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Responses to Ecological and Human Threats to a California Water Basin Governance System

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Abstract:
Institutional arrangements for managing overdrafted groundwater basins, and for allocating surface water flows, in the San Gabriel River watershed are 50 to 60 years old. In the ensuing half century, the watershed has been transformed by demographic, economic, and political changes. Periodic droughts, the discovery of major areas of groundwater contamination, and efforts to control storm-water runoff have added new physical challenges to the management regime as well. This paper describes the threats to water management arrangements in the San Gabriel River watershed, undertakes a preliminary analysis of how individuals and institutions have responded, and sets out an agenda for further research on the presence or absence, and the degree, of robustness in this complex social ecological system.

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Introduction

Generations of scholars have sought to understand the interaction between human institutions[1] and the natural world. From the research done to date, it is clear that institutions which inadequately constrain or induce human behavior frequently lead to difficulties for both the natural world and human society. Difficulties include environmental degradation, famine, conflict, and in extreme cases, societal collapse. While institutions may impact the natural world, the natural world also impacts the types of institutions chosen and how those institutions perform and evolve over time. Hence, it is clear that the study of social ecological systems (SESs) can provide an important insight into a salient area of social inquiry.

This paper uses the concept of robustness to examine and evaluate institutional changes in water governance of one such SES where water availability depends both on natural forces and human choices. The San Gabriel River Watershed is located in an area encompassing much of coastal Los Angeles County from the San Gabriel Mountains to the Pacific Ocean. As population has increased in the area, different stresses have been placed on the watershed. Institutions have been created and modified in response to the stresses which have originated both from human activity and natural causes. Although institutions became increasingly robust to certain disturbances (or threats), the complex social ecological system has remained vulnerable to other disturbances.

The paper proceeds as follows. In the next section, we present an introduction to the concept of robustness. In the following sections we present an overview of the San Gabriel River Watershed and view the demographic, economic, and physical changes which have occurred there over the past 80 years. We then provide an overview of some of the institutions created to

[1] For the purposes of this paper we define "institutions" as rules in use. See generally E. Ostrom 2005

manage the watershed and how they have changed over time. In the final section, we present an analysis of the current threats facing the watershed and set out a further agenda for research.

Robustness

The concept of robustness is helpful for understanding institutional creation and change in light of natural conditions. In its simplest terms, robustness refers to the ability of a system to meet design objectives despite internal stress or external disturbance (Anderies, Janssen, and Ostrom 2004). The concept of robustness is well developed in engineering. Engineers strive to design systems which can cope with a wide variety of internal and external variation. This process often involves tradeoffs (Janssen and Anderies 2006). A system designed to account for a particular systematic stress may become less able to deal with other disturbances. Specifically, a system may become robust to known, common, or otherwise anticipated disturbances, yet fragile to the unknown, the uncommon, or the unanticipated (Carlson and Doyle 2002). Additionally, the system may be fragile due to design flaws, as well as failures in manufacturing and maintenance. It is understood that a system cannot be robust to all contingencies, but engineers strive to design systems able to withstand as many disturbances and counter as many threats as possible.

A simple example of this process can be found in helicopters. Engineers have designed helicopters to fly despite variations in the number of passengers, cargo weight, flight distance, fuel weight, and numerous other internal stresses. Helicopters are further designed to handle variations in temperature, wind, precipitation, and other external threats. Through the process of design, engineers have produced an extraordinarily complex system, but it is understood that not all variations have been or could be anticipated. Hence, well designed helicopters may still be subject to other threats. In a recent example, U.S. military helicopters largely designed to compensate for known or predicted variables found on potential battlefields in North America and Europe, proved particularly vulnerable to damage from sand and dust commonly found in the desert areas of Iraq and Afghanistan (Swibel 2004). While robust to a wide variety of threats, the helicopters were fragile to desert sands. Sensing this problem, designers implemented modifications in equipment and maintenance practices, making the helicopters more robust to sand and dust.

Institutional Robustness and Social Ecological Systems

As human constructs, institutions are assumed to share similar properties with other designed systems. Institutions are created and change in light of the design objectives established by humans. It is anticipated that human institutions will be designed to respond to threats to society, but cannot counter all potential threats presented.

In the case of SESs, individuals in society create rules governing the system, but both the social and ecological aspects may change over time. As these changes occur, new threats and shocks are encountered and human preferences may change. Robust institutions in these systems accordingly allow for changes in rules to respond to shocks, newly perceived threats, or changes in design objectives. Again, this process involves tradeoffs. No system is robust to all threats, though the most effective systems are able to counter as many threats as possible.

Substantial evidence exists of such institutional evolution and endurance in social ecological systems. Although not framed in the context of robustness, case studies abound illustrating how human societies have formed rules capable of producing sustained community forests, complex irrigation systems, and carefully managed fisheries (among others, see E. Ostrom 1990). As will be seen below, the evidence presented for the San Gabriel Watershed shows a complex set of institutions designed with the objectives of countering specific threats, and evolving as new threats are presented.

The San Gabriel Watershed

The San Gabriel River watershed in Los Angeles County is a sub-state watershed, smaller than the county. Yet the watershed is also regional, well beyond the reach of any municipality: it encompasses all of parts of about 100 municipalities. The watershed extends from the San Gabriel Mountains to the Pacific Ocean, and from a line between La Canada-Flintridge and the Los Angeles International Airport to the San Bernardino and Orange County boundaries. It contains a major river, several creeks and washes, and four major groundwater basins. The watershed is "pinched" in the middle, where the Whittier Narrows divide the watershed's Upper Area from its Lower Area.

Two major groundwater basins are in the Upper Area: the Raymond Basin and the Main San Gabriel Basin. The two Lower Area basins, Central Basin and West Basin, are also coastal basins in hydrologic contact with the Pacific Ocean; thus they are vulnerable to sea-water intrusion. The basins in the Upper and Lower Areas are interrelated. Most of the Central Basin and all of the West Basin are confined by a surface layer of less permeable clay soils; only the northeastern portion of the Central Basin (just below the Whittier Narrows) is susceptible to direct replenishment from the land surface. Most of Central Basin's natural fresh water supply comes via Whittier Narrows from the Main San Gabriel Basin, and all of the natural fresh water inflow to West Basin comes from Central Basin. The dependence of the Lower Area basins on the Upper Area became especially apparent when a significant area of the Main San Gabriel Basin was found to be infiltrated by excessive concentrations of volatile organic chemicals (VOCs) and the basin became a U.S. Environmental Protection Agency's Superfund site.

Virtually the entire watershed below the mountains is urbanized. The paving over of soils, through which rainfall used to percolate, reduced fresh water replenishment of the groundwater basins. Most of the wastewater in the basin is treated and placed in the main surface water channels (the San Gabriel River and the Rio Hondo). Furthermore, miles of those channels have been lined with concrete for flood control purposes. Therefore, since the early decades of the 20^{th} century, the main sources of replenishment to the watershed's groundwater basins—precipitation and runoff, and waste water—have been escorted briskly to the ocean rather than percolating into the subsurface.

Similar trends have transpired in the San Gabriel's neighboring watersheds—the Los Angeles River watershed to the north and the Santa Ana River watershed to the south. There are some differences, however, that make the San Gabriel River watershed especially interesting from an institutional standpoint. Unlike the Los Angeles River watershed where water use and delivery are dominated by the Los Angeles Department of Water and Power, there is no dominant water user in the San Gabriel River watershed. Unlike the Santa Ana River watershed where there is a watershed-wide joint-powers agency, there is no comparable organization in the San Gabriel River watershed.

To put it another way, water resource management in the San Gabriel River watershed occurs in the absence of a watershed "manager." All of the arrangements for governing and managing water resources in the San Gabriel River watershed are polycentric, entailing connections among public and private organizations that are functionally specialized, or cover only a portion of the watershed, or both. The challenges of responding to changes in the watershed are therefore shared within a web of institutions.

The Transformed Physical and Social Landscape of the San Gabriel River Watershed, 1931-2006

As noted, in the 75 years from the early 1930s to the present, the watershed and the rest of Southern California have been transformed. Figure 3 is a satellite photo of the region at present, with the headwaters, midpoint, and mouth of the San Gabriel River marked. Plainly visible, the watershed's dominant surface color today is the gray of pavement, illustrating the nearly total urbanization of the landscape between the San Gabriel Mountains and the Pacific Ocean.

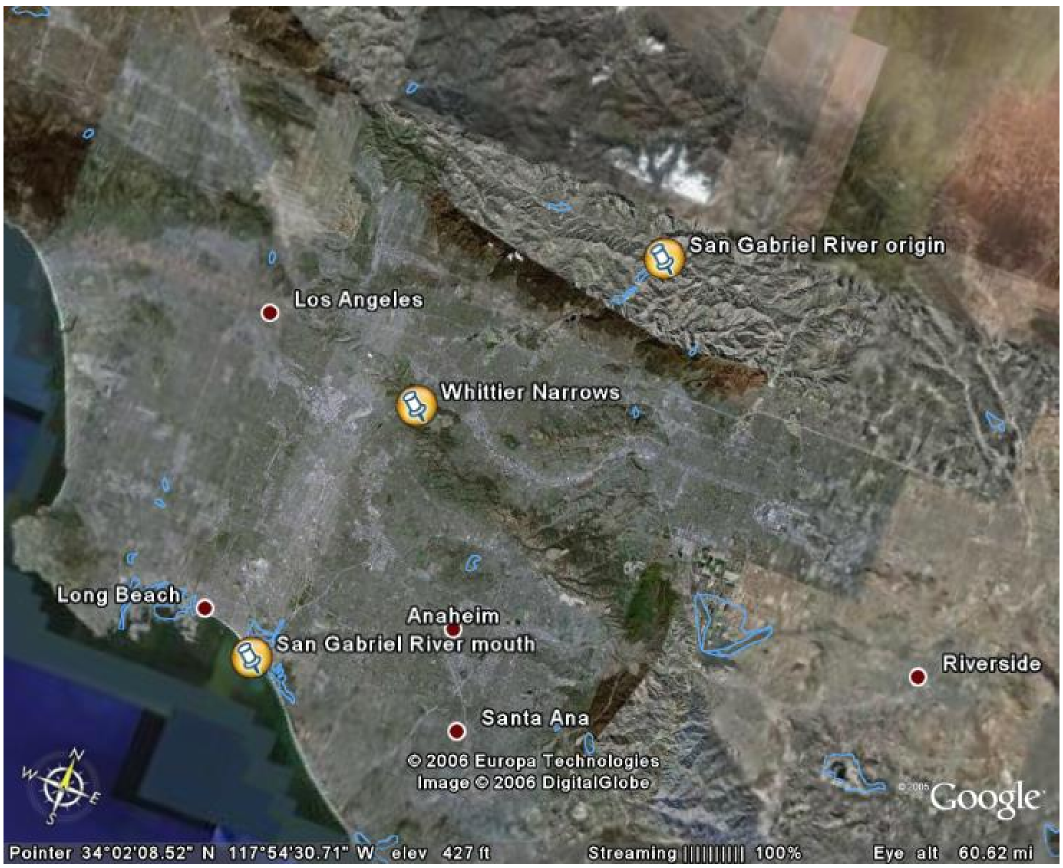

Figure 3. The paved landscape of the San Gabriel River watershed, October 2006

Seventy-five years earlier, the Los Angeles metropolitan area was developing rapidly indeed, but there were still open spaces between most of the major cities. Figure 4 is a 1939 highway map showing that a great deal of urbanization was underway in Southern California in the 1930s, but also suggesting that much of the course of the San Gabriel River (visible on the map from the upper-right corner, northeast of Monrovia, to the bottom center at Long Beach) ran through lands that were either undeveloped, or in use for agriculture and other forms of lower-density development.

Figure 4. A widely-used highway map from 1939

The photograph in Figure 5 is of a Depression-era agricultural development program in the San Gabriel Valley. The farm in the photograph is near El Monte, which is today a city of 116,000 residents, situated in the center of the upper basin of the San Gabriel River watershed and surrounded by other municipalities of like size and density. One would search the San Gabriel River watershed in vain today looking for a farmhouse or a field. The conversion of agricultural land to urban uses (residential, commercial, and industrial) from 1928 to 1995 is portrayed in Figure 6.

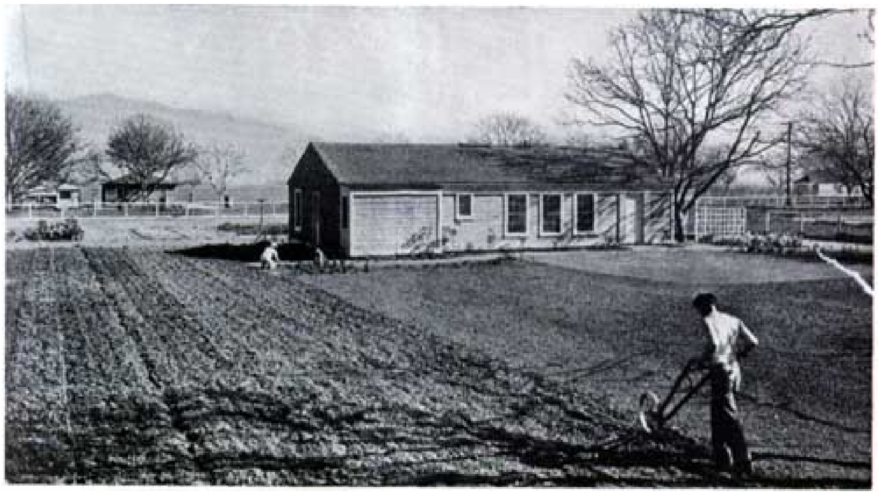

Figure 5. Subsistence farming demonstration gardens in the vicinity of El Monte, California, in the upper San Gabriel Valley during the Depression of the 1930s.

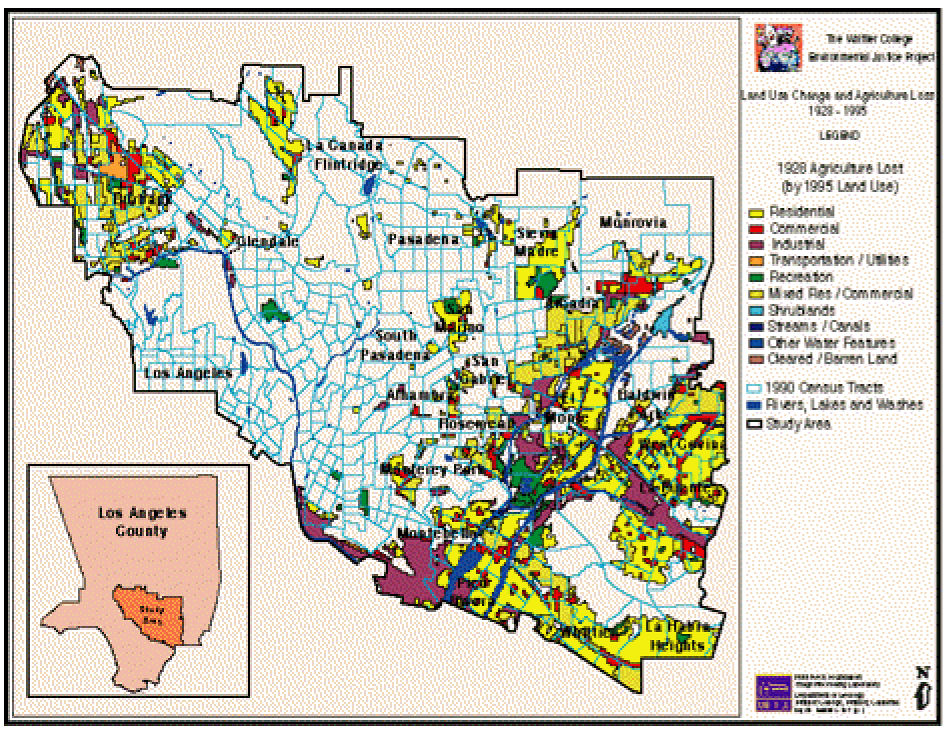

Figure 6. Transition of agricultural land in the San Gabriel Valley, 1928-1995
(Source: Swift and Henderson 1997)

The transformation of the watershed is demonstrable by numbers as well as by pictures. Census data from the end of the 1930s to the end of the 1990s (Table 1) show the changed number of residents and housing units in Los Angeles County, where the San Gabriel River watershed is located. As can be seen in the middle two columns of Table 1, the county's population and housing units more than tripled during the period.

Table 1. Population and Housing Units in Los Angeles County, 1940-2000
(Source: U.S. Bureau of the Census)

Year	Population	Housing units	Persons per housing unit
1940	2,785,643	961,531	2.897
1950	4,151,687	1,442,691	2.877
1960	6,038,771	2,143,227	2.818
1970	7,041,980	2,541,603	2.771
1980	7,477,238	2,855,506	2.619
1990	8,863,164	3,163,343	2.802
2000	9,519,338	3,133,774	3.038

As one would expect, these population changes accompanied a tremendous alteration of the region's economy. Between 1940 and 1950, for example, as the population of Los Angeles County rose 49.0 percent, the Census-reported number of employees in agriculture declined by 15.0 percent, the number of employees in machinery manufacturing rose by 42.8 percent and the number in finance, insurance, and real estate rose by 59.3 percent.[2] Although these data are not specific to the watershed, they are certainly consistent with Figure 6's depiction of a rapidly urbanizing area.

The right-hand column of Table 1 hints also at some significant changes in the composition of the area's population. Beginning in the 1980s, average household size (persons per housing unit) reversed a half-century's slight downward drift and began to rise. During the 1990s, the county's population rose by two-thirds of a million even though the number of housing units

[2] Census reports categorized many employment sectors differently in 1940, 1950, 1960 and beyond. The three employment categories used here (agriculture, machinery manufacturing, and finance/insurance/real estate) remained consistent from the 1940 to the 1950 Census reports.

declined[3] according to the U.S. Census, leaving average household size greater in 2000 than it had been throughout the period. The increase in persons per household in Los Angeles County during the 1980s and 1990s is generally attributed to the growing presence of immigrant families from Asia and Latin America, which is another aspect of the extent of regional social change. (Throughout Southern California since 1980, birth rates and rising family size have contributed more to population increase than net in-migration.)

A somewhat better, though still flawed, picture of population change within the watershed (rather than for Los Angeles County as a whole) can be derived by identifying the municipalities and Census-defined "places" that are located within the watershed. This approach also allows for a comparison of population change in the watershed's upper and lower areas, which proceeded at different rates. Table 2 presents Census data on population of communities within the San Gabriel River watershed over the period of interest.

Table 2. Population of communities within the San Gabriel River watershed, 1940-2000
(*Source: U.S. Bureau of the Census*)

a. Upper Watershed Area

City or Place	1940	1950	1960	1970	1980	1990	2000
Alhambra	38,935	51,359	54,807	62,125	64,767	82,106	85,804
Altadena			40,568	42,415	40,983	42,658	42,610
Arcadia	9,122	23,066	41,005	45,138	45,993	48,290	53,054
Azusa	5,209	11,042	20,497	25,217	29,380	41,333	44,712
Baldwin Park			33,951	47,285	50,554	69,330	75,837
Charter Oak					6,840	8,858	9,027
Claremont	3,057	6,327	12,633	24,776	31,028	32,503	33,998
Covina	3,049	3,956	20,124	30,395	32,746	43,207	46,837
Diamond Bar						53,672	56,287
Duarte			13,962	14,981	16,766	20,688	21,486
East Pasadena						5,910	6,045
East San Gabriel						12,736	14,512
El Monte	4,746	8,101	13,163	69,892	79,494	106,209	115,965
Glendora	2,822	3,988	20,752	31,380	38,500	47,828	49,415
Hacienda Heights				35,969	49,422	52,354	53,122

[3] There are a number of locations in the county where residential units have been replaced by commercial units or displaced by expanded transportation corridors.

La Canada-Flintridge			18,338		20,153	19,378	20,318
La Habra Heights					4,786	6,226	5,712
La Verne	3,092	4,198	6,516	12,965	23,508	30,897	31,638
Monrovia	12,807	20,186	27,079	30,562	30,531	35,761	36,929
Montebello	8,016	21,735	32,097	42,807	52,929	59,564	62,150
Monterey Park	8,531	20,395	37,821	49,166	54,338	60,738	60,051
North El Monte						3,384	3,703
Pasadena	81,864	104,577	116,407	112,951	118,072	131,591	133,936
Pomona	23,539	35,405	67,157	87,384	92,742	131,723	149,473
Rosemead			15,476	40,972	42,604	51,638	53,505
San Dimas				15,692	24,014	32,397	34,980
San Gabriel	11,867	20,343	22,561	29,336	30,072	37,120	39,804
San Marino	8,175	11,230	13,658	14,177	13,307	12,959	12,945
Sierra Madre	4,581	7,273	9,732	12,140	10,837	10,762	10,578
South El Monte			4,850	13,443	16,623	20,850	21,144
South Pasadena	14,356	16,935	19,706	22,979	22,681	23,936	24,292
South San Gabriel				5,051	5,421	7,700	7,595
South San Jose Hills				12,386	16,076	17,814	20,218
Temple City			31,838	31,034	28,972	31,100	33,377
Valinda				18,837	18,712	18,735	21,776
Walnut			934	5,992	12,478	29,105	30,004
West Covina	1,072	4,499	50,645	68,034	80,292	96,086	105,080
West Puente Valley				20,733	20,445	20,254	22,589
Upper Area Subtotal	***244,840***	***374,615***	***746,277***	***1,076,214***	***1,226,066***	***1,559,390***	***1,652,508***
Pct. change from previous decade		***+53.0%***	***+99.2%***	***+44.21***	***+13.9%***	***+27.2%***	***+6.0%***

b. Lower Watershed Area

City or Place	1940	1950	1960	1970	1980	1990	2000
Artesia			9,993	14,757	14,301	15,464	16,380
Bell	11,264	15,430	19,450	21,836	25,450	34,365	36,664
Bell Gardens			26,467	29,308	34,117	42,355	44,054
Bellflower			44,846	52,334	53,441	61,815	72,878
Carson			38,059	71,150	81,221	83,995	89,730
Cerritos				15,856	53,020	53,240	51,488
Commerce			9,555	10,635	10,509	12,135	12,568
Compton	16,198	47,991	71,812	78,547	81,350	90,454	93,493
Cudahy				16,998	18,275	22,817	24,208
Downey			82,505	88,573	82,602	91,444	107,323
East Compton				5,853	6,435	7,967	9,286
East La Mirada				12,339	9,688	9,367	9,538
El Segundo	3,738	8,011	14,219	15,620	13,752	15,223	16,033
Florence-Graham			38,164	42,900	48,662	57,147	60,197
Gardena	5,909	14,405	35,943	41,021	45,165	49,847	57,746
Hawaiian Gardens				9,052	10,548	13,639	14,779
Hawthorne	8,263	16,316	33,035	53,304	56,437	71,349	84,112
Hermosa Beach	7,197	11,826	16,115	17,412	180,770	18,219	18,566
Huntington Park	28,648	29,450	29,920	33,744	45,932	56,065	61,348
Inglewood	30,114	46,185	63,390	89,985	94,162	109,602	112,580

Lakewood			67,126	83,025	74,511	73,557	79,345
La Mirada			22,444	30,808	40,986	40,452	46,783
Lawndale			21,740	24,825	23,460	27,331	31,711
Lomita			14,983	19,784	18,807	19,382	20,046
Long Beach	164,271	250,767	344,168	358,879	361,498	429,433	461,522
Lynwood	10,982	25,823	31,614	43,354	48,289	61,945	69,845
Manhattan Beach	6,398	17,330	33,934	35,352	31,542	32,063	33,852
Maywood	10,731	13,292	14,588	16,996	21,810	27,850	28,083
Norwalk			88,739	90,164	84,901	94,279	103,298
Palos Verdes Estates	987	1,963	9,564	13,631	14,376	13,512	13,340
Paramount			27,249	34,734	36,407	47,669	55,266
Pico Rivera			49,150	54,170	53,387	59,177	63,428
Rancho Palos Verdes					36,577	41,659	41,145
Redondo Beach	13,092	25,226	46,986	57,451	57,102	60,167	63,261
Rolling Hills Estates			3,941	6,735	7,701	7,789	7,676
Santa Fe Springs			16,342	14,750	14,520	15,520	17,438
Signal Hill	3,184	4,040	4,627	5,588	5,734	8,371	9,333
South Gate	26,945	51,116	53,831	56,909	66,784	86,284	96,375
South Whittier				46,641	43,815	49,514	55,193
Torrance	9,950	22,241	100,991	134,968	129,881	133,107	137,946
Walnut Park				8,925	11,811	14,722	16,180
West Carson				15,918	17,997	20,143	21,138
West Compton				5,605	5,907	5,451	5,435
West Whittier				20,845	21,001	24,164	25,129
Whittier	16,115	23,433	33,663	72,863	68,558	77,671	83,680
Lower Area Subtotal	***373,986***	***624,845***	***1,519,153***	***1,974,144***	***2,263,199***	***2,387,721***	***2,579,419***
Pct. change from previous decade		***+67.1%***	***+143.1%***	***+30.0%***	***+14.6%***	***+5.5%***	***+8.0%***
Watershed Total	**618,826**	**999,460**	**2,265,430**	**3,050,358**	**3,489,265**	**3,947,111**	**4,231,927**
Pct. change from previous decade		***+61.5%***	***+126.7%***	***+34.6%***	***+14.4%***	***+13.1%***	***+7.2%***

Table 2 is not a perfect measure of the watershed's population in the watershed: data are reported by Census-defined place (incorporated municipalities or unincorporated areas of concentrated population), and the absence of a Census-defined place does not mean that no one lives there. (It is not the case that the population of Altadena, for example, was zero prior to 1960.) On the other hand, the data in Table 2 provide at least three forms of useful information for the purposes of this paper. First, the urbanization and rapid growth of the population in the watershed are evident in the population totals and percent changes. Second, the differential pace of growth between the upper area and lower area of the watershed are also evident in the percent changes; the lower area of the watershed gained population in greater amounts and at faster rates in the 1940s and 1950s, but the upper area gained population at faster rates in the 1960s and 1980s, with more nearly equivalent percentage gains in both areas during the 1970s and 1990s. Third, the rapid urbanization of the watershed during the 1940s, 1950s, and 1960s, can be inferred from the substantial increase in the number of incorporated municipalities and Census-defined places appearing in the columns from 1940 to 1970.

California Water Law and Local Control

A review of institutions governing water in California often illustrates the creation and evolution of institutions in response to the appearance of threats over time. Water needs and uses are extremely varied throughout California. Due to this variation, the state has adopted an extraordinarily complex system of water governance. State law applies principles from both riparian and prior appropriation doctrines in allocating water rights. This hybrid system of water rights allocation is protected through Article 10, section 2, of the California Constitution and stands as a testament of the willingness of Californians to creatively create and apply water rules which effectively suit their circumstances.

The California Water Code currently consists of nearly 30,000 sections addressing an enormous variety of topics. Many of the laws have been created in direct response to perceived threats. For instance, Sections 350-359 deal with contingencies surrounding water shortages, Sections 8100-8165 provide rules regarding county flood control, and hundreds of sections specifically promote clean water through curbing contamination (California Water Code, 2006).

Further complicating California water law is the state's extensive use of districts as a mechanism for local governance. General district acts regarding water first appeared in the California legislature in 1866 through the authorization of reclamation districts to reclaim tidelands, swamps, and marshes. Further general district acts authorized the creation of drainage districts in 1880 and 1897, irrigation districts in 1897, municipal water districts in 1911, county water districts and other water districts in 1913, municipal utility districts and public utility districts in 1921, water conservation districts in 1927, 1929, and 1931. Regarding the general district acts, Albert Henley observed in 1957 that, "[a] review, in chronological order, of general district acts which seem to have been found the most useful shows that the evolution of water management organizations has followed with fair accuracy the changing character of the state itself" (667).

The state has also authorized numerous special districts for various purposes. A peripheral review of these districts also indicates they were passed in response to the conditions then encountered. The first such special district was passed in 1915 when the state authorized the creation of the Los Angeles County Flood Control District. Similar acts were passed authorizing flood control districts in additional California counties between 1927 and the mid-1940s (Henley 1957). Other special districts have been created to facilitate flood control along portions of rivers crossing several counties and a water replenishment district covering Southern California counties.

San Gabriel Watershed Institutions

Due to California's longstanding tradition of home rule, dozens of institutional arrangements have been created to manage the watershed. Clearly, this study cannot identify each of these to track institutional evolution. However, we can identify several institutional objectives, identify a few institutional arrangements selected to meet those objectives, and examine how those institutions have changed over time in response to threats. For the purposes of this study, we have selected the institutional arrangements established to promote water supply and quality and institutions allocating and controlling surface waters in the watershed's rivers. Similarly, due to the size of the watershed and the time span addressed, the list of threats is not exhaustive. Rather, we have identified some of the clearest problems encountered over the past 80 years in the area. The threats we explore include increased population, drought, groundwater depletion, saltwater intrusion, and pollution.

Promoting Water Supply

The quest for Additional Water

As population increased in the San Gabriel Watershed, surface water resources became increasingly scarce. Surface water rights in the area were largely allocated by the early 1900s. Yet, people still came to the area. Early on, it became apparent that new sources of water would be necessary to support the burgeoning population. Municipalities, individuals, and businesses within the watershed started exploring options to obtain water. The City of Los Angeles began seeking other geographic areas from which water could be imported. In the early 1900s, the City selected the Owens Valley, located hundreds of miles to the Northeast, and began purchasing property and water rights(V. Ostrom 1953). The City then constructed the Los Angeles Aqueduct between 1907 and 1913, "one of the nation's largest public works projects at the time, second only to the Panama Canal" (Libecap 2005 5). The quantity of water provided from the Owens Valley project was four times greater than the surface water naturally available in the Los Angeles Basin at the time (V. Ostrom 1953).

Importing water became one of the dominating paradigms in water production for the area. It became even more salient due to the region's climate which frequently endures dry cycles lasting many years. One such dry cycle occurred between 1922 and 1937. Fully allocated surface water sources produced even less water and groundwater levels began to fall. In the mid 1920s, the City of Pasadena, which depended almost entirely on groundwater pumping, started exploring mechanisms to supplement the ever shrinking Raymond Groundwater Basin by bringing in water from an external source (Blomquist 1992).

Others were similarly interested in obtaining more water. The City of Los Angeles sought and was awarded water rights from the Colorado River in 1924, although no delivery mechanism from the river existed. In 1928, the Metropolitan Water District (MWD) formed with the overall goal of water provision and the particular goal of creating an aqueduct to bring Colorado River water into the area. Charter membership in MWD included Pasadena, Los Angeles, and eleven other cities located in Southern California. In September of 1931, voters within the district approved a $220 million dollar bond for the creation of the Colorado River Aqueduct. Soon thereafter, construction of the aqueduct started (Blomquist 1992).

The Colorado Aqueduct was completed in 1941. While the imported water from the Colorado alleviated some of the pressing need for water within the San Gabriel Watershed, it did not provide a total solution. Three direct deficiencies existed with the Colorado River water. First, Colorado water was more expensive than local sources of water (E. Ostrom 1965). Second, the Colorado water lacked quality associated with other locally obtained water. As the Colorado flowed hundreds of miles from the Rocky Mountains, the river picked up significant quantities of various pollutants in addition to salt and other minerals (E. Ostrom 1965). Finally, the Colorado water was insufficient to meet all growing needs. The Colorado River Compact allocated a fixed amount of water to California and the Aqueduct carrying water to Los Angeles was only part of the water demands within California (See Generally Reisner 1986). Due to these deficiencies, incentives remained strong to utilize other sources of water. This is particularly true in regards to the demands on groundwater discussed below.

As time went by, population continued to increase and pressed the need for additional sources of water. The City of Los Angeles completed an improved aqueduct to Owens Valley in the early 1970s and began drawing groundwater from the area (Libecap 2003). Others sought to import water from the well hydrated areas of Northern California. This project resulted in the California Water Project in which the California Aqueduct was constructed to carry water from the San Joaquin Delta to Southern California. Water from the California Water Project arrived in the mid-1970s. MWD again acquired rights to California Aqueduct water and acted as the water supplier for the San Gabriel River Watershed (Erie 2006).

These multiple sources of water proved to be a real boon to the area in the early 1990s when Southern California was ravaged by drought. Water supplied by the MWD (from Northern California and the Colorado River) made up 65 percent of water used in Los Angeles during 1991. This constitutes a massive increase from previous figures where water imported from Northern California and Colorado consisted of as low as 3 percent of water used by the city in the 1970s and ten percent in the mid-1980s. For the remainder of the 1990s, imported MWD water made up 34 percent of the water used (Erie 2006).

Imported water certainly helped meet increased needs, but also created new concerns. The water increased robustness to local drought, but increased vulnerability to distant drought (in the Rocky Mountains and Northern California), political shifts, and legal conflict. These risks were somewhat understood by those in the region even before the construction of the Colorado River Aqueduct. After all, the Los Angeles Aqueduct from Owens Valley had been a source perpetual conflict to the extent that the aqueduct had been dynamited on at least one occasion in the 1920s (Hundley 2001). Conflicts surrounding the Owens Valley Project again rose throughout the 1970s through fresh legal challenges regarding non-existent surface flows from the Owen River and the diminishing Mono Lake (Kahrl 1982). The vulnerability of other external sources of water became quite apparent in the 1990s and into the current decade.

The legality of the transfer of Colorado River water to the Los Angeles area was determined by the U.S. Supreme Court in 1963 through *Arizona v. California* (373 U.S. 546). In this important case, the U.S. Supreme Court affirmed that California had been allocated 4.4 million acre-feet of water, plus one-half of any surplus. The surplus water, however, could be lessened at the discretion of the U.S. Department of Interior. This arrangement worked well for California in that historically, many states holding Colorado River rights did not use their share of water. MWD had in fact constructed the Colorado River Aqueduct to be capable of carrying 5.2 million acre feet of water. California frequently used an additional twenty percent of Colorado water than the 4.4 million acre feet it was allotted (Erie 2006).

This surplus began to dry up through the 1980s. In 1989, reduced river flow, combined with increased water demand, led California, Nevada, and Arizona to fully use their river allotments for the first time. The U.S. Department of the Interior threatened California that the end of yearly surpluses was near. Despite the eminently threatening language, the Department of Interior did not actually enforce the end of the surplus program until 2003, limiting California's annual take to 4.4 million acre feet (Erie 2006).

In addition to diminished allocations, other threats have also called into question the wisdom of relying on the Colorado River. First, like much of the West, the river is subject to drought. It is clear that the levels appropriated to each state through the Colorado Compact may not represent future flows of the river. Accordingly, there may be less water to share in the future. Recent research shows that warming trends across the Rocky Mountains will mean less water for the Colorado River (McKinnon 2006). More immediately, other items affect the quality of water in the Colorado. Recent evidence has shown that the river is more contaminated than was previously thought. Newly discovered contaminants include irradiated uranium tailings, other heavy metals, and toxic chemicals known to cause genetic defects and cancer (Hundley 2001). Finally, other demands on Colorado River water have placed further strain on the ability of MWD to deliver water for residential use. Projects restoring the Salton Sea, protecting endangered species, and promoting agriculture have all been declared as important competing uses for the Colorado River water (Erie 2006).

As strain increased on the Colorado, MWD and water providers began to search for other reliable external sources. The other external sources of water have also proved somewhat tenuous. California Water Project water must be pumped south over the Tehachapi Mountains making water delivery expensive (Erie 2006). Although of higher quality than Colorado River Water, California Project water was frequently embroiled in environmental lawsuits regarding endangered species as well as the impact of removing freshwater from the bay delta. Lawsuits have been filed as recently as Oct. 4, 2006 when the California Sportfishing Protection Alliance sued the Department of Water Resources regarding alleged Endangered Species Act violations for pumping water from streams used for endangered salmon (Bacher 2006). Such lawsuits have made future delivery unclear. Similarly, future delivery from the Owens Valley project has been uncertain. Lawsuits regarding the Owens River restoration have lingered. Recently, a federal judge ordered that river be restored. How and with what water remain to be seen.

Finally, as external water sources have become increasingly scarce, MWD and the water providers it serves have become increasingly conservation minded. Water conservation programs originated in the 1970s, but have taken firm hold in the region. In a recent issue of Aqueduct magazine, MWD extolled the various water conservation programs currently ongoing within the Los Angeles region. MWD contended that with conservation programs, demand for water within region is 3.8 million acre feet, while demand without such programs would be 4.5 million acre feet annually. MWD's indoor water conservation program has installed over 500,000 water saving toilets since 1991. This move alone is believed to have saved 160,000 acre feet of water (Hanna 2006). In another program MWD and U.S. Bureau of Reclamation offer homebuilders up to $2,500.00 per model home to cover the costs of installing low water toilets, water efficient clothes washers, and water conscious landscaping (Hanna 2006).

Groundwater Governance

In addition to looking outside of the watershed for new sources, the demand for water led many to seek for water right under their feet. As noted above, the San Gabriel River Watershed houses four groundwater basins: Raymond Basin, Man San Gabriel Basin, Central Basin, and West Basin. Hundreds of wells were dug throughout the watershed to access these basins. A U.S. Geological Survey completed in 1904 of one of West Basin found over 100 wells operating (Blomquist 1988). Deep well turbine pumps, new technology introduced to the area in 1909, more easily facilitated groundwater extraction from each of the groundwater basins.

Groundwater levels had decreased in all four groundwater basins by the late 1920s. This was particularly problematic for West and Central Basin which were closest to the Pacific Ocean. As groundwater levels fell, pressure against the seawater changed and saltwater began to intrude into the groundwater basins. In 1929, a MWD report found that seawater was invading West Basin (Blomquist 1988). By 1934, the California Division of Water Resources (DWR) found that seawater had intruded into both the Southern and Western boundaries of West Basin. To mitigate this groundwater intrusion, the Los Angeles County Flood Control District began spreading floodwaters over the Montebello Forebay within Central Basin in 1938 (Blomquist 1988).

Adjudication

Pumpers in the Raymond Basin were also alarmed by the sharp decline in groundwater levels. While there was no fear of saltwater intrusion for the inland basin, many feared that the basin was becoming critically overdrawn. Between 1922 and 1937, water levels in Pasadena City wells dropped by over 100 feet (Blomquist 1992). Noting this decline, the City undertook legal action to ensure its continued right to groundwater. *Pasadena v. Alhambra* (1937) was initiated in California Superior Court and consisted of the first basin wide adjudication of groundwater rights in California. Through the adjudication, the court endeavored to identify water rights and safe levels of water extraction utilizing principles of equity jurisprudence—a legal approach utilized when traditional legal remedies, such a monetary damages, are inadequate. As the legal action proceeded, many water pumpers began to see that a stipulated settlement would be preferable to leaving the matter in the judge's hands. A stipulated settlement for the case was presented to the court in 1943. One holdout refused to sign the stipulation and a brief trial was held in 1944. The judge's ruling later that year supported the stipulated settlement proposed by the litigants. The California Supreme Court upheld the judgment in 1949 (206 p.2d 17) making the adjudication the law of the land.

The Raymond Basin adjudication judgment set a safe-yield limit for extraction, established water rights for the parties, enjoined any party from taking more than their decreed right, and set other administrative procedures. The judgment further mandated that parties self report extractions and diversions and empowered a Watermaster to monitor the parties and ensure no overdraft. Similar adjudication processes occurred in the other groundwater basins. The West

Basin adjudication process began in 1945, but was not completed until 1961. Although they attempted to avoid adjudication, Central Basin was forced into court for adjudication of water rights in 1962. The Central Basin adjudication judgment became effective in 1966. The Main San Gabriel groundwater basin adjudication began in 1968 and judgment was entered in 1973.

Each adjudication provided real steps forward in groundwater management. First, the adjudication decided the issue of who held water rights in the region. Second, through the establishment of watermasters, issues regarding overdraft could be decided, either through injunction by the court or other sanctions or through the administrative process listed in the judgment. Third, mechanisms for future allocation were provided. Not only could pumpers sell their current rights, exchange pools were established whereby rights could be traded temporarily. These arrangements eventually facilitated various interbasin transfers between Central and West Basins. Fourth, most of the adjudications established a safe yield for current pumping. This set basement water level below which groundwater levels could not fall. In Main San Gabriel Basin, this was a variable safe yield rather than fixed annual pumping level. These mechanisms helped navigate difficult times of drought, massive changes in composition of pumpers, and the closing of some wells due to contamination as will be discussed below.

Additionally, the court in each case retained jurisdiction over the groundwater judgments and has allowed modifications in the judgments according to need. For instance, the Raymond Basin judgment was amended to increase the safe-yield limit initially set on numbers gathered during the extremely dry period (between 1922 and 1937). The new safe-yield limit focused on years between 1937 and the mid-1950s. The judgment has also been amended to allow for basin recharge—an issue absent from the original document. A third modification allowed a shift in watermaster services provided by the California Department of Water Resources to a new office developed within Raymond Basin. This action was taken to reduce overall costs of basin management (Blomquist 1992).

In 1993, the West Basin Judgment was amended to allow for additional water carryover. This modification occurred due to drought conditions in the years leading up to 1993. Complaining of diminished external sources of water, pumpers in the West Basin successfully argued that the judgment should be allowed additional water extraction of up to 20 percent over the adjudicated right with the recognition that the excess water would be discounted from the following year's pumping amount (Department of Water Resources 2003).

Augmenting Water Supply and Resolving Upstream and Downstream Challenges

Establishing exclusive groundwater rights and limiting future extraction addressed only part of the problem. It was clear that groundwater could only meet a portion of the demand for water. Finding new sources of water was paramount to saving the groundwater basins. To meet this end, parties in West Basin sought to create the West Basin Municipal Water District in 1947. Central Basin parties followed suit in 1952 through the creation of the Central Basin Municipal Water District (Blomquist 1992). Each of these entities acted to find new sources of water. Both initially acted to contract with MWD to access water from the Colorado River. Water from the Colorado began to flow to West Basin in 1949 and to the Central Basin in 1955.

Further complications arose in resolving upstream and downstream water use of the San Gabriel River Watershed. The lower basins were particularly concerned that any activities undertaken in downstream areas would be useless if upstream users did not similarly act. Early efforts between West Basin and Central Basin resulted in joint replenishment efforts including a joint replenishment district described below. In 1959, the Central Basin Municipal Water District joined with other municipalities in suing up stream water producers within the Main San

Gabriel groundwater basin and along the San Gabriel River in order to guarantee more access to surface and groundwater in Central Basin (Blomquist 1992). The suit ended in a stipulated settlement in 1965 which guaranteed upstream and downstream rights. This judgment has operated without significant alteration since that time.

Both West and Central Basin Metropolitan Water Districts have acted as advocates for more water within their jurisdictions and as water providers the 1950s through the 1980s as water providers to those living in their jurisdiction. Although most of the imported water used came from the Colorado River via MWD, the municipal districts also began accepting water from the State Water Project in 1974.

Faced with the realities of potential imported water scarcities in the 1990s, however, the municipal water districts expanded their repertoires. In 1991, West Basin Municipal Water District and Los Angeles entered an agreement to construct and operate a water treatment plant in El Segundo. This action was followed in 1993 when West Basin built the Brewer Desalter Plant in Torrence to treat groundwater which had become brackish through saltwater intrusion. Water deliveries from the El Segundo plant began in 1995 and from the Brewer Desalter soon thereafter. Treated water from these plants has been delivered throughout the West Basin for use in industry, landscaping, and in the injection wells described below. West Basin Municipal Water District is currently the largest producer of recycled water in Southern California. In 2005, they were cited as producing 31000 acre feet of recycled water (California Water Plan 2005). West Basin is currently pursuing desalinization technology to become one of the first producers of freshwater from ocean water.

Not everything has gone well for West Basin Municipal Water District. Their role as producer and provider of water in dry years has created a significant amount of power for the agency. Recent years have witnessed some of the darkest hours of water governance in the San Gabriel River Watershed when the West Basin Municipal Water District board president and a board member were convicted in 2004 and 2005 of federal charges stemming from corrupt practices in awarding water contracts and taking bribes.

Water Replenishment and Saltwater Intrusion

Minimizing extraction and supplying additional water to the area did not adequately address the underlying issues of the diminished water levels in the Central and West Basins nor combat saltwater intrutions. Officials in both Central and West Basin undertook artificial groundwater replenishment in the early 1950s. The parties acted together to create the Central and West Basin Water Replenishment District in 1959. To fund the replenishment program, Los Angeles County authorized special tax district, Zone I. Through the program, water pumpers were taxed to fund replenishment programs and imported water was purchased and spread in the Montebello Forebay area in Central Basin.

Throughout the early 1960s, record amounts of water were recharged into the system. The replenishment district eventually cut back on artificial recharge in order to allow the fresh water to proceed down stream. In addition to artificial groundwater replenishment, the district also started an in-lieu water program in 1974 whereby water users dependant on groundwater were offered other sources of water to diminish demand for groundwater.

As external sources of water decreased in the 1990s, the Replenishment District also began contemplating a role as water producer. This role came to fruition in 2001 when the district began operation of the Goldsworthy Desalter Plant in Torrence. Through the Goldsworthy Plant, the replenishment district treats 2.75 million gallons of brackish groundwater a day.

In 2003, a California appellate court clarified the expansive role of the Replenishment District in asserting the district's exclusive jurisdiction over the management of groundwater storage in Central Basin. In the case, adjudicated water rights holders for Central Basin has asserted that by nature of being an adjudicated right holder to extract water from the basin, they also had exclusive right to store water in the basin. The trial court and the appellate court disagreed in asserting that the storage capacity of Central Basin was a public resource and that the Replenishment District had exclusive management right (Central and West Basin Water Replenishment District, et al. v. Southern California Water Company, et. al. 2003). As more sources of water are made available through desalination and water recycling, this clarification of rights and responsibilities may have far reaching implications as new storage capacity is required throughout the region.

Regarding saltwater intrusion, parties in Central and West Basins recognized that curbing overdraft, seeking additional sources of water, and promoting replenishment would not take effect quickly enough to immediately stem saltwater intrusion occurring along the coast. Additional tools were required. To this end, the West Basin Water Association and the City of Manhattan Beach began to test new technology pumping water into groundwater basin along the coast in 1950 (Blomquist 1992). The injection wells worked by making a mound of fresh water which replicated the original underground pressure and kept saltwater at bay.

After the successful test, the State allocated funds for the construction of additional injection wells. The Los Angeles County Flood Control District was selected in 1952 to construct injection wells which began operating in 1953. These initial nine wells injected treated Colorado River water into the groundwater basin and successfully stopped additional saltwater intrusion in their area of operation. To fund the continued operation of the injection wells, Los Angeles

County authorized the creation of a special tax district, Conservation Zone II (Blomquist 1992). Currently, these wells are operated and maintained by the Los Angeles Department of Public Works. Additional injection barriers were created to combat seawater intrusion into the Central Basin through the construction of injection wells in the Alamitos Gap on the border of Orange County in 1965. To fund the construction of these new wells, the parties utilized money gathered for replenishment through the Zone I program (Blomquist 1992). When Zone I expired in the mid-1970s, the Replenishment District was given the obligation of operating and maintaining the Alamitos Gap barrier along with help from Orange County. Further injection wells were constructed in1971 and 2002 stopping further saltwater intrusion.

Groundwater Contamination

Agriculture and industry left their mark on groundwater quality within the Watershed. Groundwater testing of the Main San Gabriel Groundwater Basin in 1974 found high concentrations of nitrate, a legacy contaminant from the era of intensive agriculture of the region. In order to mitigate this risk, water managers began a nitrate dilution program in 1985 and 1986 with a limited amount of success. Nitrate, however, was only the earliest discovery of serious groundwater contamination in the region (Blomquist 1990).

In 1979, further groundwater testing identified the presence of Volatile Organic Compounds (VOCs), trichloroethylene, tetrachloroethylene and tetrachloride in the Main San Gabriel Groundwater Basin. These compounds, used in various industrial processes, are suspected carcinogens. Water leaders and health officials met to discuss how best to address the problem. Contaminated wells were immediately shut down, and new groundwater monitoring was implemented that the contaminated plume would not reach the lower basins. By 1985, 88 wells in the Main San Gabriel had been shut down due to contamination.

Other movement occurred when the U.S. Environmental Protection Agency selected VOC contaminated areas within Main San Gabriel as a Superfund site. The EPA and other local actors moved to provide carbon absorption systems to the contaminated areas. In 1988, the EPA announced the construction of a water treatment plant in the Whittier Narrows in Central Basin to treat groundwater flowing downstream from the contaminated areas (Blomquist 1990).

1997 brought more bad news as water monitors in the Main San Gabriel detected percholate, a component of rocket fuel linked to thyroid deformation and lower IQs in infants, at levels forty times greater than California's provisional safety standard. After a large amount of legal wrangling, a legal settlement was reached in 2002 for the clean up of the area. In the mean time, many residents sued both the company linked to the contaminant (Aerojet Corporation) and their local water provider for supplying contaminated water. As of 2003, contaminated groundwater cleanup in the area has cost $390 million dollars and rendered 127,369 acre feet of water unusable (Jahagirdar 2003).

Groundwater contamination from nitrates, VOCs, and perchlorate are not the only contamination issues facing the region. Lower basins have dealt with contamination from oil drilling and refining operations. The West Basin Judgment, for example, was modified in 1984 to recognize non-consumptive water rights and to allow certain oil companies an additional right to withdraw water beneath their operations to clean up areas polluted with hydrocarbons. Similar modifications occurred in the West Basin judgment in 1989 and 1991 for different corporations with similar basin contamination issues (Department of Water Resources 2003).

Analysis

Over the 75 years from 1931 to 2006, the water management institutions of the San Gabriel River watershed have experienced both internal stresses and external disturbances. Arrangements for the division of river flows between the upper and lower watershed areas, for the importation of water to the watershed, and most of the arrangements for governing the groundwater resources of the watershed were designed and adopted during decades when the population of the watershed was a fraction of its current totals and when a notable portion of water use was still for agriculture and/or domestic household purposes.

Agriculture contributed to nitrate contamination of groundwater supplies in the upper watershed that were not fully recognized until the 1970s. Industry left a legacy of volatile organic contaminants (VOCs) in the upper watershed area that were largely undiscovered until the 1980s, and which threatened the lower area by the 1990s. Further contamination in the form of high levels of perchlorate in the upper watershed area discovered in the 1990s has reduced available water level. In the meantime, the availability and price of imported water has changed substantially also. Most of the institutional arrangements that were created in prior decades to manage water resources in the watershed remain in place today. The arrangements for allocating river flows between the upper and lower areas are unchanged and continue to operate as intended with no evidence of difficulty or failure.

The arrangements for adding to the water supplies of the watershed, mainly through importation, are also intact but have undergone a number of modifications. The municipal water districts that were established for the purpose of annexing to the Metropolitan Water District for Colorado River water or contracting with the California Department of Water Resources for California Aqueduct water have broadened their water-supply portfolios to include purchases (and promotion) of reclaimed wastewater and for the two municipal districts that touch the coast, desalination. These changes of organizational focus may be prudent responses to emerging and anticipated limitations on imported water supplies from the Colorado River and Northern California, or empire building by board members and bureaucrats, or a mix of the two. There have been difficulties between the municipal water districts in the lower watershed area over facilities, staff, and funding, and there have been problems of corruption within the West Basin Municicial Water District. At a minimum, we can draw the conclusion that water supply augmentation in the watershed has extended beyond water importation, and that this extension has been undertaken by the agencies that were created at a time when importation was the principal goal.

The arrangements for curtailing groundwater overdraft in the watershed, replenishing overdrafted basins, and allocating or reallocating pumping entitlements have undergone some changes and yielded some mixed results. The design of groundwater management institutions such as the Exchange Pools and transfers of pumping rights in the Central and West basins, and the assignment of shares of a variable safe yield rather than fixed annual pumping quantities in the Main San Gabriel Basin, have allowed the largest groundwater basins in the watershed to withstand massive changes in the composition of the pumpers, some significant drought episodes, and (in the Main San Gabriel Basin) the shutdown of wells as a result of contamination. The adjudication of pumping rights in all four major groundwater basins, with the retention of continuing jurisdiction by the courts, has facilitated modifications of the judgments in response to new problems or desired changes to the management approach. The replenishment district in the Central and West basins has been troubled by corruption allegations, and has been enmeshed in conflict with several municipalities within the district over the management of underground storage capacity.

Water quality problems have presented significant challenges for the management institutions in the watershed and still pose a major threat to the groundwater basins. Water cleanup programs have been somewhat effective, but have resulted in tremendous costs. Water treatment programs have also had limited success.

Agenda for Further Research

There are at least two major and pressing issues awaiting further research and development, on the question of institutional robustness in SESs generally and with respect to studying the San Gabriel River watershed particularly. The first is the development of a more precise and reliable indication of "disturbances." As researchers from a variety of disciplines continue to pursue the study of institutional robustness in the face of disturbances, it will be advantageous to move toward definitions of disturbance that are not idiosyncratic and could be used to compare cases. In the watershed context, this would subdivide into questions such as: 1) whether a drought (or flood) counts as a disturbance and if so, how severe or extended a drought (or flood) must be in order to constitute a disturbance; 2) what extent of changes in land cover, land uses, water uses, population, etc., qualify as disturbances; 3) whether changes in social values and preferences qualify as disturbances. It seems unlikely that we would reach very fine-grained indicators for such a broad concept, but it seems also that further refinement of the concept would aid the kind of comparative empirical research that is most promising as we attempt to identify the design properties of robust institutions.

Second is the development of measures of robustness in the face of these disturbances. Whether the establishment of new institutional arrangements in reaction to a disturbance counts as institutional robustness, or as a failure of existing institutions to adapt and cope with the disturbance, or something else, is part of this pursuit. So too are means of distinguishing between robustness and adaptability, i.e., whether the latter is encompassed by the former, equated with the former, or something else. Is modification of an institutional arrangement in reaction to a disturbance, in and of itself, evidence of robustness? Are other performance indicators needed, and if so, what should their characteristics be?

Both of these pressing considerations will have much to do with the direction of further inquiry into the institutions for managing water resources in the San Gabriel River watershed. We look forward to undertaking that further inquiry, and hope it will contribute to the further development of explanation and understanding of institutional robustness.

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