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Analysis of the impacts of well yield and groundwater depth on irrigated agriculture

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SUMMARY

Previous research has found that irrigation water demand is relatively insensitive to water price, suggesting that increased pumping costs due to declining groundwater levels will have limited effects on agricultural water management practices. However, non-linear changes in well yields as aquifer saturated thickness is reduced may have large impacts on irrigated production that are currently neglected in projections of the long-term sustainability of groundwater-fed irrigation. We conduct empirical analysis of observation data and numerical simulations for case studies in Nebraska, USA, to compare the impacts of changes in well yield and groundwater depth on agricultural production. Our findings suggest that declining well pumping capacities reduce irrigated production areas and profits significantly, whereas increased pumping costs reduce profits but have minimal impacts on the intensity of groundwater-fed irrigation. We suggest, therefore, that management of the dynamic relationship between well yield and saturated thickness should be a core component of policies designed to enhance long-term food security and support adaptation to climate change.

1. Introduction

Expansion of groundwater-fed irrigation has increased crop yields, promoted economic development, and helped to buffer farmers around the world against the effects of drought (Giordano and Villholth, 2007; Siebert et al., 2010). However, intensive abstraction has also lowered water tables and depleted aquifer storage in many regions including the U.S. High Plains and Central Valley (Famiglietti et al., 2011; Scanlon et al., 2012; Breña-Naranjo et al., 2014), the Indo-Gangetic Plain (Rodell et al., 2009), and the North China Plain (Chen, 2010). A key challenge for research is to identify strategies to manage groundwater resources more sustainably and minimize the negative impacts of changes in aquifer storage on long-term agricultural productivity (Gleeson et al., 2010; Aeschbach-Hertig and Gleeson, 2012; Steward et al., 2013). Integrated hydro-economic modeling is a useful approach for assessing the effectiveness of different groundwater management policies, and has been applied to evaluate strategies such as water use reductions (Steward et al., 2009; Bulatewicz et al., 2010; Mulligan et al., 2014), water pricing (Medellín-Azuara et al., 2012), trading systems (Kuwayama and Brozović, 2013; Palazzo and Brozović, 2014), technological improvements (Peterson and Ding, 2005), and cooperative resource management (Saak and Peterson, 2007; Madani and Dinar, 2012).

When modeling integrated systems an important decision is how to describe mathematically the feedbacks between the various interconnected individual components of the system, in this case groundwater and agricultural production. Hydro-economic models typically represent the economic feedback from changing groundwater storage in terms of changes in the depth to groundwater (Koundouri, 2004). As the water table is lowered, the energy required to lift groundwater to the surface increases. Consequently, the cost of pumping groundwater increases approximately linearly with changes in water table depth in groundwater-fed irrigation systems where energy cost is the sole, or primary, component of water price. However, in this study we suggest that increased pumping costs may not be the most important driver of the impacts of variations in groundwater storage on irrigation practices and the resulting agricultural landscape. Specifically, we emphasize how the inability of current integrated hydro-economic analyses to consider changes in other hydrogeological parameters, such as well yield that controls the maximum rate of groundwater extraction, may limit the ability of integrated models to inform reliably the management of groundwater and agricultural production.

An extensive body of literature indicates that the price elasticity of irrigation water demand, which describes the proportional

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change in irrigation demand for a given change in price, is in fact inelastic and, therefore, unlikely to respond to price signals. Using a meta-analysis of 24 studies in the United States since 1963, Scheierling et al. (2006) found that the estimated price elasticity of irrigation water demand was, on average, relatively inelastic at −0.48. Comparable results have also be found by others authors. Hendricks and Peterson (2012), using an econometric approach based upon 16 years of data for over 14,000 wells overlying the High Plains Aquifer in Kansas in the United States, found irrigation water demand to be highly unresponsive to price increases with a calculated elasticity of −0.10. Similarly, Wheeler et al. (2008) in a study of irrigators in the Goulburn–Murray Irrigation District in Australia, found that irrigation demand is negatively related to water price and is inelastic. Some studies have found slightly higher estimated price elasticities of irrigation water demand. Schoengold et al. (2006), for example, estimated the price elasticity of irrigation water demand to be approximately −0.79 of which between −0.18 and −0.42 was the estimated intensive margin elasticity and −0.37 was the estimated extensive margin response, highlighting that a higher responsiveness to price signals may occur when considering farmers long-run decisions related to crop type or irrigation technology choices. Scheierling et al. (2006) drew similar conclusions from their meta-analysis study, while also highlighting that elasticity is likely to be higher for larger base water prices. However, de Fraiture and Perry (2007) note that it is unlikely that such higher water prices would be imposed in practice due to the large welfare impacts that this would create for resource users.

It is clear that, although variability exists in estimates of price elasticities, irrigation water demand generally can be characterized as unresponsive to price signals. As a result, it would be expected that groundwater-fed irrigation water demand would be relatively insensitive to changes in groundwater pumping costs that occur as water tables are lowered by extraction (Hendricks and Peterson, 2012). Contrastingly, it has been demonstrated anecdotally and empirically that well yield may exert significant control on farmers' irrigation scheduling and crop yield potential (O'Brien et al., 2001; Peterson and Ding, 2005; Lamm et al., 2007; Wines, 2013; Foster et al., 2014). In particular, Foster et al. (2014) highlighted that low well yields may force farmers to reduce irrigated area in order to limit the negative biophysical and economic impacts of intraseasonal groundwater supply constraints. This calls into question whether hydro-economic models, which are actively being used to inform groundwater management and policy development, are focused on the correct hydrogeological variables and if such models are capable of capturing the important feedbacks that occur natural and human components of coupled agricultural groundwater systems.

In this study we evaluate both empirically and numerically the relative effects of increased pumping costs and declining well yields on groundwater-fed irrigation practices in the Republican River Basin in Nebraska, USA. First, we use well-level data to investigate observed relationships between both well yield and water table depth, and irrigated area size. Subsequently, we apply the crop simulation model AquaCrop (Steduto et al., 2009) within a hydro-economic modeling framework to simulate optimal irrigation decision-making under variable well pumping capacities and groundwater table depths. Our findings show that well yield exerts a much stronger control on groundwater-fed irrigation than changes in pumping cost that are a function of depth to groundwater. We suggest, therefore, that long-term management of groundwater for agriculture therefore must not focus solely on limiting increases in pumping costs, but should also consider the value of well pumping capacities for both hydrological sustainability and food security.

2. Methodology

In this section the methods that are used to evaluate the impact of depth to groundwater and well yield on irrigation decision-making are described. Section 2.1 focuses on the empirical data and methods, while Section 2.2 describes the numerical simulations.

2.1. Empirical data analysis

Observed relationships between irrigation decision-making and both groundwater depth and well yield, are developed using a unique dataset obtained from the Nebraska Department of Natural Resources Groundwater Wells Database (Nebraska Department of Natural Resources, 2014). From this database, we extract records for active irrigation wells located within the Republican River Basin (Fig. 1) that account for 10,673 of the total 215,058 wells recorded. For each well, the database provides information about the location of the well in the form of geographic coordinates, the date of well installation, the area that is irrigated using the well, and the well yield and pumped groundwater level at the time the well was installed. The reported irrigated area supplied by each well was verified during the certification process of the Republican River Compact Agreement (RRCA) (McKusick, 2002) that resulted from a multi-state legal dispute between the states of Nebraska, Kansas, and Colorado. The irrigated areas reported in the database therefore represent a reliable estimate of actual irrigated areas in a period before the introduction of water use restrictions in the basin that are likely to have led to changes in irrigation practices that are unrelated to hydrogeological conditions.

Before the data obtained for the 10,673 wells can be used to estimate observed relationships, a number of data processing steps have to be conducted. First, for a number of wells in the Republican River Basin the pumped groundwater level (922 wells) or well yield (273 wells) is reported as zero. Given that other information appears to be reported correctly for these wells, for example certified irrigated area is positive and non-zero, it is assumed that this is a reporting error. To correct this, the pumped groundwater level and/or well yield for these wells is set equal to the value given by the nearest neighboring well within a distance of 1 km. Subsequently, it is necessary to modify the reported well yield for all 10,673 wells using the adjustment given in Eq. (1). Equation (1) was developed as part of the RRCA to adjust well yields based on a comparison of actual metered pumping rates and the registered pumping rates reported in the groundwater wells database (Koester, 2004). This calibrated adjustment is necessary as registered pumping rates are based on short duration well pumping tests that overestimate the actual well pumping capacity that can be sustained during longer periods of pumping (e.g., over a period of several days to a full growing season) (Koester, 2004). Finally, a number of additional variables not reported in the database, but which will be used in the empirical analyses, are also estimated for each well. Percentage soil sand is estimated as a proxy for soil type by comparing the geographic location of each well with a weighted average of the soil textural properties in the upper 1.5 m of the soil column as reported in the SSURGO soil dataset (U.S. Department of Agriculture, 2014). In addition, distance to the nearest major perennial stream is calculated by comparing well location with the stream network distribution given in the National Hydrography Dataset (U.S. Geological Survey, 2014).

$$W_{act} = \frac{1.3842 \cdot W_{reg}}{\left(1 + 7.5023 \cdot 10^{-4}\right) \cdot W_{reg}} \quad (1)$$

where W_{act} is the adjusted well yield (m^3 day^{-1}), and W_{reg} is the registered well yield (m^3 day^{-1}) reported in Nebraska Department of Natural Resources (2014).