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Research article

Landscape irrigation management for maintaining an aquifer and economic returns

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ABSTRACT

Expanding irrigated agriculture and dryer climatic conditions has led to large-scale withdrawals of groundwater and the decline in shallow aquifers. Policy makers must wrestle with the challenge of maintaining economic growth while conserving the groundwater resource. A spatially explicit landscape level model analyzes consequences of optimally chosen crop mix patterns on an aquifer and economic returns. The model of the groundwater use incorporates irrigation needs of the crops grown, initial aquifer thickness, hydro-conductivity of the aquifer, and distance to surrounding grid cells. The economic model incorporates the site specific yield, crop mix, and irrigation practice investments to predict economic returns. A tradeoff occurs between the volume of the aquifer and economic returns due to groundwater withdrawal for irrigation, but the farm's ability to grow profitable lower irrigation crops dampens the intensity of this tradeoff. Allowing for multiple unconventional irrigation practices that are yield increasing and water conserving significantly increases the economic returns of a given crop mix while maintaining the aquifer.

1. Introduction

Groundwater is a vital component of the earth's water resources. Nearly all community water systems in rural America rely on groundwater, and in times of drought groundwater feeds streams and rivers to provide environmental benefits. Roughly 42 percent of agricultural irrigation water in the United States is obtained from groundwater (National Groundwater Association, 2010). Due to the reliance of irrigated crops on groundwater, many shallow aquifers have declined over the past century by several hundred feet. This raises the cost of pumping groundwater and puts at risk the economic returns of agriculture. However, the tradeoff between the aquifer volume and economic returns for a spatially explicit landscape has not been explored for a model using a large selection of crop types and irrigation practices. We believe by quantifying this tradeoff that this will aid the conversation between agricultural producers and groundwater regulators about the balance of the aquifer conservation and economic returns.

Successful conservation requires taking aquifer depletion into account across the entire agricultural landscape where the spatial mix of crops grown that affect groundwater cones of depression matter as much as the total amount groundwater pumped. There are some crops that generate valuable economic returns that are also consistent with at least some groundwater conservation. Natural recharge can sustain an aquifer while some level of irrigated agriculture remains on the land above. The broader environmental management question, beyond where are the best places to adopt water-saving irrigation technologies, is whether aquifer conservation is possible on a landscape with both irrigated and dryland agriculture. While farm production decisions based solely on economic returns can be detrimental to the aquifer, securing some economic return from farm land need not be mutually exclusive with a sustainable aquifer. Careful consideration of the pattern, extent, and intensity of crop production across the landscape can achieve a desired aquifer level while also generating reasonable economic returns. By encouraging multiple irrigation practices, this can enhance economic returns and affect the tradeoff between conservation and economic returns.

Spatially explicit aquifer and economic models are integrated to analyze the consequences of alternative crop type and irrigation decisions for aquifer and economic objectives. The aquifer model evaluates how well groundwater can be sustained on a large landscape given a spatially explicit pattern of crop types and irrigation practices. The aquifer's thickness, hydro-conductivity, and

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distance to surrounding grid cells affect the underground flow of the aquifer due to pumping on each grid cell. Based on the irrigation demand of the crop types and underground aquifer flow, we estimate the depletion of the aquifer under each grid cell. By summing the aquifer depletion over all cells, we track the total volume of the aquifer. The economic model predicts the economic returns for each grid cell under different crop types, including irrigated rice, soybeans, corn, and cotton, as well as non-irrigated soybeans, sorghum, and wheat. Location specific soil characteristics and initial depth to the aquifer affects the yield of the crops and groundwater pumping cost. The pumping cost of groundwater increases as the aquifer is depleted. Irrigation practices influence the yield, demand for irrigation water, and production cost of the crops. We combine commodity prices data with yields and production costs to generate economic returns for these crop types. The total economic return is the sum of the present value of crop returns of all grid cells.

We combine results from the aquifer and economic models to search for optimal crop and irrigation practice patterns. An efficient pattern generates the maximum economic return for a given volume of the aquifer sustained. By maximizing the economic returns over the entire range of possible aquifer volumes, an efficiency frontier is created for the landscape. The frontier illustrates what can be achieved in terms of aquifer and economic objective by careful spatial arrangement of crop types and irrigation practices. The efficiency frontier also demonstrates the degree of inefficiency of arrangements not on the frontier.

The application of the model is to the Mississippi River Valley Alluvial Aquifer (MRVA), the third most used aquifer in the United States. The sustainability of the MRVA is vital to maintaining long-term agricultural profitability in the Lower Mississippi River Basin (LMRB), one of the most productive agricultural regions in the United States (Maupin and Barber, 2005; Konikow, 2013). Arkansas is the largest consumer of water from the aquifer (Maupin and Barber, 2005), and the current rate of withdrawals from the aquifer is not sustainable although irrigated acres continues to increase each year (Barlow and Clark, 2011; ANRC, 2012). The LMRB has average annual precipitation ranging from 50 to 57 inches per year and is thus often considered an area rich in water resources (NOAA, 2014). However, the lack of timely rainfall and the use of irrigation to increase yields have meant the increasing installation of irrigation wells. A number of counties in east Arkansas have been designated as critical groundwater areas due to the continued decline in groundwater levels (ANRC, 2012). Studies predict that some parts of the alluvial aquifer will become commercially useless as early as 2015 if current pumping levels continue uncurbed (Sullivan and Delp, 2012). Federal programs have contributed to the voluntary implementation of alternative irrigation practices such as on-farm storage reservoirs, tail-water recovery ditches, and sensor technologies, among others.

While there is a large literature on multi-objective analysis in water resource planning (see Hajkowicz and Collons, 2007; for a recent review), much of this literature focuses on efficient water policy and supply planning. This literature typically does not incorporate analysis of working agricultural lands, either in terms of the landscape's ability to sustain an aquifer or in terms of economic returns. Water supply planning (Joubert et al., 2003) and infrastructure selection (Eder et al., 1997) have impacts on numerous stakeholders and must handle multiple objectives for which multi-criteria analysis is well-suited. Several papers have used multi-criteria analysis to incorporate infrastructure costs and economic returns in water resource planning (e.g. Mimi and Sawalhi, 2003; Karnib, 2004; Raju and Kumar (1999); Cai et al., 2004). Almost all prior work that combines water models of aquifer depletion and economic models to evaluate conservation and economics returns focus on a single irrigation technology or a single crop such as cotton or corn (e.g. Darouich et al., 2012; Gillig et al., 2004; Rodrigues et al., 2013).

The papers closest to our paper in terms of analyzing multiple irrigation technologies and multiple crops while comparing objectives such as aquifer conservation and economic returns are those by McPhee and Yeh (2004) and Xevi and Khan (2005). McPhee and Yeh (2004) derive the tradeoffs among three competing objectives by minimizing the magnitude and extent of drawdown of an aquifer. Xevi and Khan (2005) analyze the conflicts that arise between profitability, variable costs of production, and pumping of groundwater for multiple crops within a network of reservoirs, canals, and irrigation districts. Neither of these papers though considers the optimized configuration of the landscape in their study of sustained aquifer and economic return tradeoffs.

In the next section we describe the land, water, and economic models as well as the optimization algorithm used to find efficient land and water patterns. The section that follows describes the data for the application of the approach to the Arkansas side of the Mississippi Delta. The last two sections include the results and a conclusion with a discussion of the methods and results.

2. Methods

The crops grown in the farm production region of the Arkansas Delta depend on the land suitability and on the supply of water in the underlying aquifer. A grid of m cells (sites) represents spatially specific crop yields associated with soil quality and spatially symmetric cones of depression from groundwater pumping with the available groundwater based on the pumping decisions of farms in and around the site weighted by distance. The time frame is the 30 year period from 2013 to 2043.

2.1. Land constraint

We track the cumulative amount of land in use j for n land types for each of the major crops in the region (irrigated corn, irrigated cotton, rice, irrigated soybean, double crop soybean/winter wheat, non-irrigated sorghum, and non-irrigated soybean) using an irrigation technology k for the K major irrigation technologies of the region (conventional i.e. furrow for crops other than rice and flood for rice, center pivot, computerized poly pipe-hole selection, surge, land leveling, alternate wet-dry, multiple-inlet) at the end of period t with $L_{ijk}(t)$ site i. Another potential land use j is on-farm reservoirs for storing surface water to reduce reliance on groundwater and created from existing crop land. We refer to the on-farm reservoir use as $j = R$, and the cumulative amount of land in reservoirs in period t is $L_{iRk}(t)$.

Any land use j can be chosen in period t so long as the cumulative amount of land equals the original amount of land in production at site i (Eq. (1)),

$$\sum_j \sum_k L_{ijk}(t) = \sum_j \sum_k L_{ijk}(0). \tag{1}$$

The land balance equation is constrained by historical crop-specific minimum and maximum acreage ($L\min_j \le \sum_i \sum_k L_{ijk}(t) \le L\max_j$). The constraints reflect historical limits on acreage in the crops associated with land suitability, crop rotation restrictions, availability of capital, and producer knowledge of alternative crop production methods (Popp et al., 2011). The objectives of aquifer or economic returns described in later subsections of the methods are optimized subject to these land constraints.