The final publication is available from now publishers via http://dx.doi.org/10.1561/102.00000010

Local Negotiation with Heterogeneous Groundwater Users*

Gordon C. Rausser[†], Susan Stratton Sayre[‡], and Leo K. Simon[†]

Abstract

This paper assesses the political implications of intra-aquifer heterogeneity in the benefits and costs of optimal groundwater management. We use simulation modeling to predict groundwater extraction regimes under two alternative local decision-making structures and compare these structures to optimal management. Local collective action performs poorly when the intra-aquifer disparity in the potential gains is large. Moreover, large intra-aquifer disparity is generally associated with large potential gains. As a result, local collective action is unlikely to be successful in capturing the largest welfare gains. Individual subregions within a groundwater basin almost always benefit most from political structures whose outcomes diverge from optimal management. These results may be of particular interest to policymakers in California. The state of California currently allows local regions to make their own decisions about groundwater management with little outside intervention. The analysis in this paper suggests that there may be regions where large potential gains from optimal management are available, but cannot be realized by the two alternative local political institutions. This suggests that there may be a role for State intervention in the local political processes by which local water management decisions are made.

Keywords: collective action, Nash bargaining, groundwater

1 Introduction

Groundwater is an important source of water for much of the world. It is estimated that of the world's fresh water, almost 75% is locked in the polar ice caps and 25% is groundwater. In other words, surface water makes up less than 1% of the world's fresh water supply

*The authors thank W. Michael Hanemann, Gerard Roland, David Sunding and David Zilberman for feedback on earlier versions of this work. We also gratefully acknowledge the support of the California Policy Research Center and the Giannini Foundation for Agricultural Economics. Any remaining errors are our own.

†Department of Agricultural Economics, University of California, Berkeley

‡Corresponding Author, Department of Economics, Smith College, Northampton, MA 01063, ssayre@smith.edu

(Alley et al., 1999). As pressure on water supplies has increased around the world, so has groundwater pumping. In many areas, groundwater is being pumped at a much faster rate than it can be replenished, causing groundwater levels to fall. These drops *per se* do not indicate an economic problem; because of discounting of future costs and benefits, it can be rational for users to prefer using water today despite increased pumping costs or lower supplies in the future. However, since groundwater aquifers are common-property resources, in the absence of a carefully managed and enforced system of private property rights to the groundwater stock, water users have an incentive to pump more water than is socially optimal, causing water levels to decline too rapidly.

Economic simulations have shown the aggregate welfare losses of this overpumping to be quite small in many circumstances. This fact was first observed by Gisser and Sanchez (1980a,b), and has been confirmed by many later studies (e.g. Kim et al., 1989; Rubio and Casino, 2001, 2003; Knapp et al., 2003). While these studies model groundwater model aquifers as homogeneous, groundwater levels can in fact vary substantially within an aquifer. Brozovic et al. (2003, 2010) demonstrate that such intra-aquifer variations can lead to a substantial increase in the size of the common property externality.

This paper investigates the political implications of intra-aquifer variations. In many regions, including the state of California, authority to regulate groundwater lies with local entities whose boundaries do not match those of groundwater aquifers. As a result, multiple local authorities are involved in decisions about whether and how to regulate groundwater withdrawals within a given aquifer. A critical question is whether local collective action among these entities can implement effective management regimes or whether regimes should be imposed from above by a central regulator (e.g. a state or national government).[1] Elinor Ostrom evaluates the local institutions that have been involved in such decisions, specifically for groundwater management systems in Southern California (1990). She contrasts the success of collective action to manage groundwater in the Raymond, Central, and West Basins

[1] In this case of aquifers whose boundaries cross national borders, there is no such central regulator available.

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with the failure of local collective action in San Bernardino county. She offers several conditions that increase the likelihood of successful collective action. These include a common expectation of harm from failing to act, similar impacts of proposed changes, low discount rates, low information, transformation, and monitoring costs, pre-existing trust among the players, and a small group of players. Of particular interest to us is her focus on homogeneity; she emphasizes that effective management is far more likely to emerge when all players are affected similarly by implementable management decisions.

In addition to Ostrom's Southern California study, there are several others that have investigated the political dimension of groundwater management. Hellegers and van Ierland (2003) argue that groundwater management alternatives should be assessed for both their economic efficiency and their political feasibility. They specify several normative criteria for policy instruments including: their equity, ease of implementation, their political acceptability and their capacity to achieve environmental and economic objectives. They conclude that traditional economic instruments (taxes and subsidies) score poorly because they are hard to implement, impose unequal impacts, and/or are politically unacceptable. Blomquist (1992) outlines the management regimes developed in various areas of Southern California and argues that allowing local agencies to develop groundwater management regimes on their own may be preferable to imposing management from above by a central regulator because local autonomy allows for a high degree of individualization and creativity in confronting problems.

White and Kromm (1995) review groundwater management districts in Colorado and Kansas. Most groundwater in these regions is used for irrigation. In both states, management districts have authority to restrict the drilling and location of wells, to institute pumping limits, and to assess taxes to pay for management expenses. Stephenson (1996) examines the development of groundwater management in Nebraska's Upper Republican Natural Resource District (URNRD). The URNRD adopted well-spacing requirements and imposed 5-year pumping limits. Stephenson identifies situational and policy factors that affect the potential for self-regulation. In particular, he emphasizes the importance of substitute water sources, existing knowledge base, belief systems, dynamics of conflict, boundary rules, decision rules, regulatory rules, financing, and monitoring/enforcement.

As noted above, spatial variation in water levels within aquifers leads to intra-aquifer heterogeneity with respect to the gains and losses from centralized management relative to unregulated common property. Thus, real-world hydrological conditions tend to create exactly the situation Ostrom identifies as problematic for local collective action.

In this paper, we construct a political economy model of local action and use it to assess the political implications of intra-aquifer heterogeneity in benefits and costs. In particular, we evaluate how various political institutions perform compared to optimal management. Since there are many possible local institutions that could be involved in groundwater management, we also discuss the choice of alternate institutions, from the perspective of both aggregate welfare as well as from the perspectives of individual subregions within a groundwater basin.

Because there are no closed form solutions to the political economy models used in this paper, we employ Monte Carlo simulation and response surface analysis to investigate the impacts. The Monte Carlo analysis allows us to evaluate the impacts for a broad set of possible aquifer conditions. The response surface analysis provides a concise way to summarize how these varying conditions influence political outcomes. Although our model is not explicitly tied to any specific region, the parameters of interest and their distributions were chosen to be representative of California's Central Valley. California has no statewide groundwater management institutions so the local political action models developed in this paper are indicative of groundwater management institutions within the state.

In Section 2, we present a model of groundwater use in several subregions within a given aquifer, coupled with models of various political structures for determining subregional groundwater use levels. In Section 3, we explain our Monte Carlo simulation methodology. Section 4 presents the results of these simulations and uses response surface analysis to obtain insights about the patterns driving differences in performance across the simulation we examine.

2 The Model

Groundwater extraction and management decisions are dynamic; decisions about how much to extract today are made in part on the basis of expected future benefits and costs. In this paper, however, our primary interest is in the political interaction between subregions of a given groundwater basin, rather than the dynamic path of groundwater extractions. To focus the intra-aquifer interaction, we construct a static model calibrated to match the results of a dynamic model that was developed in Stratton (2008).

This dynamic model tracks water levels in several subregions of an aquifer on an annual basis. Year to year changes are caused by extractions within subregions and the partial equalization of water level variation between subregions. Fundamentally, the results of a dynamic hydrological model are driven by two major factors: the demand for groundwater and the impact of each subregion's pumping on its own and its neighbors' costs. Our static model is thus based on these two components. The demand parameters are driven by a region's overall demand for water, the amount of surface water it has available, and the efficiency of its surface water delivery system. The cost parameters and regional interaction parameters are driven by the depth to groundwater, the distance between cells and the hydrological characteristics of the aquifer. In our static model, the cost of water is proportional to a weighted sum of groundwater use in each subregion where the weight is inversely proportional to the distance between subregions. Thus, the effect of water use by adjacent districts increases as the distance between the districts shrinks.

Formally, in our static model, the aquifer contains several subregions, indexed by n. Each subregion has a present value water benefit function of the form

$$B_n\left(x_n\right) = \alpha_n x_n - \frac{1}{2}\beta_n x_n^2 \tag{1}$$

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and a present value cost function of the form

$$C_n(\mathbf{x}) = \phi_n x_n \sum_m \gamma_{nm} x_m \tag{2}$$

where $\mathbf{x} = (x_n)$ is a vector of subregional (constant) annual groundwater extractions, γ_{nm} is a coefficient whose value decreases as the distance between subregion n and subregion m increases. The parameters α_n and β_n are the intercept and slope, respectively, of a subregion's demand for groundwater and ϕ_n measures the impact of a subregion's pumping on its own costs. We refer to ϕ_n as the cost coefficient. In our simulations, all of these parameters are calibrated based on the results of derived from the dynamic model developed in Stratton (2008). The calibration process is described in Section 3.

A subregion's utility function is represented by net benefits:

$$u_n(\mathbf{x}) = B_n(x_n) - C_n(\mathbf{x}).$$

For notational simplicity in discussing the results, we define the aggregate benefit function as

$$U(\mathbf{x}) = \sum_n u_n(\mathbf{x}).$$

Under unrestricted common property, each subregion will maximize its own net benefits, taking the actions of the other subregions as given. The common property solution is the vector $\hat{\mathbf{x}}$ defined by

$$\alpha_n - \beta_n \hat{x}_n - \phi_n \sum_m \gamma_{nm} \hat{x}_m - \phi_n \gamma_{nn} x_n = 0 \tag{3}$$

for all n.[2] By contrast, the manager seeking to maximize aggregate benefits would set extractions equal to $\mathbf{x}^*$ where

$$\alpha_n - \beta_n x_n^* - \phi_n \sum_m \gamma_{nm} x_m^* - \sum_m \phi_m \gamma_{mn} x_m^* = 0 \tag{4}$$

[2]This format assumes an interior solution where all subregions extract positive amounts of groundwater.

for all n. The difference between the two solutions is the common property externality(Rausser and Zusman, 1992). In the common property solution, subregions care only about the impact of their pumping on their own costs, while optimal management takes account of all impacts of pumping.

In reality, it is very unlikely that the optimal management solution will be implemented. Instead, the management regime must emerge from some political process. The political structures within which groundwater policy is formulated vary across aquifers. In what follows, we focus on two models of these processes: Nash bargaining between subregions and maximizing weighted average subregional utility.

Local Nash Bargaining. One conceptualization of groundwater management policy formation is as a local bargaining process among subregions of the aquifer. We model this process using the bargaining model introduced in Nash (1950). The Nash bargaining solution is given by

$$\mathbf{x_N} = \arg\max_{\mathbf{x}} \prod_{j=1}^{J} \left[u_j\left(\mathbf{x}\right) - u_j\left(\mathbf{x_0}\right)\right]. \tag{5}$$

where $\mathbf{x_0}$ denotes the default outcome, and J denotes the number of players. In this setting, the elements of the vector $\mathbf{x}$ are groundwater extractions in each subregion. The default vector $\mathbf{x}_0$ is the outcome under the status quo. In the present case, the status quo would be the common property solution $\hat{\mathbf{x}}$, so the Nash solution becomes

$$\mathbf{x_N} = \arg\max_{\mathbf{x}} \prod_{j=1}^{J} \left[u_j\left(\mathbf{x}\right) - u_j\left(\hat{\mathbf{x}}\right)\right]. \tag{6}$$

Area Weighted Average Utility (AWAU). Another way to conceptualize the formation of groundwater management policy is by maximizing the weighted average utility of the subregions of the aquifer. This emerges as the solution to at least two different political economy models of local policy-making: probabilistic voting and lobbying of a central regulator.There is a substantial literature devoted to the outcome of democratic voting. Much

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of this work uses the median-voter model formulated by Hotelling (1929) and Downs (1957). In the present setting, however, the policy space is multi-dimensional—the level of water extraction in each subregion—and in this context, the median voter model is not well-defined. There will in general be no voter who is the median along all dimensions simultaneously. To deal with multi-dimensional voting problems, Hinich (1977), Coughlin and Nitzan (1981), and Ledyard (1981, 1984) introduce an alternate voting model referred to as probabilistic voting. In this model, there is uncertainty regarding whether and how voters will cast their ballots. When applied to our groundwater model, the solution to the probabilistic voting model is the vector that solves

$$\max_{\mathbf{x}} \sum_{i} \alpha_i u_i \left(\mathbf{x}\right)$$

where i indexes voters and α_i is a weight representing the probability that voter i will change her vote based on changes in $\mathbf{x}$. Voters who are highly responsive to changes in $\mathbf{x}$ have high values of α_i, while voters who are less responsive have low values of α_i. This probabilistic voting model therefore implies that the chosen policy will maximize a weighted average of voter utility.

An alternate specification is that a central regulator is granted the power to set management policy. Individual interest groups will lobby the regulator to adopt a policy advantageous to their interests. Rausser et al., (2010) demonstrate that the solution to such a game is the solution to

$$\max_{\mathbf{x}} \left\{ U\left(\mathbf{x}\right) + \sum_{j} \beta_j u_j \left(\mathbf{x}\right) \right\} \tag{7}$$

where j indexes interest groups and β_j is a coefficient representing interest group j's ability to influence the regulator. Groups that are able to improve the regulator's welfare at the lowest cost to themselves have the highest values of β_j.

The objective functions derived from the central regulator and local voting models are formally indistinguishable; the only difference is one of interpretation, the source of the power weights. Moreover, if each voter or interest group had exactly the same weight, either model would produce the utilitarian social optimum as its equilibrium solution. In our empirical analysis, we consider weights based on the relative size of subregions and thus do not distinguish between the local voting and central regulator formulations. Area-based weights are of particular interest in the agricultural regions of California because many water districts there are explicitly governed by a one-acre, one-vote principle rather than a one-person, one-vote principle. We will denote the solution to the area-based weighted average objective function as $\mathbf{x_A}$.

We use the solutions to our two political models to determine the potential effectiveness of local collective action. Specifically, we compare the payoff vectors $U(\mathbf{x_N})$ and $U(\mathbf{x_A})$ generated by these political models to the payoff vectors under optimal management $U(\mathbf{x}^*)$ and under unrestricted common property, $U(\hat{\mathbf{x}})$. Due to non-negativity constraints, only the common property model has a closed form solution; the other three solution vectors are obtained by numerical methods. As a result, we cannot use analytical comparative statics to determine the relative performance of our different political structures in varying aquifer conditions. Instead, we conduct a Monte Carlo simulation exercise in which we vary the parameters describing the aquifer and its subregions. These simulations allow us to evaluate the performance of these political structures under a broad variety of circumstances.

3 Monte Carlo Simulation

In this section, we explain how we use Monte Carlo simulations to analyze our model under a variety of parameterizations. Each simulation run involves four steps: parameterizing the dynamic hydrological model, calibrating the static model to that parameterization, computing our four solution concepts, and comparing the performance of each concept.

In the first step, we take random draws from the parameter distributions that drive our Monte Carlo simulations. We use MATLAB's pseudorandom number generator to draw values for the hydrological parameters of a dynamic groundwater model with four subregions

Table 1: Randomized Dynamic Model Parameters

Parameter	Minimum	Maximum
Subregion area (thousand acres)	250	1250
Surface water available (acre feet/acre)	0.0	3.0
Surface water evaporation losses (%)	0	30
Water recharge per acre (acre feet/acre)	0	0.04
Current water demand (acre feet/acre)	0.5	3.0
Current groundwater depth (ft)	30	300
Demand elasticity	-2	-1
Subregion interaction (%)	1	10

sharing a single groundwater aquifer. Each parameter is uniformly distributed on some interval. These hydrological parameters and the intervals from which their values were drawn are shown in Table 1. The values were chosen to be representative of conditions within California's Central Valley.

In the second step, we calibrate the parameters α_n, β_n, ϕ_n, and γ_{nm} in Equations (1) and (2) to the hydrological parameters drawn in the first step. To do this , we conduct a second Monte Carlo simulation, embedded within the first. That is, we randomly draw values for a vector $\mathbf{y}$ of subregional annual groundwater use levels. We then construct 50 year time paths of groundwater benefits and costs assuming subregion n extracts y_n in each year. We discount the resulting totals to present dollar values using a discount factor of 96%.[3] Finally, we use least-squares estimation to select the values of the parameters in Equations (1) and (2) that best fit our simulated data.

In the third step, we compute the values of $\hat{\mathbf{x}}$, $\mathbf{x}^*$, $\mathbf{x_N}$, and $\mathbf{x_A}$ using numerical optimization techniques. In the last step, we compute the aggregate benefits of groundwater use associated with each of these solution vectors and compare the values.

In each simulation run, the labeling of subregions is arbitrary; all that matters is the relationship between parameters across subregions. Table 2 presents summary statistics describing these relationships. The critical parameters are α_n (demand intercept), β_n (demand

[3]The choice of discount rate is somewhat subjective and varies in previous groundwater studies. Both 4% (Brill and Burness, 1994; Burness and Brill, 2001; Knapp et al., 2003) and 5% (Kim et al., 1989; Provencher and Burt, 1994; Knapp and Olson, 1995) are common choices. Our discount factor of 0.96 is comparable as it implies a rate of 4.17%.

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slope), ϕ_n (cost coefficient), and ν_n (interaction coefficient). The interaction coefficient is equal to

$$\nu_n = \sum_{m \neq n} \gamma_{nm}$$

and is an aggregate measure of the degree to which a subregion influences and is influenced by its neighbors. For each of these parameters, we compute for each iteration the mean, maximum, minimum and spread across subregions.

Table 2 presents the distribution of values for these induced parameters across simulation runs. In the results section below, the statistics listed in Table 2 are the explanatory variables we use to explain the performance of the different political structures. In each case, the relevant statistic in the left-hand column was computed across subregions within a given iteration of the Monte Carlo simulations. The summary statistics listed in the columns to the right were computed across simulations. For example, in the first row we see that on average, the mean (absolute value) demand slope was 1.52, but there was substantial variation. In one iteration, the mean subregional demand slope was as low as 0.40 and in another, it was as high as 5.58. The standard deviation across iterations of the mean subregional slope was 0.69. Moving down to the parameter minima section of the table, we see that on average, the smallest subregional demand slope was 0.59, but that in one iteration, the subregion with the smallest slope had a slope of 0.16 and in another iteration, the subregion with the smallest demand slope had a slope as large as 2.03. Similar interpretations apply to the remaining rows of the table.

4 Results

The impact of imposing optimal management is summarized in Table 3. We compute several measures to summarize the potential gain. First, we calculate the percentage gain in

Table 2: Net Benefit Function Parameter Draws: Summary Statistics

	Summary Statistics Across Iterations			
	Mean	Std Dev	Minimum	Maximum
Parameter Means				
Slope	1.52	0.69	0.40	5.58
Intercept	2.20	0.35	1.27	3.37
Cost	0.75	0.26	0.27	2.23
Interaction	0.34	0.11	0.09	0.82
Area Share*	0.25			
Parameter Minima				
Slope	0.59	0.28	0.16	2.03
Intercept	1.50	0.37	0.88	3.05
Cost	0.40	0.13	0.19	1.54
Interaction	0.13	0.06	0.02	0.33
Area Share	0.15	0.04	0.07	0.24
Parameter Maxima				
Slope	2.97	1.88	0.53	15.28
Intercept	2937.55	477.86	1472.10	4002.80
Cost	1.25	0.60	0.30	5.56
Interaction	0.58	0.26	0.13	2.03
Area Share	0.36	0.05	0.26	0.5
Parameter Standard Deviation				
Slope	1.09	0.88	0.05	6.80
Intercept	647.14	238.62	36.41	1298.90
Cost	0.39	0.27	0.02	2.29
Interaction	0.20	0.12	0.01	0.88
Area Share	0.09	0.03	0.01	0.20
Parameter Spread				
Slope	2.38	1.87	0.12	14.94
Intercept	1.44	0.53	0.08	2.74
Cost	0.86	0.57	0.04	5.20
Interaction	0.45	0.27	0.02	1.84
Area Share	0.21	0.07	0.02	0.43

*Since there are four regions, the mean is always 0.25.

Table 3: Benefit of Imposing Optimal Management

	Summary Statistics Across Iterations			
Variable	Mean Value	Standard Deviation	Minimum	Maximum
% Gain from Optimal Management	4.39	2.02	0.68	13.20
Mean Subregional % Gain	−3.46	7.46	−42.61	6.56
Minimum Subegional % Gain	−29.16	32.23	−100.00	3.38
Maximum Subegional % Gain	9.99	5.63	1.17	46.52
Std Dev of Subregional Gains	18.38	17.14	0.49	69.36
Spread of Subregional Gains	39.16	35.84	1.07	146.52

aggregate benefits from optimal management relative to the common property solution, i.e.,

$$\frac{U\left(\mathbf{x}^{*}\right)-U\left(\hat{\mathbf{x}}\right)}{U\left(\hat{\mathbf{x}}\right)}\times 100.$$

On average, optimal management increases the aggregate benefits of groundwater use by approximately 4.39% relative to common property. There is substantial variation in the gains across simulation iterations, ranging from virtually no gain to an increase of approximately 13.2%.These relatively small gains are consistent with the results observed by Gisser-Sanchez and others, referenced in Section 1.

We then compute the percentage gains for each of the four subregions, i.e., for each n:

$$\frac{u_{n}\left(\mathbf{x}^{*}\right)-u_{n}\left(\hat{\mathbf{x}}\right)}{u_{n}\left(\hat{\mathbf{x}}\right)}\times 100.$$

While the aggregate gain must be non-negative, individual subregions can and do experience losses due to the move from common property to optimal management. All four regions experience gains in only 4.3% of the iterations. Individual subregions may gain up to 46.5% as a result of imposing optimal management, but other subregions may experience extremely large losses. In some iterations, optimal management implies the complete cessation of extraction in one or more subregions, i.e., those subregions lose 100% of their current benefits from groundwater use. These large losses mean that on average, the mean subregional percentage is negative.[4]

4.1 Performance of Nash Bargaining

Politically, the subregional variation has very important consequences. The variation severely limits the potential for a Nash bargaining game to capture large gains. Because the Nash function is concave in the gain experienced by each subregion, it places some value on keeping

[4]Note the while the mean subregional gain measured in dollar values is simply the aggregate gain divided by the number of regions and thus necessarily has the same sign as the aggregate gain, the mean *percentage* gain can be negative even if the aggregate *percentage* gain is positive.

Table 4: Performance of Nash Bargaining

	Summary Statistics Across Iterations			
Variable	Mean Value	Standard Deviation	Minimum	Maximum
% Gain from Nash Bargaining	2.286	0.750	0.350	4.647
% of Potential Gain Captured by Nash	57.256	17.582	13.679	99.570
% Gain Moving from Nash to Optimal	2.104	1.675	0.005	11.396

gains roughly equal across subregions. Moreover, since the Nash model is consensus based, losses relative to common property cannot be imposed on one subregion in order to realize larger gains in some other one.

The performance of the Nash model is summarized in Table 4. The first row in Table 4 reports the percentage increase in the benefits of groundwater use under Nash bargaining compared with common property. The second row describes how well Nash bargaining performs relative to an optimal management regime, listing the percentage of the potential gains from management that are captured by Nash bargaining. The last row presents the percentage gain moving from Nash bargaining to optimal management, i.e.

$$\frac{U(\mathbf{x}^*) - U(\mathbf{x}_N)}{U(\hat{\mathbf{x}})} \times 100.$$

The distribution across iterations of the performance of Nash bargaining is fairly narrow, ranging from 0.35% gain to a 4.65% gain. While optimal management can generate gains as large as 13.2%, Nash bargaining never generates gains higher than 4.65% of the common property benefits of groundwater use. On average, Nash bargaining results in a gain of only 2.29% relative to common property.

On average, Nash bargaining is able to capture only 57% of the gains captured by optimal management. At the high end, Nash bargaining captures nearly all of the gains; at the low end, it captures only 13.7%. Moreover, the correlation between the optimal management gains and the fraction of those gains captured by a Nash bargaining process is -0.64. That is, the higher the potential gains from management, the lower the fraction of those gains captured by bargaining. This result is driven by the strong positive correlation between the size of optimal management gains and the maximum *losses* experienced by an individual subregion. Large gains from optimal management are obtained by restricting pumping in one or more subregions in order to improve the situation in others.. In a consensus-based model such as Nash bargaining, the adversely affected subregion(s) would veto any such redistribution.

We use response surface analysis to gain further insight into what drives the relative performance of Nash bargaining. This methodology involves fitting a response surface to the results of the numerical simulation model. Mechanically, the process is similar to regression analysis; we choose a functional form and estimate the values of the parameters that best fit our data.[5] The dependent variable in our regressions is the percentage gain moving from Nash bargaining to optimal management. The larger this value, the worse the performance of Nash bargaining relative to optimal management. Explanatory variables include the parameter calculations described in Section 3, summarized in Table 2, as well as the information about the potential gains from optimal management and their distribution across subregions shown in Table 3. We also include squared values of the descriptive statistics about the potential gains from management to determine whether the impacts are nonlinear.

Because it is unclear whether the appropriate surface is linear in levels or logs, we first perform a Box-Cox transformation. The estimating equation is

$$\frac{\mathbf{y}^{\theta}-1}{\theta}=\beta_0+\sum_i \beta_i \mathbf{z}_i.$$

Our point estimate for the value of θ is 0.7855 with a standard error of 0.0204; we thus reject the null hypotheses that either a level or a log regression dependent variable is appropriate. We report three separate response surfaces in Table 5. In the first column, the dependent variable is the level of the percentage gain moving from Nash bargaining to optimal man-

[5]See Kleijnen (1995), Kleijnen (1997), Kleijnen and Sargent (1997), Kleijnen (2001), Kleijnen et al. (2002), and Kleijnen et al. (2005) for a discussion of the application of response surface analysis to the results of simulation models.

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Table 5: Percentage Gain Moving from Nash Bargaining to Optimal Management

	Percentage Gain	Log of % Gain	$\frac{\%\ \text{Gain}^{0.7885}-1}{0.7885}$
Potential % Gain			
Aggregate	0.622**	70.679**	1.730**
Mean	−0.106**	−3.437**	−0.230**
Minimum	−0.023**	−0.131	−0.037**
Std Dev	−0.069**	3.362†	−0.089**
Aggregate^2	1.704**	−296.354**	−0.002
Mean^2	−0.161**	−5.616**	−0.378**
Minimum^2	−0.018**	−0.691	−0.036**
Variance	0.082**	−4.621†	0.104*
Parameter Means			
Slope	0.002**	0.101	0.004**
Intercept	−0.001**	−0.081	−0.003**
Cost	0.000	−0.201	0.000
Interaction	−0.027**	−1.987**	−0.061**
Parameter Minima			
Slope	0.000	0.241**	0.002
Intercept	0.001*	−0.012	0.002
Cost	−0.002	−0.354	−0.007
Interaction	−0.025**	−1.370**	−0.058**
Area	−0.008*	0.218	−0.014
Parameter Spreads			
Slope	−0.002**	−0.114*	−0.003**
Intercept	0.000**	0.000**	0.000**
Cost	0.003*	0.635**	0.008*
Interaction	0.010**	0.285	0.018**
Area	−0.015**	−0.465	−0.028*
Constant	0.002	−6.138**	−1.263**
N	1000	1000	1000
R^2	0.983	0.896	0.981
F	2621.4	382.1	2301.5

$^{**}p < 0.01$, $^{*}p < 0.05$, $^{\dagger}p < 0.10$

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agement. In the second, it is the natural log of this percentage gain. In the final column, the percentage gain is transformed by our point estimate for θ.

The response surfaces are able to explain between 90% and 98% of the variation in the underlying data depending on the particular specification. These results provide additional detail on how the size of aggregate gains influences the performance of Nash bargaining: we see that the linear effect of higher potential gains is positive and significant in all three specifications. The quadratic effect is positive and significant in the first specification, negative and significant in the second, and positive but insignificant in the third. This implies that Nash bargaining performs poorly relative to optimal management, precisely when the percentage gains from optimal management are large. Moreover, this impact is increasing in the gains from optimal management.[6]Both the linear and quadratic coefficients on the minimum subregional percentage gain are negative in all three specifications and significant in the first and third. This implies that Nash bargaining comes closer to replicating optimal management when the minimum percentage gain experienced by a subregion increases. Nash bargaining will not impose losses on any region; when optimal management requires imposing losses, Nash bargaining will diverge significantly from optimal management. Increasing the minimum gain decreases the probability that a region must experience a loss under optimal management.

Both coefficients for mean gains are also negative and significant in all specifications. Because we are comparing percentage gains, the mean tends to be lower when those who do well under common property do even better under optimal management and vice versa. In these situations, Nash bargaining will perform worse relative to optimal management. This reflects the tendency of Nash bargaining to balance gains across subregions.

In the first and third specifications, the coefficients for the standard deviation of subregional percentage gain is negative and significant while the coefficient for the variance is

[6]This conclusion is consistent with the negative quadratic coefficient in the second specification. The dependent variable in the second regression is the natural log of the improved performance. The natural log can increase at a decreasing rate while the level increases at an increasing rate.

Table 6: Performance of Area-Based WAU

Variable	Summary Statistics Across Iterations Mean Value	Standard Deviation	Minimum	Maximum
% Gain from AWAU	2.172	3.066	−21.151	13.031
% of Potential Gain Captured by AWAU	43.762	66.027	−342.120	99.998
% Gain Moving from AWAU to Optimal	2.218	2.637	0.000	31.267

positive and significant. Given the coefficients themselves and the range of values for the standard deviation of percentage gains, these estimates imply that increasing the variation in subregional percentage gain under optimal management improves the performance of Nash bargaining relative to optimal management, albeit at a decreasing rate. While this may seem surprising a priori, it is a reflection of the other controls in the regression. The pairwise correlation between the percentage gain moving from Nash to optimal and the variation in percentage gains under optimal management is positive, implying that, as we would expect, Nash bargaining performs worse when optimal management requires large variation in regional gains.

Finally, increasing the average degree of interaction between subregions increases the performance of Nash bargaining, but increasing the spread of interaction across subregions decreases performance. That is,all else equal, the more interconnected are the subregions, the greater is the congruence between their interests, and Nash bargaining will do a better job of capturing potential gains. However, as variation in the degree of interconnection across subregions increases, subregional interests will diverge, making it more difficult to simultaneously balance gains across subregions and achieve large aggregate gains.

4.2 Performance of the AWAU model

There is substantial divergence between the performance of the Nash bargaining game and that of the AWAU model. Results for the latter are summarized in Table 6. On average, the AWAU model results in gains of only 2.17% relative to common property, less than the average gain of 2.29% for Nash bargaining. However, the distribution of gains is much larger

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than for Nash bargaining. The AWAU model can result in a net loss of up to 21% relative to common property. However, it could also result in a net gain of over 13%. The AWAU model can be almost as effective as optimal management. This result is not surprising; if all the subregions are equal in size, the AWAU model will replicate the utilitarian social welfare maximizing solution. But since the AWAU model can result in losses, it is clear that the political structures that it represents can also perform far worse than optimal management.

The key question is: *when* does the AWAU model perform well? Table 7 reports coefficients for a response surface explaining the increase in percentage gains relative to common property, moving from AWAU to optimal management. As this number increases, the performance of AWAU relative to common property declines. As before, we first consider a Box-Cox transformation. Our point estimate for θ is 0.2444 with a standard deviation of 0.0141, once again suggesting that neither the level or the log is the appropriate variable. We report all three surfaces as before.

All three surfaces perform less well than those estimated for Nash bargaining, explaining between 60% and 76% of the variation in outcomes. Notably, the performance of the AWAU model exhibits a different pattern from Nash bargaining with respect to aggregate gains. While the linear coefficient on aggregate gains is similarly positive, the quadratic coefficient is negative. This implies that like Nash bargaining, the relative performance of AWAU falls as the percentage gains increase. However, while this effect is magnified at the largest values under Nash bargaining, it is attenuated at the largest values under AWAU.There is a positive relationship between the smallest element of the weighting vector and the fraction of gains captured. This is logical as the AWAU approaches the social welfare maximizing policy as the weights get closer, i.e. as the minimum weight approaches 0.25. Increasing the standard deviation of weights has a negative impact on the performance of AWAU. Again, this is expected as a standard deviation of zero would reproduce optimal management. Increasing the average interaction between regions still increases the performance, just as increasing the standard deviation of that interaction **decreases** the performance.

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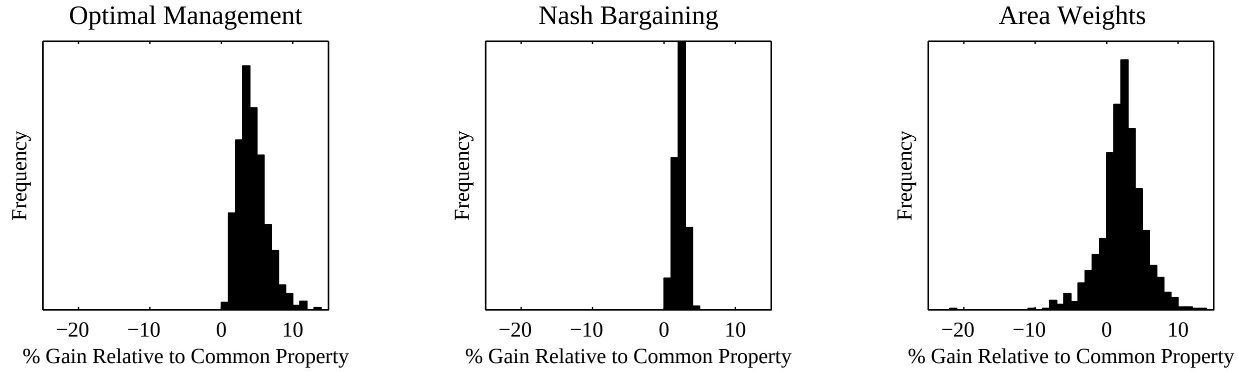
Table 7: Percentage Gain Moving from AWAU to Optimal Management

	Percentage Gain	Log % Gain	$\frac{\text{\% Gain}^{0.2444}-1}{0.2444}$
Potential % Gain			
Aggregate	0.907**	59.696**	22.678**
Mean	0.227**	6.072**	2.529**
Minimum	0.054	−0.752	−0.077
Std Dev	0.111	−0.096	−0.160
Aggregate^2	−3.799*	−201.862**	−94.143**
Mean^2	0.236*	3.746	2.697†
Minimum^2	0.094**	3.640**	1.136**
Variance	−0.333**	−20.725**	−5.432**
Parameter Means			
Slope	0.002	0.232	0.085
Intercept	0.007†	0.209	0.099*
Cost	−0.040*	−1.283†	−0.487*
Interaction	−0.142**	−6.816**	−2.312**
Parameter Minima			
Slope	−0.004	−0.012	−0.013
Intercept	−0.009*	−0.317†	−0.134**
Cost	0.036*	0.778	0.266
Interaction	0.082**	3.591**	0.963**
Area	0.020	−4.986**	−1.377**
Parameter Spreads			
Slope	−0.004	0.071	−0.020
Intercept	0.000	0.000	0.000
Cost	0.033**	0.249	0.239
Interaction	0.144**	5.333**	1.812**
Area	0.499**	26.595**	8.627**
Constant	−0.039**	−6.917**	−3.490**
N	998	998	998
R^2	0.600	0.701	0.756
F	66.377	103.970	137.007

$^{**}p < 0.01$, $^{*}p < 0.05$, $^{\dagger}p < 0.10$

Figure 1: Distribution of Political Structure Performance (Aggregate)



4.3 Second Best Political Structure

The results in the previous two subsections suggest that Nash bargaining and the AWAU model perform quite differently in certain situations. Figure 1 compares the distribution of percentage gains across iterations for the three models. As noted previously, Nash bargaining has the tightest distribution and AWAU utility has the widest.

By definition, optimal management produces the largest possible aggregate gains. Figure 2 compares the distributions of the fractions of these potential gains that are captured by Nash bargaining and AWAU. While AWAU is able to capture some of the largest potential gains, Nash bargaining cannot.

In this section, we examine the circumstances under which one of the models performs better than the other, i.e. when $U(\mathbf{x}_N) > U(\mathbf{x}_A)$ or vice versa. Since optimal management

Figure 2: Fraction of Gains Captured

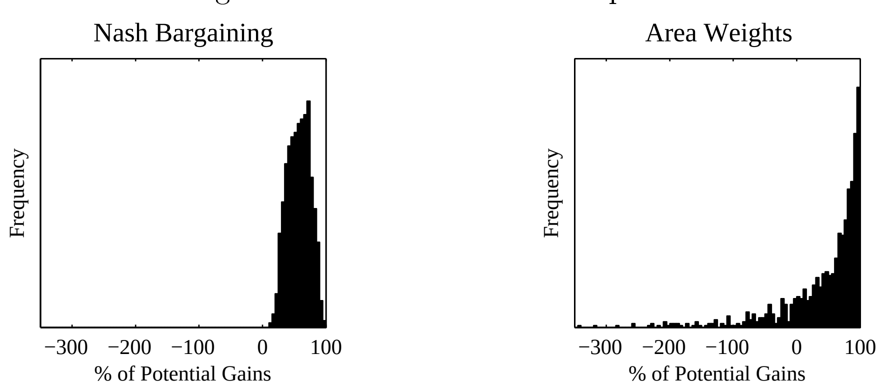


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Table 8: Aggregate Political Structure Preference

	Logit Coefficient	$\Delta\hat{Pr}$ Max - Min	Marginal Effect
Potential Gain			
Aggregate	-3.919^{**}	-0.989	-0.879^{**}
Minimum	4.213^{**}	0.930	0.945^{**}
Std Dev	2.658	0.930	0.596
Aggregate^2	0.538^{**}	0.904	0.121^{**}
Minimum^2	0.148	0.381	0.033
Variance	-0.644	-0.477	-0.144
Parameter Means			
Slope	-0.025	-0.029	-0.006
Intercept	3.390^{**}	0.943	0.760^{**}
Cost	-2.594	-0.630	-0.582
Interaction	-2.002	-0.293	-0.449
Parameter Minima			
Slope	-2.506^{**}	-0.590	-0.562^{**}
Intercept	0.626	0.318	0.141
Cost	-1.505	-0.328	-0.338
Interaction	5.245	0.366	1.176
Area	-47.428^{**}	-0.940	-10.636^{**}
Parameter Spreads			
Slope	1.868^{**}	0.913	0.419^{**}
Intercept	-0.003^{**}	-0.593	-0.001^{**}
Cost	-6.638^{*}	-0.817	-1.489^{*}
Interaction	-0.264	-0.044	-0.059
Area	69.205^{**}	0.993	15.520^{**}
Constant	$3.492^{\dagger}$	0.000	0.000^{**}
N	1000		
Pseudo R^2	0.554		

$^{**}p < 0.01$, $^{*}p < 0.05$, $^{\dagger}p < 0.10$

performs the best in the aggregate by definition, these calculations determine whether Nash bargaining or the AWAU model is the second-best structure. Table 8 reports a logit response surface for the likelihood that Nash bargaining dominates. Specifically, we define a dummy variable equal to 1 if Nash bargaining outperforms the AWAU model on an aggregate basis and equal to 0 if the AWAU model dominates and use this as the dependent variable in the logit regression. The left column of the table reports the logit coefficients and their significance. The center column gives the change in the predicted probability that Nash bargaining outperforms AWAU induced by moving the given variable from its minimum value to its maximum value, holding all other independent variables fixed at their means.

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Finally, the right column of the table reports the marginal effect of increasing the given independent variable from its mean. Again, all other variables are held fixed at their means. In this regression, the explanatory variables are the dollar value of optimal management gains rather than percentage increases over common property values.

Overall, Nash bargaining dominates in approximately 44.7% of the iterations. The logit estimates indicate that the AWAU model is far more likely to dominate when the minimum area weight is larger and when the spread in area weights is smaller. This result is expected since these conditions indicate that the area weights are close to equal and therefore that the the AWAU model more closely approximates optimal management.

Of more interest is the fact that the coefficient on aggregate gains to optimal management is negative, implying that the Nash model is less likely to dominate when the percentage gain to optimal management is large. In other words, regions with the most to gain from managing groundwater would be better off if water management policy were to emerge from the kinds of political structures represented by the AWAU model than by the consensus-based structures represented by Nash bargaining. These results suggest that an outside entity seeking to determine which political structure would best serve the aggregate interests of stakeholders in a particular region would need to investigate the particular situation quite closely to ensure selection of the appropriate structure. In other words, it would be unwise to encourage or foster either of the two structures we examine in all situations. Nash bargaining limits the extent to which some subregions can gain advantages at the expense of others, but it inhibits the exploitation of large potential gains, while AWAU does the reverse. This result lends support to the Blomquist (1992) argument for flexibility in local management of aquifers. While Blomquist advocated flexibility in the choice of mechanisms by which groundwater is managed, our results have implications for the political processes from which these mechanisms emerge. Specifically, our comparison of the Nash and AWAU models suggest that flexibility in the design of the institutions for aquifer management may be required in order to match political structures to different local conditions.

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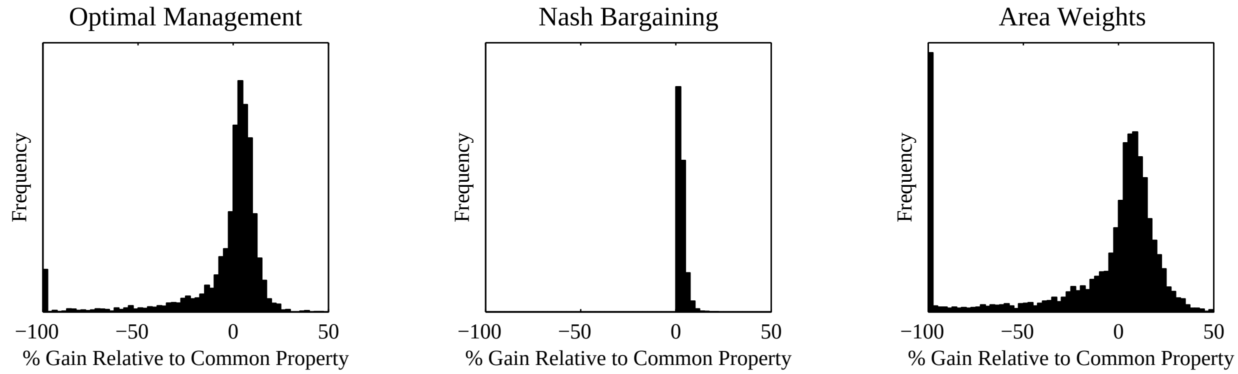
Figure 3: Distribution of Subregional Gains



4.4 Subregional Political Structure Preference.

In the previous subsection, we compared political structures from an aquifer-level perspective. However, it is extremely unlikely that all subregions within an aquifer will agree about the choice of political structure, especially when these subregions have diverse characteristics. As an obvious example, larger subregions will prefer political structures in which size is an important determinant of political power, while smaller ones will likely prefer structures in which each subregion has more or less equal political power.

Figure 3 shows the distribution of subregional gains across iterations for the different political economy models. Once again, the distribution for Nash bargaining is much tighter, due to a combination of preventing any region from experiencing losses and its preference for distributing gains equally. Both optimal management and AWAU have significant spikes at 100% losses, although the spike is much larger for AWAU than for optimal management.

Table 9 investigates the distribution of subregional preferences over the different political structures. For each parameter draw, we count the number of subregions that do better under either Nash, AWAU or optimal management. Table 9 summarizes this data in a block diagonal matrix: for $i = 0, \ldots, 4$ and $j = 0, ..., 4 - i$, the i, j'th entry in the matrix is the frequency with which i subregions do best under WAU, j subregions do best under Nash and the remainder do best under optimal management. In no case do all four subregions do best under the same political structure. The single most common configuration of preferences

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Table 9: Subregional Preferences for Political Structure

# That Prefer AWAU	# That Prefer Nash Zero	One	Two	Three	Four
Zero	0	3	7	0	0
One	0	55	97	26	
Two	7	214	384		
Three	6	201			
Four	0				

is that the two larger subregions do best under WAU while the two smaller subregions do best under Nash bargaining. On average, just under two of the four subregions do better under WAU than either Nash bargaining or optimal management. Optimal management is rarely preferred. The lowest diagonal (i.e., the one with five elements) represents the five possible combinations in which no subregion prefers optimal management. Only three of the five elements have nonzero entries, but these cases account for 61% of the total observations. Thus in only 39% of the cases does some subregion prefer optimal management. More than one subregion prefers optimal management in only 7% of the cases.

5 Conclusions

The results reported here confirm that intra-aquifer heterogeneity has important political consequences. The Nash bargaining model used to study local collective action formalizes the conclusions offered by Ostrom (1990). In particular, the analysis in this chapter confirms that local collective action is far more likely to be successful when subregions are relatively homogeneous.It also highlights the importance of heterogeneity as an impediment to successful collective action and so raises serious concerns about the ability of local political structures to mitigate groundwater problems on their own.

Our results for the Nash bargaining model suggest that on average local consensus-based political structures might capture a little more than half of the potential gains from collective action. Our results also suggests, however, that such structures will perform least well precisely when there is the most to gain. This result lends credence to suggestions that the State of California may need to intervene to promote better management. It also suggests that the benefits intervention are likely to vary across subregions.

Our analysis of the AWAU model suggests that under some circumstances, political structures based on either voting or lobbying may perform better than consensus-based bargaining. One institutional change that would move in this direction would be to assign to existing water agencies the authority and obligation to develop water management plans. However, this approach should be pursued with caution as such regimes also have the potential to decrease welfare from current levels. Finally, intra-aquifer disparity in the preferences of local stakeholders over political structures implies that reaching agreement on future groundwater decision-making authority will be challenging.

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