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The regulation of a spatially heterogeneous externality: Tradable groundwater permits to protect streams

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ABSTRACT

Groundwater pumping can reduce the flow of surface water in nearby streams. In the United States, recent awareness of this externality has led to intra- and inter-state conflict and rapidly-changing water management policies and institutions. Although the marginal damage of groundwater use on stream flows depends crucially on the location of pumping relative to streams, current regulations are generally uniform over space. We use a population data set of irrigation wells in the Nebraska portion of the Republican River Basin to analyze whether adopting spatially differentiated groundwater pumping regulations leads to significant reductions in farmer abatement costs and costs from damage to streams. We find that regulators can generate most of the potential savings in total social costs without accounting for spatial heterogeneity. However, if regulators need to increase the protection of streams significantly from current levels, spatially differentiated policies will yield sizable cost savings.

1. Introduction

Groundwater pumping from aquifers can reduce the flow of surface water in nearby streams through a process known as *stream depletion*. In the United States, recent awareness of this externality has led to interstate conflict over the role of groundwater use in the fulfillment of compacts governing the distribution of water in trans-boundary rivers. Groundwater regulations have been implemented in response to claims filed in the U.S. Supreme Court by Texas against New Mexico over flows in the Pecos River, by Kansas against Colorado over the Arkansas River, and by Kansas against Nebraska and Colorado over the Republican River [16,27]. Interstate commissions that manage other trans-boundary rivers, such as the Delaware River, which flows through New York, Pennsylvania, New Jersey, and Delaware, have expressed concern over the role of groundwater withdrawals on stream flow [9]. In addition, large-scale groundwater use in several parts of the country has degraded species habitats that depend on surface water. The ecological impacts of stream depletion have resulted in litigation between local stakeholders and federal agencies over species protected under the Endangered Species Act in Idaho [41] and Texas [25], as well as species that are economically and culturally important, like Pacific Northwest salmon [2]. As a result, although groundwater use is typically unmonitored and unregulated in the United States, concerns over stream depletion have led to rapidly-changing groundwater allocation policies and management institutions.

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In this paper, we analyze whether adopting a spatially differentiated groundwater permit system can lead to significant reductions in compliance costs and damages to streams relative to a spatially uniform system. A factor that complicates the design of management policies to protect streams is the spatial heterogeneity of the stream depletion externality; the marginal damage of groundwater use on stream flows depends crucially on the location of pumping relative to streams. Under these circumstances, economic theory predicts that spatially differentiated policies can achieve an aggregate reduction in stream depletion cost effectively. However, whether spatially differentiated policies offer significant abatement cost savings and environmental improvements over simpler, alternative policies is an empirical question.

Using a population data set of active groundwater wells in the Nebraska portion of the Republican River Basin, we implement an optimization model of each well owner's crop choice, land use, and irrigation decisions to determine the distribution of regulatory costs. We model the externality of pumping on streams by employing an analytical solution from the hydrology literature that determines reductions in stream flow caused by groundwater pumping over space and time. The economic and hydrologic model components are then combined into one dynamic optimization framework, which allows us to measure steady-state farmer abatement costs and stream damage costs to society under an optimal market that features spatially differentiated, tradable groundwater permits. We compare this outcome to the cost effectiveness of alternative second-best policies, including spatially uniform permit markets and pumping restrictions based on geographic zones.

We find that regulators can achieve most of the potential savings in total social costs (i.e. farmer abatement costs plus stream damage costs) by establishing a one-to-one tradable permit system that does not account for spatial heterogeneity. We obtain this surprising result because the agronomic and climatic parameters in our data set that determine farmer abatement costs are spatially correlated with hydrologic parameters that determine the marginal damage of groundwater use on streams. We also find that although current levels of stream depletion in the Republican River Basin might be close to the optimal level, if future legal or political circumstances require regulators to increase significantly the protection of streams from current levels, spatially differentiated policies will generate sizable cost savings compared to policies that ignore spatial heterogeneity.

Our analysis makes two main contributions to the environmental economics literature. First, we evaluate the management of a spatial and lagged externality using an analytical approach that is flexible enough to yield a variety of concrete policy implications. In addition to stream depletion, there are other important environmental externalities that vary over space and are subject to time lags. Economic studies of these externalities generally rely on cell-based numerical models of resource flows (e.g. [4,8,23,29,32,34]) or on regression-based equations that may not capture nonlinear and lagged effects in externalities (e.g. [15,19,25,31]). Our analytical approach allows us to solve a large number of economic optimization problems for different policy scenarios and environmental targets, while also modeling important properties of the natural system. We add to the small economic literature that applies analytical solutions from the natural and physical sciences to quantify environmental externalities (e.g. [6,24,36]), but to our knowledge, ours is the first study to implement these solutions to compare the cost effectiveness of spatially differentiated permits to that of alternative policies. While the application in this paper is specific to stream depletion, similar analytical solutions exist to explain the diffusion of air [37] and water pollutants [11], as well as the dispersal of species populations [42]. Therefore, there is potential for broader use of our approach to study a wide variety of economic issues in environmental regulation.

Our second contribution to the literature is to provide new evidence regarding the factors that determine the relative cost effectiveness of spatially differentiated and spatially uniform permit systems. While most existing empirical studies find that spatial differentiation in a wide range of regulatory settings leads to large reductions in compliance costs [3,10,24,29,38], only two studies predict small cost savings. In a study of nitrogen dioxide (NO_2) standards in Baltimore, Krupnick [23] concludes that the outcome of spatially differentiated control policy can be closely approximated by an effluent fee varying only by source type. O'Ryan [32] finds that for low levels of required abatement of urban air pollution in Santiago, Chile, a uniform concentration standard for all sources is a suitable alternative to a spatially differentiated ambient permit system. Our analysis predicts similarly modest gains from spatial differentiation in a numerical application with a much larger number of spatial units (over 10,000 compared to several hundred) and with finer-scale data that captures variability and heterogeneity in marginal environmental damages at the level of the individual decision-maker. In addition, while the two previous studies attribute the relative cost effectiveness of spatially uniform permits to the placement of different types of users or the weakness of the environmental standard, we show how cost effectiveness can be driven by the spatial distribution of underlying physical characteristics that affect both economic and environmental outcomes, such as climatic, agronomic, and hydrologic parameters. By providing empirical evidence that spatial correlation in physical parameters can be an important determinant of cost effectiveness, we also help explain how spatially uniform permits may or may not be cost effective in other contexts.

2. Background: stream depletion and spatial heterogeneity

Economic theory predicts that when aggregate production by heterogeneous firms generates an environmental externality, minimization of the sum of firm abatement costs and costs from environmental damages can be achieved if each firm undertakes abatement until marginal abatement costs are equalized across all firms. If the marginal damage of the externality is equivalent for all firms, this outcome can be induced with marketable permits that are traded on a one-to-one basis, where marginal abatement costs of all firms will equal marginal damage. A key feature of groundwater flow that