Spatial dynamics and hydro-economic modeling of transboundary aquifers

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ABSTRACT

Extraction from a transboundary aquifer, where no single entity has the authority to control all the pumpage, may result in a divergence between competitive and optimal rates of extraction. This paper develops a hydro-economic model to estimate the size of the payoffs from this divergence under alternative spatial representations. Results show that when an aquifer is heterogeneously distributed spatially, assuming a spatially homogeneous distribution can underestimate the losses with competitive extraction. An application of the model to a sector of the Guarani Aquifer System shows the importance of recognizing spatial heterogeneity in groundwater extraction problems to: (1) provide robust estimates of the costs of sub-optimal extraction and; (2) implement appropriate corrective policies.

Key words: hydro-economic modeling; spatial dynamics; groundwater extraction; transboundary aquifers.

1. INTRODUCTION

Tractable but realistic integrated models are a prerequisite for the sound management of transboundary aquifers. Given the high costs of implementing international regulatory frameworks, careful hydro-economic modeling assessing the need and structure of feasible measures becomes crucial. Indeed, a precise estimate of the size of the loss from competitive (unregulated) extraction is critical to delineate the appropriate size and scope of aquifer management policy.

Although considerable research has been devoted to estimating the magnitude of the welfare loss from competitive extraction of groundwater, studies have neglected to consider the robustness of their results to heterogeneous spatial representations of the aquifer. To address this gap, we build a theoretical model to compare optimal and competitive extraction paths of spatially distributed users yielded by two different spatial representations of the aquifer. The first representation resembles the most commonly used by economic studies. This specification assumes that the aquifer is spatially homogeneous and evolves independently of the history of past extractions. The alternative representation relaxes these standard restrictions and allows for a heterogeneous distribution of groundwater, and lagged effects of past extractions.

Our results show that a homogeneous 'bath-tub' representation of groundwater flow fails to capture well-interference areas, thus underestimating the welfare and hydrological costs from competitive extraction. Overall, our results suggest that assumptions about homogeneity of groundwater distribution are particularly important in terms of the role and scope of corrective policies. The sensitivity of policies to the spatial characteristics of the aquifer is particularly important in a transboundary context where the absence of a single authority increases the likelihood of overexploitation. In these cases, if the benefits of cooperation are derived from spatially simplified models, perverse incentives for noncooperation are likely to result in welfare losses and unsustainable hydrological outcomes.

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2. THE CASE STUDY

The Guarani Aquifer System (GAS), or rather the aquifers that form the GAS, are located in the sedimentary Parana Basin located in the subsoil of the east and center-south of South America, underlying parts of Argentina, Brazil, Paraguay and Uruguay. The present paper focuses on a section of the aquifer that was identified by a Global Environment Facility (GEF) project as critical within the GAS: the Concordia-Salto pilot project. Concordia and Salto are two cities located on opposite sides of the Uruguay River, which is a natural boundary between the Argentinean north-eastern province of Entre Rios and western Uruguay. The wells in the area extract thermal groundwater for balneological purposes.

The total number of operating thermal wells on the Concordia-Salto area is six on the Uruguayan side and three on the Argentinean. However, thermal water extraction is likely to rise in accordance to the development of tourism in the coming years. In the area, the notion of common property characterizes exploitation of thermal groundwater reserves. Although access is limited by extraction permits, tourism operators own groundwater as a common property resource subject to the rule of capture and a transboundary legal framework has not been implemented. Thus, the rate of groundwater mining and recycling and the location of new wells are the result of private decision-making.

3. THE MODEL

The hydrologic conceptual model of the local area was developed and parameterized by a study of a Global Environmental Facility (GEF)'s project (Charlesworth, Sangam and Assadi 2008). Following Morel-Seytoux and Daly (1975), the finite difference model is run 50 times by applying different levels of stress at the seven existing and seven potential stress locations. Due to computational constraints, the duration of the study (40 years) is divided in two management/stress periods of 20 years during which extraction rates are held constant.

Let $Q_{k,1}$ and $Q_{k,2}$ be the extraction rates (in m3/h for a 16-hour daily extraction regime) applied at location k during the first and second stress periods respectively. Let $s_{i,1}$ and $s_{i,2}$ be the aquifer's response at location i after 20 and 40 years due to all such stresses. The first spatial representation entails estimating drawdown as:

$$(1)\ s_{i,1} = \beta \sum_{k=1}^{14} \left(Q_{k,1} \right)$$

$$(2)\ s_{i,2} = \beta \sum_{k=1}^{14} \left(Q_{k,1} + Q_{k,2} \right)$$

Note that the drawdown of the water table is uniform throughout the aquifer and the contribution of each well's extraction is constant across time and space (the coefficient β is constant).

The alternative representation is derived by adapting Theis (1946) solution for transient well response to pumping and using the principle of superpositioni to estimate drawdowns $s_{i,1}$ and $s_{i,2}$ as a linear function of $Q_{k,1}$ and $Q_{k,2}$ $\forall k = 1,\ldots,14$ as:

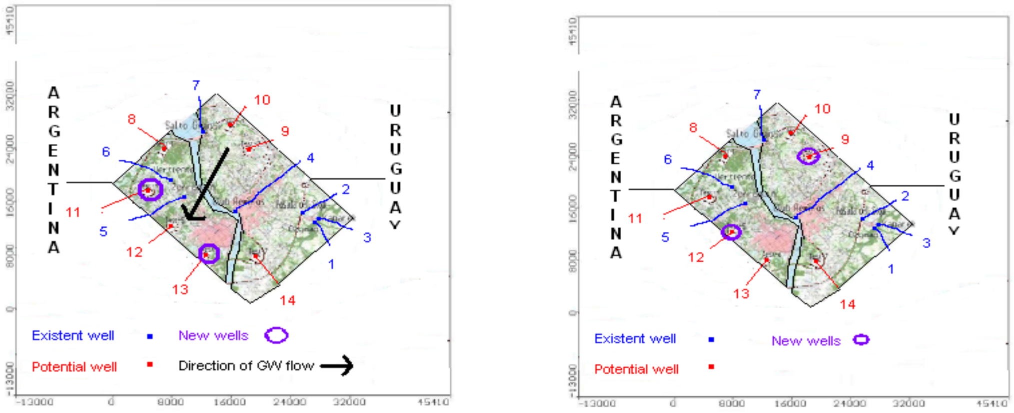
$$(3)\ s_{i,1}=\sum_{k=1}^{14}Q_{k,1}\beta_{i,k,1}$$

$$(4)\ s_{i,2}=\sum_{k=1}^{14}\left[Q_{k,1}\beta_{i,k,2}+\left(Q_{k,2}-Q_{k,1}\right)\beta_{i,k,1}\right]$$

Since users fulfill their demand for water by self-extraction from the aquifer (facing no external price for it), the optimal design policy is derived from a cost-minimization problem. The decision variables are (a) where to install two new wells from a set of potential locations[ii], (b) whether to install/de-install a water recycling system at each existent and new location in the first or second period, (c) whether to install/de-install a pumping system at each existent and new location in the first or second period. The constraints are that (a) extraction at each well exceeds a given demand minus the equivalent recycled water (if any), (b) hydraulic heads at all operative well locations must exceed the distance between ground surface and the lower datum of the aquifer by more than 10m if no equipment is installed and more than 3m if water recycling systems but no pumps are installed, and (c) the aquifer's response to extraction patterns represented by equations (1-2) or (3-4).

In the competitive management scenario, one of the locations for the new wells is given by a well that has already been drilled in the area. The other location is assumed to be selected in a 'myopic' fashion based on the largest head excess -expected after the first 20 years- of the distance between ground surface and the lower datum of the aquifer. Two potential sites (one in Argentina and one in Uruguay) are analyzed for the second location.

4.RESULTS AND DISCUSSION



(A) First representation (B) Alternative representation

Figure 1. Optimal new well locations and technology installed.

The two spatial representations derive different optimal new well locations: under the alternative representation, costs are minimized when the new wells are located at sites #11 and #13 because head and demand constraints are satisfied without the need to invest in any technology in neither the first nor the second management period. Conversely, as figure 1 shows, under the first representation optimal well locations are sites #9 and #12 and no technology is needed given the drawdown predictions of this physical specification.

The location of new wells in the competitive management scenario is the same regardless of the aquifer's representation used. At the start of the first management period, all users expect their hydraulic heads to be sufficient to cover their water needs during the period, and no equipment is installed. During the second 20 years, drawdown in the north-eastern corner of the area increases dramatically if measured with the alternative representation. It is worth noticing that this happens regardless of the position of the second new well. Hence, two users in that area are forced to invest in recycling systems. Since the first representation averages out drawdown throughout the aquifer, it fails to acknowledge the interference area in the north-western corner of the aquifer. As summarized in table 1, the first representation underestimates the welfare losses of a competitive management scheme and calculates an equal difference between initial and final heads for every location irrespective of the positioning of new users and management scheme.

Table 1. Optimal vs. Competitive Groundwater Management.

	Management scheme		Difference
	Competitive	Optimal	
A. NUL representation			
Location of new wells	**8 and 10 or 13**	**11 and 13**	**YES**
Location of recycling systems	**7 and 8**	**None**	**YES**
Location of pumping systems	**None**	**None**	**NO**
Total discounted cost	**US$2,330,554**	**US$2M**	**+16.53%**
Average drawdown after 40 years	**22.41m**	**17.56m**	**+27.62%**
B. UI representation			
Location of new wells	**8 and 10 or 13**	**9 and 12**	**YES**
Location of recycling systems	**None**	**None**	**NO**
Location of pumping systems	**None**	**None**	**NO**
Total discounted cost	**US$2M**	**US$2M**	**0%**
Average drawdown after 40 years	**15.57m**	**15.68m**	**-1%**

In conclusion, our empirical findings show that significant welfare and hydrologic costs from competitive extraction are overlooked if the aquifer is assumed to be a homogeneously distributed resource. This is because such a representation fails to capture well interference areas. Thus, the location of new wells is an irrelevant decision for users in both the optimal and competitive extraction scenarios.

From a policy perspective, the present study raises important issues. An implication, at least in terms of the aquifer studied, is that second-best economically defined spacing regulations are likely to have better efficiency results than uniform taxes or quotas. While policies that vary idiosyncratically across space may, in some transboundary cases, be prohibitively costly to implement, spatially-based policies do offer the potential of higher payoffs than conventional approaches with spatially heterogeneous resources.

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[i] The principle of superposition means that for linear systems, the solution to a problem involving multiple inputs (or stresses) is equal to the sum of the solutions to a set of simpler individual problems that form the composite problem.

[ii] The locations used are the ones proposed by Charlesworth, Sangam and Assidi (2008).