Income Distributional Effects of Using Market-Based Instruments for Managing Common Property Resources

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Abstract

In the face of growing management problems and conflicts over increasing demands and dwindling or increasingly variable supplies of surface and groundwater, the need for revising the conventional water resource allocation methods has been increasingly felt among natural resource managers and policy makers. For the past 30 years economists have advocated for the application of various types of market-based instruments (MBIs) as an efficient means of effecting the re-allocation water resources among competing uses. While MBIs have been implemented in several countries, they have continued to encounter strong socio-political opposition, due to the impacts imposed on third-parties during transfers and re-allocations, as well as the distributional effects across different types of water users.

Despite the demonstrable efficiency gains of MBIs, the resulting equity or distributional effects of MBI-driven re-allocations can be of equal or greater importance to policy-makers and the constituents that they serve. At the same time, the realized gains in economic efficiency from the application of MBIs depend heavily on the heterogeneity of the agents they are targeted towards, as well as the degree of information asymmetry that the regulator faces.

In this paper, we use a simple theoretical framework to show the trade-offs between efficiency and equity that might arise from the application of MBIs to a heterogenous population of agents drawing non-cooperatively from a natural resource pool. Using the idealized centralized planner as a benchmark of dynamic, allocative efficiency, we compare the realized efficiency gains that can be realized by alternative policy instruments and the resulting impacts on distributional equity, in terms of the cumulative net benefits over time. Using the specific example of groundwater and the empirical setting of Southern California, we are able to highlight the trade-offs between efficiency and equity that might exist among alternative policy instruments, and how MBIs perform with respect to those dual criteria. We find that under agent heterogeneity, there are asymmetric gains in efficiency when the centralized planner allocations are constrained by equity considerations. Through such results, this paper demonstrates the importance of considering both efficiency gains and the minimization of disparities in distributional inequity, when designing policy instruments that create winners and losers with potentially serious socio-political ramifications.

1. Overview

1.1 Introduction

Policy makers and researchers have faced the challenge of addressing pressing issues of environmental and natural resource management and regulation with policy instruments that are both effective, in terms of achieving the desired outcomes, while striving to improve the economic efficiency, as defined in terms of the resulting change in net benefits of the economic agents involved. The consideration of such problems ranges, in the literature, from that of pollution of air and water, to that of the management of water, soil and other natural resources. Among the challenges that are faced by environmental managers and policy makers are that of coordinating the behavior of individual economic agents whose actions have direct impacts on the environment and the state of important natural resources, which lie under their stewardship. While direct centralized control and intervention might be called for, resource and personnel limitations necessitate the application of decentralized policy instruments, which are designed with a view to maximizing overall benefits, and achieving the best possible environmental outcomes. Nonetheless, some form centralized regulation is often considered due to the difficulty of realizing de-centralized Coasian bargaining, either due to the presence of transactions costs, asymmetry in information (Farrell, 1987), scale considerations (Nalebuff, 1997) or other reasons.

One of the primary obstacles that lie in the way of achieving both the desired environmental and economic goals is that of agent heterogeneity, which complicates the design of the appropriate policy instrument that the regulator wishes to apply. In the case of homogeneity, a simple, decentralized policy instrument can be applied to bring the actions of the agents in line with that of the idealized central planner, whose actions form the benchmark for economic efficiency. As the characteristics of the multiple agents diverge from that of uniform homogeneity, the amount of information the regulator requires to design the appropriate set of efficiency-enhancing policy instruments, increases.

Market-based instruments (MBIs) have slowly gained popularity among those environmental managers who seek to improve environmental outcomes within a context in which there are multiple agents, whose heterogeneity might other reduce the efficiency of a non-discriminatory policy instrument. The classical application of market-based policy instruments of environmental regulation, has been that of pollution control, in which the costs of abatement might vary across the polluters (Baumol and Oates, 1975). The seminal works of McGartland and Oates (1985) and Tietenberg (1985) were the first to discuss a decentralized system of tradable permits that could be bought and sold within a transparent market structure that could be used to improve the environment. The application of market-based instruments can also be found within the context of natural resource management, such as in the application of tradeable quotas in fishery management (Anderson, 1995; Hanley *et al.*, 1997). The success of the system of tradable emissions permits to address the acid-rain problem in North America has been noted widely, and is a recognized example of the successful application of economic theory to institutional and market design (Tietenberg, 1985; Joskow *et al.*, 1998).

While achievement of environmentally-sound outcomes is important, policy makers must also take into account considerations of equity, which can sometimes have stronger socio-political ramifications than the simple achievement of welfare-neutral gains in overall economic efficiency. The typical, stylized analytical models that are used in the quantitative investigation of efficiency gains under alternative policies, tend to impose the assumption of agent homogeneity, for the purposes of simplicity and analytical convenience. While necessary, for complex types of problems, the assumption of homogeneity, nonetheless, overlooks important questions of equity, and what implications that alternative policy regimes might have on the distribution of benefits across different agents. While some authors have investigated efficiency and equity considerations within the context of water management, these have mostly centered around the issue of surface water pricing (Tsur and Dinar, 1995), but have not directly addressed the context of groundwater usage – which has strong implications for resource dynamics over time, and long-run sustainability.

The aim of this paper is to contribute to the literature on groundwater management policy by examining the tradeoffs between efficiency and equity, when applying market-based policy instruments aimed at reducing the negative externalities imposed by non-cooperative groundwater pumping. Using a stylized model within a specific empirical context, we examine how the distribution of potential gains to groundwater management changes under the application of alternative policy instruments, in the presence of agent heterogeneity. Through this exercise, we gain useful insights into how policy makers and environmental managers might address issues of equity and efficiency when considering policy intervention in other groundwater basins, as well as in other common-pool problems, more generally. We also demonstrate the importance of addressing agent heterogeneity when trying to address the issues of equity and efficiency in policy design, especially in a dynamic context.

The rest of this paper is designed as follows. Following a brief description of the policy problem, we describe the simple analytical framework that will be used to assess the tradeoffs between economic efficiency and equity, later in the paper. This section is followed by a brief description of the empirical hydrological model that is used for the policy analysis in this paper, and the type of market-based policy instruments that will be applied to the investigation of changes in economic efficiency and equity. Following the simulation of the model, under alternative instruments, we summarize the results and compare the changes in efficiency and distributional consequences for the heterogeneous. These results and other summary comments and policy recommendations are included in the closing section of the paper.

2. Groundwater Management Policy and Problems

Common Property regimes are well-studied in the economic literature, due to the externalities that are typically imposed on users of the resource and the difficulty of regulation and enforcement (Hardin, 1968; Gordon, 1954). These externalities arise from over-exploitation of the common-pool resource by users, who typically have unrestricted access to it, and consider only their own private benefits when deciding how much of the resource to exploit (Scott, 1954; Dasgupta and Heal, 1979). Regulation is often required due to the difficulty of realizing decentralized Coasian bargaining, either due to the presence of transactions costs, asymmetry in information (Farrell, 1987), scale considerations (Nalebuff, 1997) or other reasons.

Groundwater is a frequently over-exploited common-pool resource for irrigated agriculture, and its depletion, in numerous cases that have been studied, has led to serious conflicts between users (Ostrom, 1990). Gisser and Sanchez (1980) were among the first to examine the externalities arising from the extraction of groundwater as a common-property problem. In this article, the authors examined the loss of efficiency that occurs when a groundwater aquifer moves from a sole-owner extraction regime to one in which there is competition in pumping. Various other authors within the natural resources literature have also addressed the efficiency problems that arise under competitive in groundwater pumping (Allen and Gisser, 1984; Feinerman and Knapp, 1983; Kim et al., 1989), both theoretically and empirically.

In periods of severe water scarcity, such as that which faced California during the drought in the early 1990s, novel mechanisms for re-allocation have been applied – but have inevitably led to conflicts and disputes, often highlighted by those who able to mobilize political support, and who perceived undue harm was done to them in the re-allocation process. Some of these conflicts arose from disputed third-party impacts attributed to policy-promoted water transfers, such as those made to the California Emergency Drought Water Bank (Hanak, 2003) or from other voluntary market transactions (Murphy *et al.*, 2003). While the State Water Bank was initiated with the understanding that third-party interests would be observed and adequately protected (Thilmany and Gardner, 1992), the majority of the impacts resulting from the water transfers to the Drought Bank were borne by the groundwater basin, causing third-party impacts on the local economies (resulting from sale of surface water rights) to be substituted for third-party impacts on groundwater users (Howitt, 1993a,b). As an illustration of this effect, nearly 37% of the increased depletion of groundwater in the Lower Cache Unit of Yolo County was attributable to transfers made to the Water Bank in 1991 (McBean, 1993).

From these examples, one sees that the dual criteria of both efficiency-enhancement and equity-preservation exist in tandem within the minds of policy makers and resource managers who are accountable to the concerns of the voting public. In this paper, we examine more closely how these criteria can be evaluated and compared, when addressing the design of market-based instruments of re-allocation applied to the context of groundwater.

3. Assessing Efficiency and Equity of Policy Interventions

In this section we describe the particular analytical framework that we use to assess the trade-off between economic efficiency and distributional equity, when applying alternative policy instruments to the management of groundwater resources. Most papers that have looked at issues of efficiency and equity in water policy have been grounded in a static framework of analysis which, while capturing the essential trade-offs, tends to overlook the true nature of the benefits that accrue to natural resource stocks such as groundwater, which endure over time and whose social value is measured in terms of a stream of benefits that accrue over a given horizon. The analytical framework that we use in this paper, to examine the trade-offs between the efficiency of water allocations and the implications for equity in the distribution of benefits is a dynamic one, which explicitly takes into account the dynamic nature of the externalities that arise when socially-optimal, inter-temporal behavior is replaced by non-cooperative and myopic behavior of heterogeneous agents.

3.1 Defining the Benchmark of Efficiency

The problem facing the social planner who takes the inter-temporal welfare of all agents into account, when making allocations of the natural resource over time forms the benchmark for efficiency that economists consider, when comparing the performance of decentralized policy instruments and regimens. Considering the case of i players, who differ according to the marginal benefits that they enjoy in the exploitation of the resource. Denoting the marginal benefit curve as $MB(w_i) = a - b \cdot q_i$, where a and b are, respectively, the intercept and slope of the agent's demand curve for water withdrawals q_i. For i heterogeneous agents, we could consider a distribution of slope parameters, such that we have values ranked as $b_1 < \ldots b_i < \ldots < b_N$ along an interval of length $b_N - b_1$. Taking into account the costs of groundwater pumping, which depend on the depth of the groundwater table below the surface $(s-h)$[1], the aggregate benefits accrued by all N agents would then be given by

$$\sum_{i=1}^{N} B_i(q_i) = \sum_{i=1}^{N} \left[a \cdot q_i - \tfrac{1}{2} b_i \cdot q_i^2 - e(s-h) \cdot q_i \right] \tag{3.1.1}$$

where e is the common energy cost of pumping that is faced by all agents pumping from depth of $(s-h)$. According to the principle of optimality laid out by Bellman (1957), and which is commonly used in the definition of the inter-temporal benchmark of allocative efficiency in

[1] where s and h are, respectively, the heights of the ground surface and groundwater table above a given reference level.

natural resource economics, the central manager (social planner) of the groundwater resource water, would make a centralized distribution of groundwater resources over time according to the solution of the following problem.

$$V^{SP}\left(h\right)=\max_{\{q_i\}}\left\{\sum_{i=1}^{N}\left[a\cdot q_i-\tfrac{1}{2}b_i\cdot q_i^{2}-e\left(s-h\right)\cdot q_i\right]+\beta_{SP}V^{SP}\left(h+\gamma\sum_{i=1}^{N}q_i-\overline{r}\right)\right\} \qquad (3.1.2)$$

where, in addition to the aggregate benefits captured in (3.1.1), the planner also takes into account the value of groundwater stock that remains in the next period (and by implication, into the future). The Bellman equation (3.1.2), shown above, captures the maximized value of the current value of total net benefits of all players, as well as that discounted value which will be realized from the stock of groundwater which remains (and is treated optimally) in the following period[2]. The 'value function' $V^{SP}\left(h\right)$ captures this maximized value, and is a mapping of the allocations accruing to all agents (an N-dimensional vector) onto the real number line – and which is recursively defined for both the current stock of groundwater (captured by h), as well as for that which remains in the following period h^{+}. Given the recursive nature of the value function, it must be solved as a fixed-point problem which finds the functional form whose maximization implies the relationship between adjacent periods given by (3.1.2). The evolution of the state of the groundwater table between one period and the next is governed by the equation of motion

$$h^{+}=h+\gamma\sum_{i=1}^{N}q_i-\overline{r} \qquad (3.1.3)$$

which includes the recharge into the aquifer $\left(\overline{r}\right)$ and a parameter $\left(\gamma\right)$ which translates units of pumping volume into groundwater table height.

The social planner's solution for each agent can be summarized by a policy function, which takes into account the current height of the groundwater table, and the marginal net benefits accruing to each agent, as it is affected by all the parameters of the problem and the planner's own inter-temporal preferences, such that we have the "rule" shown below

[2] where β^{SP} is the discount factor considered by the social planner, and which embodies the planner's inter-temporal preferences and tradeoff between benefits accrued in the current period, and those which are realized in future.

$$q_i = f\left(h \left| \beta^{SP}, a, b_i, e, \gamma \right.\right) \tag{3.1.4}$$

which governs the allocation of groundwater over time, for any value of h along the time horizon. This function embodies the trade-off between inter-temporal benefits captured by the first-order conditions of the Bellman equation (3.1.2), which yield the following Euler equation

$$a - b_i \cdot q_i - e\left(s-h\right) + \gamma \cdot \beta_{SP} V_q^{SP}\left(\square\right) = 0 \tag{3.1.5}$$

This 'policy function' could be contrasted to the much more simplified extraction 'rule' implied by an individual agent who pumps myopically and, therefore, ignores the additional benefit that would accrue if additional groundwater stock were held over into the next period – which is captured by the 'user cost' embodied in the term $\gamma \cdot \beta_{SP} V_q^{SP}\left(\square\right)$ of the social planner's Euler equation. The extraction rule of such an agent is simply given by

$$q_i = \frac{a - e\left(s-h\right)}{b_i} \tag{3.1.6}$$

and which only takes into account the current period's marginal benefits and costs. The divergence in pumping and therefore total net benefits between the solutions given by (3.1.4) and (3.1.6) represent the 'gain' that can be realized under centralized (and socially-optimal) management of the aquifer, using equation (3.1.1), they are

$$Gain = B^{SP}\left(q_i\right) - \sum_{i=1}^{N} B^i\left(q_i\right) \tag{3.1.7}$$

and forms the basis by which water economists measure the efficiency gains to centralized control.

The efficiency gains of alternative decentralized policy instruments can be measured relative to this benchmark, and thereby used to rank the efficacy of those policy regimes. In this paper, we use such a criterion to compare alternative policy instruments, but also compare the implications for distributional equity, that is measured in the manner described in the next sub-section.

3.2 Defining Distributional Equity

Given the definition of inter-temporal allocative efficiency given in the previous sub-section, we can now define the measure of distributional equity that will be used in this paper to compare the various market-based policy instruments that will be examined. This comparison will reveal not only the degree to which these instruments can capture the efficiency gains that the social planner could realize through centralized management of the aquifer, but also the degree to which these alternative instruments change the distribution of benefits among the heterogenous agents. Similar to the way in which we consider the net benefits that accrue to the agents over time, we also define the distributional benefits in terms of the long-run sum of discounted net benefits that accrue across the distribution of agent-types over the extraction horizon. By doing so, we obtain a consistent basis from which to compare inter-temporal outcomes of equity and efficiency gains.

A simple and convenient measure of inequality, was defined by Theil (1987) in his seminal treatise of economic applications of information theory. A simple index which he constructed is that based upon the principle of 'entropy', which conveys the degree to which a distribution differs from a uniform and un-informative profile -- thereby capturing the "surprise" that is embodied in a (random) outcome (Shannon, 1948a, 1948b). In juxtaposition to Shannon's entropy measure $H = \sum_n -p_n \log(p_n)$ for n discrete, random events, we can also express the *cross-entropy* of a distribution by the measure $CE = \sum_n -p_n \log\left(\frac{p_n}{\overline{p}_n}\right)$, which includes the *prior* distribution of weights (or probabilities) $\{\overline{p}_n\}$ that can be assigned for each random outcome. As shown by Kullback (1959), the maximization of the Shannon criterion with respect to the adding up constraint $\sum_n p_n = 1$ is equivalent to the minimization of the cross-entropy criterion, similarly constrained, if the prior distribution is uniform (i.e. assigns an equal likelihood to each outcome). The divergence of a calculated distribution from prior beliefs, as calculated by the cross-entropy criterion conveys information content in a similar way to that calculated by the Shannon measure of information (Kullback and Liebler, 1951).

The Theil index for inequality has a similar cross-entropy formulation to the Kullback-Leibler criterion, and can be written as

$$T = \sum_{i=1}^{N} \left[\left(\frac{y_i}{Y} \right) \cdot \log\left(\frac{y_i / Y}{1/N} \right) \right] \tag{3.2.1}$$

where y_i is the income of the ith individual, and Y is the sum over all N agents. The share of aggregated income held by an individual $\frac{y_i}{Y}$ is contrasted to the share that would be held if the distribution were strictly uniform (i.e. if $\frac{y_i}{Y} = \frac{Y/N}{Y} = \frac{1}{N}$). However, rather than seeking the minimizing distribution, the Theil index simply uses the implied cross-entropy to convey the sense of inequality in existing distribution of incomes among individuals. By this measure, the income distribution of a N-membered population can range from 0 (for complete equality) to $\log(N)$, which conveys a maximal level of inequality.

For the purposes of our paper, we use this measure to convey the inequality in the distribution of net benefits that accrue over time to each heterogeneous agent pumping water from the aquifer, in order to assess the impact of the alternative policy instruments on equity, and to contrast them to the outcome derived by the social planner's outcome. Given the present value net benefit of each player $PVB_i = \sum_{t=1}^{T} \beta^{t-1} \cdot B_i\left(q_{i,t}\right)$, we can calculate the Theil measure of inter-temporal inequality as

$$T = \sum_{i=1}^{N} \left[\left(\frac{PVB_i}{PVB_T} \right) \cdot \log\left(\frac{PVB_i / PVB_T}{1/N} \right) \right] \tag{3.2.2}$$

where $PVB_T = \sum_{i=1}^{N} PVB_i$. By using this criterion of inequality, we are able to compare equity outcomes across various policy instruments and compare them with that of the social planner's outcome.

4. Empirical Specification of Policy Instruments and Model

In the policy analysis that follows, we contrast the non-cooperative behavior of myopically-extracting agents with the socially-optimal, dynamic equilibrium of the central planner's economic model that was discussed in the previous section. The efficiency gains and equity outcomes of alternative decentralized, market-based policy instruments are also assessed and compared to the centralized planner's outcome, such that we are able to assess the tradeoffs between efficiency and equity that are realized under them.

4.1 Empirical Parameterization of the Model

In our discussion we use the specific empirical context of groundwater extraction in Kern County, in Southern California, but can extrapolate the findings of our experiments more generally. While the economic characteristics of ground and surface water usage in Kern County, California have been examined by several authors (Feinerman and Knapp, 1983; Feinerman, 1988; Dixon, 1991; Knapp and Olson, 1995; Knapp *et al.*, 2003), none of these studies have ever considered the trade-off between efficiency and equity in the application of alternative market-based policy instruments. Feinerman (1988) did examine equity issues in the imposition of pump taxes and quotas, but did not extend his analysis to consider market-based trading of quotas, or the type of equity analysis that we will consider in this paper.

Following Feinerman and Knapp (1983), the simplified hydrology of this example includes the net recharge into the aquifer ($\bar{r}$) inside an equation of motion with condensed notation for γ and $\bar{r}$, representing the translation of volumetric aquifer recharge and net groundwater withdrawal, into units of lift, according to the following definitions

$$\gamma = \frac{(1-\theta)}{As} \quad \bar{r} = \frac{\left(1-\xi+\theta\xi\right)I+\hat{r}}{As} \tag{4.1.1}$$

In these expressions, θ represents the deep percolation into the aquifer, while A represents the areal extent of the aquifer, and s is its specific yield. Recharge is given in terms of total inflow into the aquifer, I, a base annual level of recharge $\hat{r}$, and a calibrating parameter ξ. These parameters γ and $\bar{r}$ are both used in the equation of motion (3.1.3), which govern the evolution of the state of the groundwater resource over time.

In order to empirically solve and simulate the behavior of the infinite-horizon carry-over value function for groundwater stock $V^{SP}(h^{+})$ given by (3.1.2) for the social planner's problem, we employ standard numerical procedures for solving dynamic programming problems, as described by Judd (1998) and Miranda and Fackler (2002). By doing so, we are able to implement a robust, numerical polynomial approximation to the infinite-horizon carry-over value function, necessary for solving the social planner's problem, and which takes on the form, shown below,

$$V^{SP}\left(h^{+}\right) \approx \tilde{V}^{SP}\left(\psi\left(h^{+}\right)\right) = \sum_{k=1}^{K} a_k \phi_k \left(\psi\left(h^{+}\right)\right) \tag{4.1.2}$$

where a_k is the coefficient which is fitted by an iterative numerical fixed-point algorithm, which must be evaluated at the node points indexed by k. This coefficient is multiplied with the corresponding basis function $\phi_k\left(\psi\right)$, which represents the orthogonal terms of the Chebychev polynomial that is employed for the function approximation. The basis functions are defined over a domain ψ, which is restricted to the interval [-1,+1], and onto which the state variables, h^{+} must be mapped.

On the basis of these parameter definitions, we can now proceed to carry out the analysis of alternative market-based instruments for re-allocation. The essential hydrological parameters used to characterize groundwater usage in Kern County are summarized in Table 1.

4.2 Groundwater Policy Instruments

The de-centralized policy instruments used to capture the efficiency gains realized under central management controls will be of two types – market-based and non-market based. The market-based instrument that will be considered will be that of a tradable quota on groundwater pumping, that are imposed on each of the agents. The non-market counterpart to this is a fixed limit on pumping, that is imposed by a central regulator, and which ignores the heterogeneity of the agents and assign a limit based on the "average"-type across all individuals. This is a fairly representative type of mechanism, as informational asymmetries typically prevent regulators from imposing highly differentiated instruments on a heterogeneous population of economic agents. The fixed limit is assigned according to the average pumping solution of the social planner, with respect to both time (*t*) and the number of agents (*i*), such that

$$\overline{q} = \frac{\sum_{t=1}^{T}\sum_{i=1}^{N} \hat{q}_{i,t}^{SP}}{T \cdot N} \tag{4.2.1}$$

where $\hat{q}_{i,t}^{SP}$ is the optimal, inter-temporal solution of the social planner.

The performance of each of these instruments is contrasted with the imposition of a tax (which is non-market based and whose revenue is re-distributed in lump-sum), and that of no intervention at all. The tax is calculated on the basis of the social planner's optimization problem, and takes on the average value, over time of the socially-optimal "user cost" given by the term $\gamma \cdot \beta_{SP} V_q^{SP}(\cdot)$, which is embedded in the Euler condition (3.1.5) of the dynamically-optimal solution. This term represents the divergence between the marginal cost imputed to groundwater pumping by the social planner and that imputed by the optimality criterion of the agent who extracts myopically, which is simply

$$a - b_i \cdot q_i - e(s-h) = 0 \tag{4.2.2}$$

and which leads to the simple, myopic extraction rule given, earlier, by (3.1.6). By equating the average value of this 'user cost', over the social planner's extraction horizon, to an optimal per-unit tax on pumping (tx), such that $tx = \sum_{t=1}^{T} \left\{ \gamma \cdot \beta_{SP} V_q^{SP}(\cdot) \right\}_t$, we can re-cast the myopic extraction problem as

$$q_i^{opt} = \arg\max \left\{ a \cdot q_i - \tfrac{1}{2} b_i \cdot q_i^2 - e(s-h) \cdot q_i - tx \cdot q_i \right\} \tag{4.2.3}$$

and would expect the behavior of the individual agent to conform closely to that of the social planner.

The efficiency gains of both the market and non-market instruments are compared with that of the socially-optimal solution imposed by the centralized groundwater manager, and also compared in terms of the equity outcomes. Given that the idealized social planner faces no informational asymmetries and knows all the 'types' of the individual agents, we expect that the divergences in outcomes also incorporate the effect of information-deficit that is faced by the regulator when imposing de-centralized policy instruments. The market-based instrument, however, is better able to handle this deficit, as it relies on the interactions between individual agents, who each have knowledge of their own preferences and who can act accordingly. The specification of this market interaction between agents, is described in the next sub-section.

4.3 Tradable Quotas in Groundwater Allocations

In order to characterize the market-based re-allocation that we consider in this paper, we describe a regime in which the (otherwise) fixed allocations on groundwater pumping assigned to each heterogenous agent can be traded between individuals. Starting from the basic idea of assigning a maximum quantity – or a quota – of allowable pumping to each economically-behaving (and extracting) agent in an economy, we conjecture that each agent has a preference to receiving greater amounts of quota. This assumes, of course, that more pumping is correlated (positively) with a higher level of economically productive activity – which creates the willingness for an agent to pay for an additional amount of quota, on the margin. This marginal value of quota (denoted $\lambda\left(\bar{Q}\right)$) depends on the amount of quota being held $\left(\bar{Q}\right)$ – and is conjectured to decrease with increasing allocations of quota. This declining relationship between willingness to pay and the amount of quota held is, essentially, a demand relationship for an individual agent with a given allocation of allowable pumping$\left(\bar{Q}\right)$, and the slope of this demand relationship can be expressed as

$$\frac{\partial\lambda}{\partial\bar{Q}}<0 \qquad (4.3.1)$$

This demand relationship is as a downward-sloping curve, whose integral represents the total benefit that the agent would derive from an allocation of quota Q_1, denoted by the area underneath the curve, $B\left(Q_1\right)$, as shown in Figure 1.

Having now defined the demand for quota for a single agent, we can now extend our discussion to consider the problem facing two agents, so as to motivate a de-centralized system of tradable quota allocations. If each agent is assigned rights to a portion of the total allowable limit on pumping, as individual quota $\bar{q}_1+\bar{q}_2=\bar{Q}$, we would have the situation depicted in Figure 2, where the length of the horizontal axis underlying the demand curves of both agents represent the total limit on pumping. From Figure 2, we see that the initial allocations of quota $\left(\bar{q}_1,\bar{q}_2\right)$ is such that the marginal value that agent 2 is willing to pay for an extra unit of quota allocation, is greater than that which agent 1 is willing to pay for an extra unit. The resulting differential in marginal values, therefore, indicates that there are gains to re-allocation of quota between the two agents. The point at which the marginal values are equated, as a result of the de-centralized transfer of z units of quota from agent 1 to agent 2, is indicated in Figure 2 as $\lambda_1\left(\overline{q}_1 - z^*\right) = \lambda_2\left(\overline{q}_2 + z^*\right)$, and corresponds to the first-order, necessary conditions of the 'social' optimization problem, in which the combined surplus under the demand curves of both agents is jointly maximized by the central planner who can make a frictionless transfer or rights with full information on both agents, as shown below

$$\max_{z \le \overline{q}_1} \int_0^{\overline{q}_1 - z} \lambda_1\left(q_1\right) dq_1 + \int_0^{\overline{q}_2 + z} \lambda_2\left(q_2\right) dq_2 \tag{4.3.2}$$

The de-centralized re-allocation of quota described above, however, corresponds to the case where there are no transactions costs facing the two agents, and is a highly idealized environment in which to study a tradable permit scheme. The more realistic situation is one in which there is a per-unit transaction cost for every unit of quota that is transferred from one agent to another, which can be denoted by τ. This transaction cost can be conceptualized as the cost that must be incurred in administratively re-assigning the rights embodied in each unit of quota from one agent to another, such that the central authority recognizes the re-allocation as a legitimate re-assignment of permissible pumping – such as by undergoing some administrative or legal procedure that approves and documents the transfer between farmers[3].

The more realistic case of non-zero transaction costs gives rise to the re-allocation of the initial endowment of quota that corresponds to the equilibrium depicted in Figure 3. In this situation, the equilibrium re-allocation of initial quota endowment between agents corresponds to the condition $\lambda_2\left(\overline{q}_2 + \hat{z}\right) = \lambda_1\left(\overline{q}_1 - \hat{z}\right) + \tau$, which drives the optimized re-allocation $\hat{z}$ to fall short of that which would result from a cost-free transfer $\left(z^*\right)$, as indicated in Figure 2. The "wedge" created by the per-unit transaction cost of transfer would widen if the cost τ were to increase further.

It is for this reason, that the reduction of transactions costs in policy implementation remains the matter of greatest importance and concern to policy researchers involved in the

[3] The reader can most readily identify with this procedure through the example of selling an automobile. Not only is there a cost in identifying a suitable, trustworthy, and willing buyer through costly advertising and screening of numerous inquiries, but there is also the necessary paperwork that must be done with the vehicle licensing authority, such that the transfer is recognized as being a legitimate re-allocation of property.

design of market-based institutional mechanisms to regulate and manage environmental quality. Since it is the transactions cost which cause ‘decentralized’, market-based allocation mechanisms to deviate from the ideal of efficiency – as epitomized in the allegorical problem facing the social planner – the reduction of such costs is foremost amongst the goals of the policy maker. Since most individual agents (or policy makers) cannot make decisions with the same level of information that the idealized central planner has, such mechanisms will always fall short – but those which are better designed will deviate less from the ideal outcome.

By using the inverse demand relationships for each farmer type $\left(p = a_i - b_i q, \quad i = 1,2\right)$, we integrate under them to obtain the total benefit that each farmer receives for a given allocation of quota q, as $B_i(q) = a_i q - \frac{1}{2} b_i q^2$ and can use this to specify the following equilibrium model. Following Takayama and Judge’s (1964) formulation for a spatial equilibrium model, the surplus maximizing, de-centralized re-allocation of quota can be obtained by solving the following problem

$$\begin{aligned} &\max_{z_1, z_2 \geq 0} \sum_{i=1}^{2} \left[a_i \cdot q_i - \tfrac{1}{2} b_i \left(q_i\right)^2 \right] - \sum_{i=1}^{2} \tau_i z_i \\ &s.t. \\ &\qquad q_1 = \overline{q}_1 - z_1 + z_2 \\ &\qquad q_2 = \overline{q}_2 - z_2 + z_1 \end{aligned} \tag{4.3.3}$$

where the initial allocations for the type 1 and 2 farmers is given as $\overline{q}_{i=1,2}$ and the outgoing transfers from farmer 1 $\left(z_1\right)$ or farmer 2 $\left(z_2\right)$ incur a per unit transaction cost of $\tau_{i=1,2}$. The solution to this problem can then be compared to that from an egalitarian re-distribution, which would result a total surplus of $\sum_{i=1}^{2} \left[a_i \cdot \hat{q}_i - \frac{1}{2} b_i \left(\hat{q}_i\right)^2 \right]$, where $\hat{q}_1 = \hat{q}_2$.

The application of this type of spatial equilibrium model has been applied, in the literature, to the analysis of trade-based re-allocations of water between heterogenous users, beginning with Vaux and Howitt (1984). In this paper, we apply this to the re-allocation of pumping quota, in order to characterize the operation of a market-based policy instrument, and so that we can contrast the efficiency gains and equity outcomes with other decentralized policy instruments. In this paper we also ignore the transactions costs, and proceed on the basis of friction-less transfers, for the purpose of simplifying our analysis.

5. Empirical Analysis of Groundwater Policy Instruments

5.1 Evaluating the Efficiency-Equity Frontier

By turning back to the benchmark efficiency case, embodied in the social planner's solution, described in section 3.1, we can evaluate the possible combinations of economic efficiency gains and equity outcomes that are possible in the planner's socially-optimized outcome. We can do this by introducing a constraint into the basic formulation of the social planner's optimization problem, described by (3.1.2), such that we obtain the modified problem shown below

$$V^{SP}(h) = \max_{\{q_i\}} \left\{ \begin{array}{l} \sum_{i=1}^{N} \left[a \cdot q_i - \frac{1}{2} b_i \cdot q_i^2 - e(s-h) \cdot q_i \right] + \beta_{SP} V^{SP}\left(h + \gamma \sum_{i=1}^{N} q_i - \bar{r} \right) \\ s.t. \\ \sum_{i=1}^{N} \left[\left(\frac{PVB_i}{PVB_T} \right) \cdot \log\left(\frac{PVB_i / PVB_T}{1/N} \right) \right] \le T^{\lim} \end{array} \right\} \quad (5.1.1)$$

where $T^{\lim}$ is an imposed limit on inequality, and where PVB_i and PVB_T are cumulative measures of the present value of net benefits for each individual i as well as for all agents, as it is measured in each time period of the social planner's horizon.

By 'parameterizing' the right hand side value ($T^{\lim}$) of the constraint in (5.1.1), we can observe how the efficiency gains change with the mandated limit on intra-agent inequality. By so doing, we can derive a 'frontier' that describes the possible combination of 'best' social outcomes that are possible under centralized control, when maximum levels of inequality are defined for a heterogeneous population of economic agents.

The result of this parameterization exercise are shown in Figure 4, which illustrates that higher levels of efficiency gains are possible, when the social planner is constrained so as not to exceed increasingly lowered levels of intra-agent inequality, as captured by the Theil cross-entropy measure. This frontier also demonstrates that the unconstrained social planner's problem does not necessarily represent the 'best' outcome that is possible, when one considers agent heterogeneity. As shown in Table 2, the unconstrained socially-optimal outcome gives both a lower level of efficiency gains and a higher level of inequality, as compared to the constrained cases, where the social planner is constrained to adhere to more egalitarian social standards of inter-temporal welfare. Table 2 also shows that as the limit on inequality is lowered, there is a noticeable shift in the distribution of aggregate present value of net benefits such that the allocations at the two "ends" of the spectrum of heterogeneous agents become more equal, as is also shown in Figure 5. But in doing this, the percentage of the total gains that are realized under centralized management intervention become more "skewed", as shown in Figure 6, such that they begin to accrue more to that "end" of the spectrum that was the most disadvantaged (in terms of the share of aggregate net benefits received) in the unconstrained case – i.e. the N^{th} agent. Given that the slope of the demand curve gets steeper for those approaching the N^{th} agent, the management gains (under centralized intervention) get skewed to favor the agents who pump a relatively small amount of groundwater, compared to those towards the "front" of the spectrum, who perceive a larger marginal benefit for a given quantity of pumping, while still allowing the distribution of actual aggregate net benefits to become more even. The unconstrained case corresponds to the T_lim = 0.0005 line, where the share of aggregate present value net benefits are more un-evenly distributed (in Figure 5), but where the percentage gains to centralized management intervention are distributed more evenly across players (Figure 6).

These results point to the gap that exists in the natural resources management literature, which has not treated the issue of agent heterogeneity with respect to the welfare implications and outcomes of distributional equity. The classical benchmark of efficiency, as embodied in the social planner's problem, can only ensure the globally 'best' social optimum if the case of symmetry and homogeneity is considered – as is often done in the literature. If considerations of equity are important, then a more nuanced analysis must be done in order to determine the true welfare benchmark, if the case of heterogeneous agents is treated – and the assumption of global optimality in the simple planner's problem may be violated. Given that most empirical situations violate the assumption of homogeneity, more work on the part of researchers is warranted, in this regard.

5.2 Evaluation of Alternative Policy Instruments and Discussion

By implementing the analytical framework described in section 4, we can now analyze and compare the realized efficiency gains and equity outcomes that arise from the market- and non-market-based policy instruments that are considered, and contrast them to the social planner's outcome, as well as that which myopic agents realized without any centralized or de-centralized management intervention. The insight that is gained from these experiments are discussed within the context of more general resource management policy, in the next sub-section and the concluding section of the paper.

The results of our policy analysis, under the alternative scenarios described in the previous sub-section, are given in Tables 3 and show a trade-off in efficiency and equity between the market- and non-market-based policy instruments. While the tradable pumping quota is able to achieve a higher level of efficiency gains and, thus, capture a higher percentage of the centralized management benefits, there is a significant increase in inequality over the fixed quota instrument. Given that we have not imposed a preference structure that weighs inequality against efficiency gains, we cannot assign an ordinal ranking that would necessarily declare one outcome 'worse' or 'better' than the other. These results serve, simply, to illustrate that the objective of efficiency gain can, indeed, be at odds with equity considerations, when weighing the two objectives against each other, within the context of a public policy problem. Policy makers and natural resource managers are constantly confronted with these kinds of trade-offs, and must weight the political benefits and penalties that accrue to each outcome, when making public policy decisions on the management of resources and the imposition of regulation and policy instruments. As we have not assigned penalties to greater inequality or rewards to efficiency gains, the determination of the "optimal" trade-off within the context of this particular problem, remains beyond the scope of our paper, but remains squarely within the realm of consideration for the actual policy maker.

6. Conclusions

In this paper, we constructed a theoretical framework in which to analyze the trade-offs between efficiency and equity, when considered within the context of groundwater extraction, and the market-based policy instruments that might be considered, when trying to impose regulation and de-centralized control on the otherwise myopic and mutually-harmful actions of heterogenous agents. The benchmark of efficiency that we considered was that of the socially-optimizing, idealized central planner, who considers the dynamically-optimal carry-over value of groundwater, when making allocation decisions for each heterogeneous agent. While this planner faces no informational asymmetries, with respect to the preferences of the individual agents, she might not necessarily achieve the globally 'best' outcome, with respect to both efficiency and inequality, unless explicit welfare criteria are considered.

By examining the performance of alternative policy instruments, we see that there is a clear trade-off between efficiency and equity when moving from the market-based to the non-market-based instruments of regulation. While the market-based outcome shows higher efficiency gains than the outcome for non-market instrument, there is a clear increase in inequality levels among the agents. This highlights the trade-offs policy-makers often face in making politically-sensitive decisions on the adoption of policy measures that may create winners and losers in a heterogeneous (and real) world. While the political influence of the winning or losing parties often determines, in large part, the policy outcomes, the importance of equity in the minds of the public should not be under-estimated or ignored by the policy researcher, while designing decentralized regulation schemes.

While researchers are not subject to the socio-political influences of voting constituencies, the closer examination of these types of issues should remain high in the agenda of further research, so that better, more widely-acceptable, and less 'friction'-prone policy instruments can be designed for the use of policy makers who are subject to these forces. Not only will this serve to push forward the state-of-the-art of this type of policy science, but it will also enable policy makers and researchers alike to understand the potential trade-offs and pitfalls of otherwise appealing decentralized schemes of policy intervention.

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Appendix : Figures and Tables

Figure 1: Derived Demand for Quota and Gross Benefit for a Single Agent

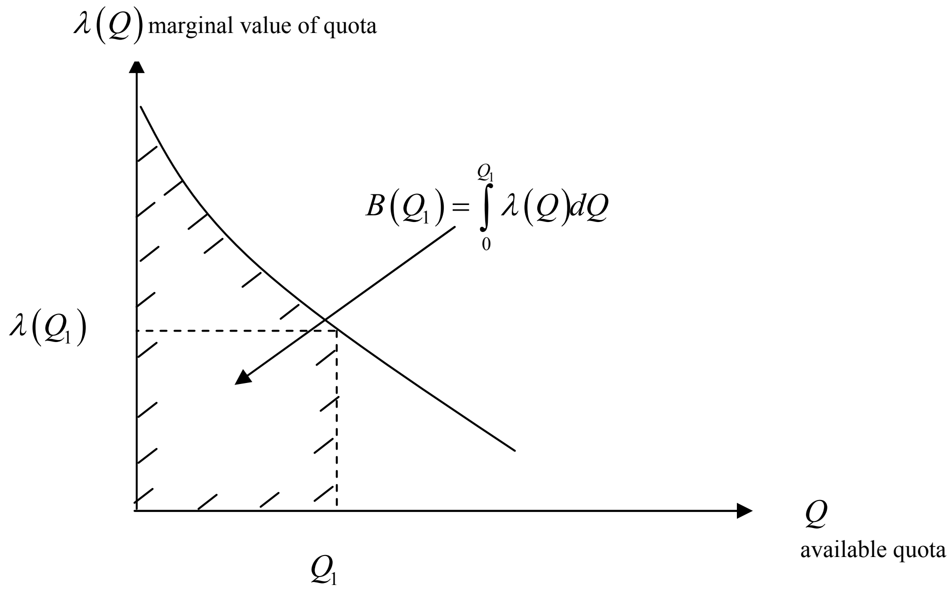

Figure 2: Equilibrium Re-Allocation of Quota between Two Agents

(No Transactions Costs)

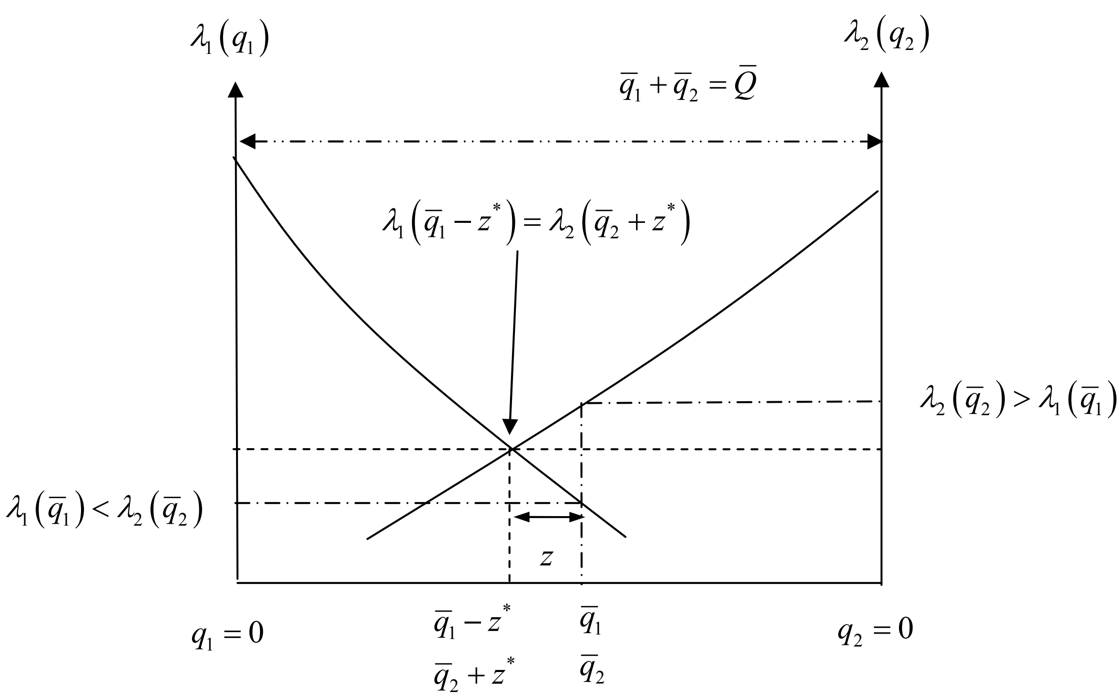

Figure 3: Equilibrium Re-Allocation of Quota between Two Agents

(With Transactions Costs)

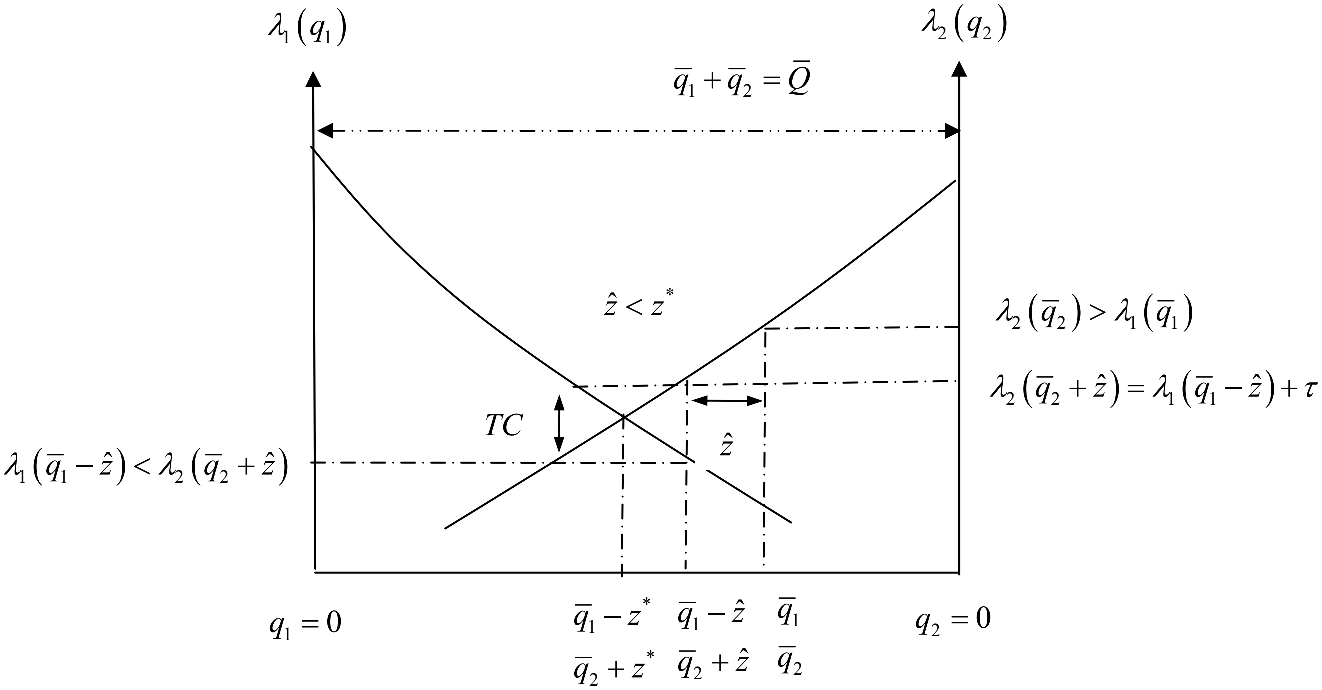

Figure 4: Frontier of Efficiency and Equity Derived from Social Planner's Problem

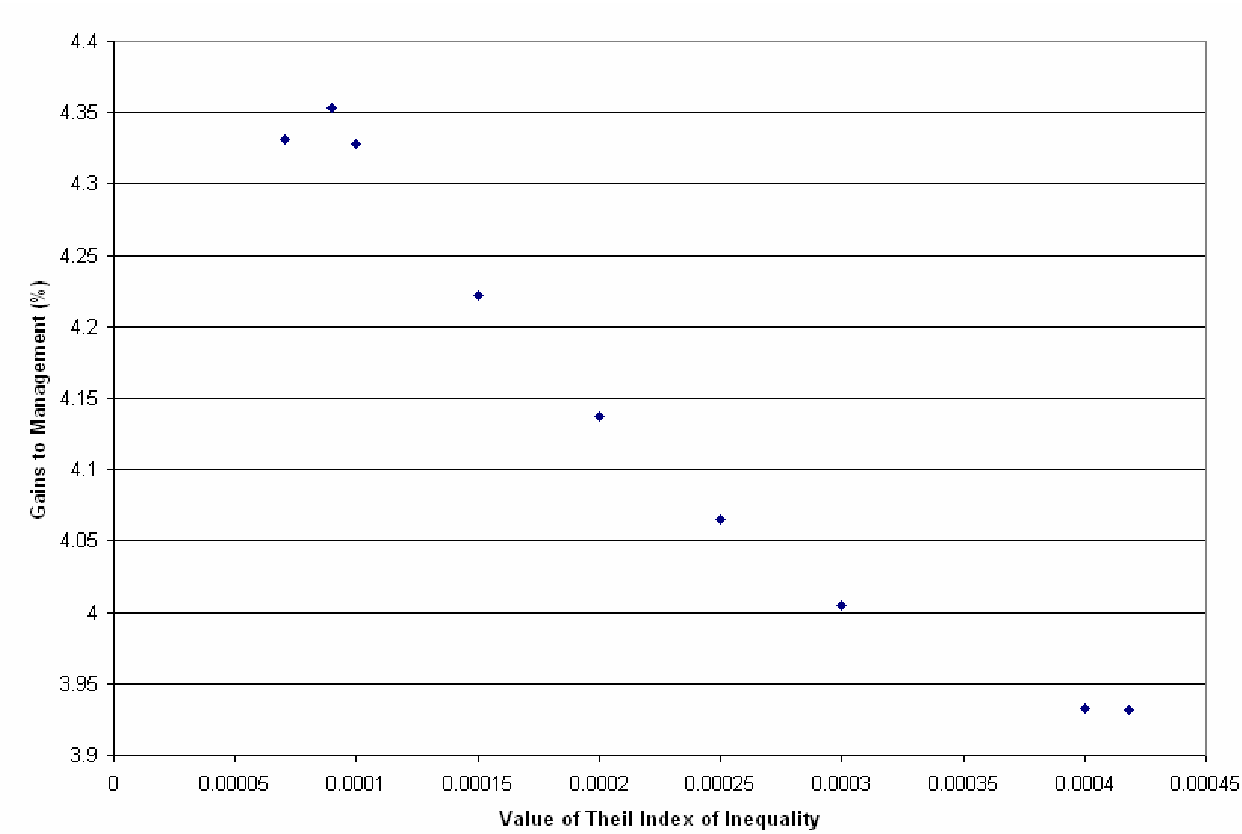

Figure 5: Distribution of Efficiency Gains under Various Limits of Inequality

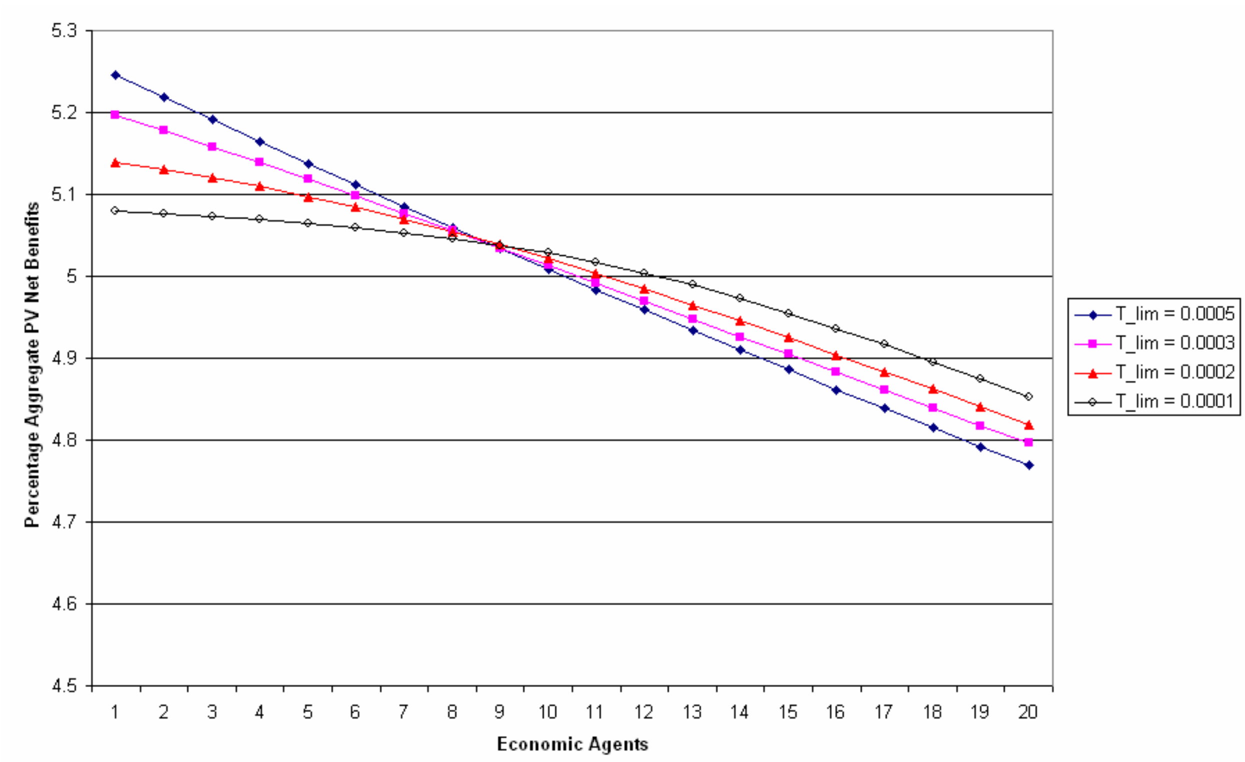

Figure 6: Distribution of Efficiency Gains under Various Limits of Inequality

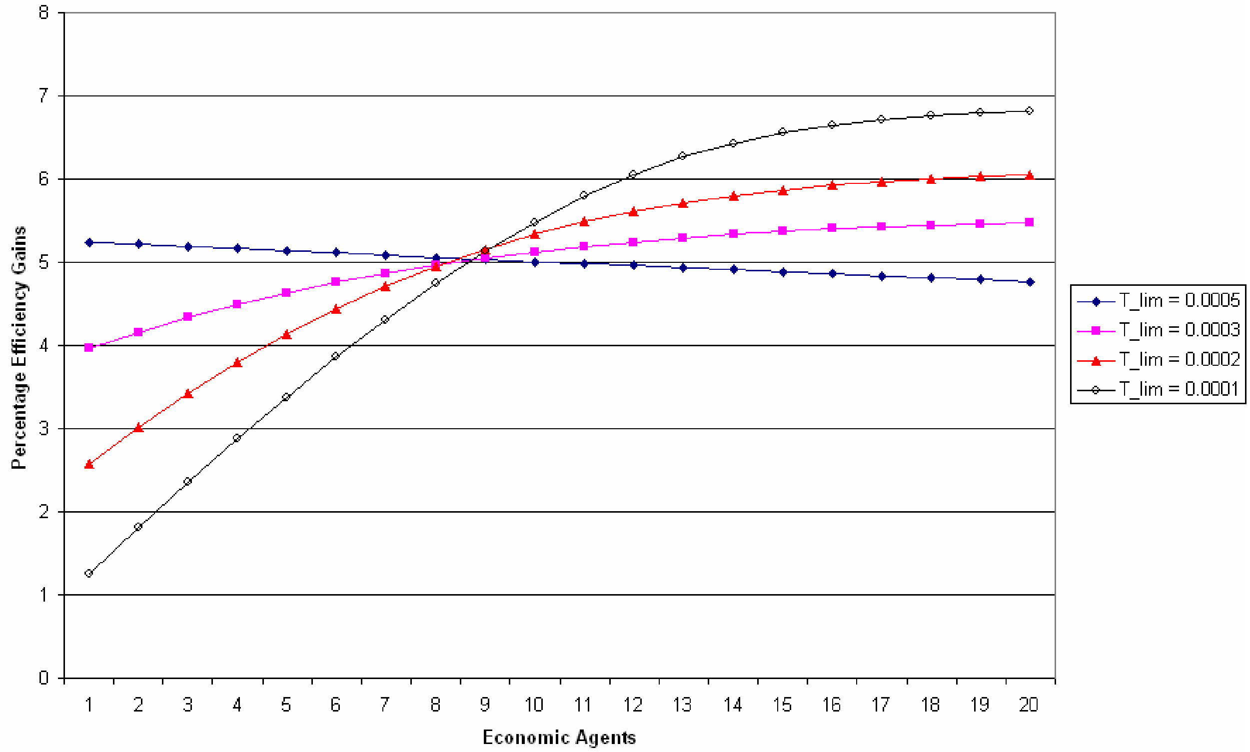

Table 1: Hydrological Parameters for Aquifer Model of Kern County

Parameter	Description	Value
A	Area Overlying aquifer	1.26 (million acres)
s	Specific Yield of Aquifer	0.1
θ	Deep percolation coefficient	0.2
e	Energy cost per unit pumping lift	\$0.09 acre-ft/ft
h_1	Initial lift (depth-to-water)	220 ft
$\hat{r}$	Reference level for aquifer recharge	1410 ft
ξ	Calibrating parameter for recharge eqn	0.7
I	Average annual surface water inflow	1.90 (million acre-ft)
a	Demand curve intercept	\$92.7/acre-ft
b	Demand curve slope	\$0.0000175/(acre-ft)^2
i	Real interest rate	0.05
(β)	(discount factor)	(0.952)

Table 2: Gains in Cumulative Net Benefits to Adopting Centralized Management of Groundwater with and without Equity Constraints

	Total % Gain from Centralized Management	**% Share of PV Net Benefits of 1st agent**	**% Share of PV Net Benefits of Nth agent**
	Unconstrained Social Planner Problem		
Unconstrained	3.9	5.25	4.77
	Constrained Social Planner Problem		
$T \leq 0.0003$	4.0	5.20	4.80
$T \leq 0.0002$	4.1	5.14	4.82
$T \leq 0.0001$	4.3	5.08	4.85

Table 3: Comparison of Efficiency Gains and Equity Outcomes of Alternative Policy Instruments

	Total % Efficiency Gain	**Value of Theil Inequality Index (x 10^{-4})**	**% of Centralized Management Gain Captured by Policy**
	Market Instruments		
Tradable Pumping Quota	0.19	4.2	5
	Non-Market Instruments		
Fixed Pumping Quota	0.15	0.56	4
Pump Tax	3.93	4.2	100
No Intervention	0	4.2	0