifies the actual cases and the interaction terms among variables in those cases that are necessary or sufficient causes of the dependent variable, which can complement the predicted interaction effects from the logit model.

Using the Boolean analysis, all data are coded as binary variables, indicating the presence or absence of each independent variable and the dependent variable. The data reduction process in the Boolean method is designed to reduce the possible combinations of variables associated with the dependent variable by identifying necessary and sufficient causes. For this analysis, combinations of independent variables coded for each case include the same variables used in the logit model. Therefore, the QCA model is concerned with the combinations of the presence or absence of the different independent variables in relation to the presence or absence of conjunctive water management. The following equation models the feasibility of conjunctive water management (CWM):

$$CWM = f(R.I, B, R, W, A, C, D, S) \quad \text{(Eq. 2)}$$

where *P* is high population density, / is high irrigated acreage, *B* is high basin storage capacity, *R* is high annual rainfall, *W* is project water access, *A* is an AB3030 Plan, C is a county ordinance, *D* is an adjudicated basin, and S is a Special District. Appendix A presents all 70 cases, coded with the presence or absence of these variables, as well as the Boolean equations for the data reduction process.

The results from the QCA model overlap the logit results on a number of key points, but also offer insights not provided by the logit model. In general, both the logit and QCA analyses point to the importance of overlying groundwater management institutions in California for facilitating conjunctive water management, supporting Hypothesis 1. Moreover, they show that institutional settings that are devised around the boundaries of the resource, through basin adjudication or special groundwater management districts are associated with conjunctive water management, as proposed by the CPR literature. Adjudication is insignificant in the logit model, but the QCA results add that adjudication is associated with conjunctive management, usually in conjunction with high water demand and physical variables that promote conjunctive management. Moreover, the QCA results explain that a lack of adjudication is a necessary condition for the absence of conjunctive water management in the sample of basins.

In addition, both models indicate that county ordinances are not necessarily effective in promoting conjunctive water management in California. The logit model shows that county ordinances have a large negative impact on the likelihood of conjunctive management. The QCA method shows that the presence of county ordinances, in fact, is often associated with the absence of conjunctive management. Unlike the logit model, the QCA model indicates that county ordinances can be associated with conjunctive water management when other institutional variables also are present. At the same time, the QCA results show that the association between the presence of county ordinances and the absence of conjunctive management is not necessarily due to a lack of water demand or physical capacity.

Another key point of overlap in the two models is that water providers engage in conjunctive water management under institutional settings where they can coordinate with other providers in the basin (AB3030 Plans). The majority of the causal conditions associated with the presence of conjunctive management in the QCA data reduction process indicate that AB3030 plans are positively associated with conjunctive management. The results also bolster Hypothesis 2 in that inter-jurisdictional coordination is likely to be positively related to the presence of conjunctive management programs. However, the QCA method does indicate that the presence of AB3030 Plans can be a casual condition associated with the absence of conjunctive management. Since AB3030 Plans are new and some are not well developed, this result is not surprising. AB3030 Plans, while not devised as a single institution surrounding a basin, can still provide control over basin management by coordinating across existing jurisdictions.

One of the ways the QCA results differ from the logit results is that they highlight more clearly whether multiple institutions shape basin management decisions. Also, the QCA results show that the presence of one or two types of institutions is frequently combined with the absence of two or three alternative institutional vari-

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APPENDIX

QCA Methodology

The first step in the QCA method is to sort all possible combinations, or configurations, of independent and dependent variables that exist in the data. In these data, there are 38 possible combinations of variable configurations. Almost twice as many different combinations of independent variables are associated with an absence of conjunctive management as the number of configurations related to a presence of conjunctive management in a basin. Only one of the 38 possible configurations is associated with both the presence of conjunctive management and the lack of conjunctive management. The QCA method requires that all variables be coded as dichotomous. Thus, like the logit analysis, the dependent variable (conjunctive management in a basin) and the four institutional variables are scored as 1 for the presence and 0 for the absence of these variables in a basin. Unlike the logit analysis, the first four interval-level variables in the QCA model (population density, irrigated acres, storage capacity, and rainfall) are dichotomized using a cutoff point that approximates the mean score of each variable from the sample observations. The last interval-level variable used in the logit model is project water access. For the QCA model, this variable is dichotomized based on whether or not water providers have access to project water in a basin, regardless of amount.

In order to conduct the process of Boolean minimization, the QCA method first constructs a "truth table" that contains binary output values for each independent variable and the dependent variable, as shown in Table A. 1 (Ragin, 1987). The rows in the truth table represent all possible combinations of the values of the independent variables present in the data set. The truth table also shows the number of cases in the data that match each combination of independent variables, or each row. Table A. 1 presents the complete set of configurations found in the data, with the number of cases associated with each combination of independent variables. Using Boolean algebra, the QCA method minimizes the configurations coded as present and absent in the truth table. Since QCA utilizes Boolean algebra, minimized solutions are evaluated based on combinatorial logic. This means that a combination of conditions (a configuration) indicates that the presence or absence of each independent variable in the configuration needs to be found together in order for the dependent variable to be present or absent in any given case (Ragin 1987). Data minimization relies on comparing pairs of cases in order to identify causal conditions that could be considered irrelevant. Irrelevant conditions are found where two cases differ in only one independent variable, but still produce the same outcome. Through the data minimization process, the QCA method derives an equation for both the presence and the absence of the dependent variable, which includes the minimized configurations of causal conditions.

Equations A.1 and A.2 show the minimized combinations of variables that are associated with basins using conjunctive management and basins not using conjunctive management respectively. Variables represented in capital letters signify the necessary presence of a causal condition in a configuration, and variables in lower case letters indicate the necessary absence of a causal condition in a configuration. Where a variable is absent from a configuration, this shows that the condition is irrelevant as a causal condition.

Minimized Configurations of Conjunctive Management Cases

CWM = *PIBRWAcd* + *pIBrWcdS* + *pIBracds* + *pBrwAcds* + *PIBrWacDs* + *PiBrWACas* + *PiBrWacdS* + *PibrWaCDs* + *piBrwacDS* + *piBrWacDs* (Eq.A.1)

Minimized Configurations of Nonconjunctive Management Cases

No Conjunctive Management = *piwads* + *piacds* + *iRwacds* + *prwacds* + *pBrwACds* + *pibrWaCd* + *piBrwCds* + *PibraCds* + *PibrWads* + *ibrwaCds* + *ibrWacds* + *piBrwacd*+ *pIBrWaCds* (Eq. A.2)

To interpret these equations, each set of variables represented by a multiplier is a combination of conditions of independent variables, or a configuration. Each of these configurations signifies that those causal conditions must be found together when the dependent variable, conjunctive management, is present. The entire equation is the sum of all minimized combinations of independent variables. When added together, each individual configuration represents an "either/or" condition that is associated with the presence of the dependent variable in Equation A. 1 and the absence of the dependent variable in Equation A. 2.

Table A1. Truth table configurations and corresponding raw data cases.

Config	Variable Configurations[a] P I B R W A C D S	Conj. Mgmt[b]	Number of Cases
1	1 0 1 1 0 0 0 0 0	N	1
2	0 0 0 1 1 0 0 0 0	N	2
3	0 0 1 1 1 0 0 0 0	N	1
4	0 0 1 1 0 0 1 0 0	N	2
5	1 1 1 1 1 1 0 0 1	Y	1
6	0 0 0 1 0 0 0 0 0	N	3
7	1 0 0 1 0 0 0 0 0	N	2
8	0 1 1 0 0 0 0 0 1	Y	1
9	0 0 1 0 0 1 0 0 0	Y	1
10	0 0 0 0 0 0 0 0 0	N	10
11	1 0 0 0 0 0 1 0 0	N	1
12	0 0 0 0 0 0 1 0 0	N	2
13	1 0 1 0 1 1 1 0 0	Y	1
14	1 0 0 0 1 0 1 0 1	N	1
15	1 1 1 0 1 0 0 1 0	Y	2
16	1 0 0 0 1 0 1 0 0	N	4
17	1 0 1 0 1 0 0 0 1	Y	1
18	0 0 0 0 1 0 0 0 0	N	1
19	1 0 0 0 1 0 0 0 0	N	2
20	1 0 0 0 1 0 1 1 0	Y	1
21	1 1 1 1 1 1 0 0 0	Y	1
22	0 0 1 1 0 0 0 0 0	N	1
23	0 0 0 1 0 0 1 0 0	N	4
24	0 1 1 1 1 1 0 0 0	C	1(Y), 1(N)
25	0 1 1 0 1 1 0 0 1	Y	1
26	0 1 1 0 1 0 0 0 1	Y	1
27	0 1 1 0 0 0 0 0 0	N	2
28	0 1 0 0 0 0 0 0 0	N	5
29	0 0 1 0 0 0 0 0 1	N	1
30	0 0 1 0 0 1 1 0 0	N	1
31	0 0 1 0 0 0 1 0 0	N	1
32	0 0 1 0 0 0 0 0 0	N	4
33	0 0 1 0 0 0 0 1 1	Y	1
34	0 1 1 0 0 1 0 0 0	Y	1
35	0 1 1 0 0 1 1 0 0	N	1
36	0 0 1 0 1 0 0 0 0	N	1
37	0 1 1 0 1 0 1 0 0	N	1
38	0 0 1 0 1 0 0 1 0	Y	1

[a]Variables: P = Population Density, I= Irrigated Acres, B = Basin Storage Capacity, R = Av. Annual Rainfall, W = Project Water Access, A = AB3030 Plans, C = County Ordinance, D = Adjudicated Basin, S = Special Groundwater Management Districts.
[b]Conj. Mgmt.: Refers to the dependent variable outcome associated with each configuration. Y = presence, N = absence, C = contradictory case.