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Groundwater and Economic Dynamics, Shadow Rents and Shadow Prices: The Punjab

Rodney B. W. Smith*, Harumi Nelson and Terry L. Roe
University of Minnesota, USA
**smith142@umn.edu*

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This study investigates the effect of electricity subsidies on economic and groundwater dynamics. The analysis follows from a dynamic, multisector and general equilibrium model in which both aquifer hydrology dynamics in the Punjab region of India and capital accumulation across India are endogenous. The model predicts Punjabi aquifer depletion which has distinct regional impacts and slight spillovers on the rest of the Indian economy. From the Punjab perspective, electricity subsidies encourage higher levels of groundwater extraction than one would observe in the absence of the subsidy. In turn, the higher levels of groundwater extraction increase agriculture's ability to compete for labor and other farm inputs. Even with the subsidy, however, as the economy transitions to the long run equilibrium, groundwater tables fall and more electricity is needed to supply the same amount of water used in the previous period. These forces slowly diminish agriculture's ability to compete for resources and the sector eventually loses resources to the rest of the economy and in turn, agricultural income falls over time. These dynamics are accentuated when the subsidy is removed, leading to a more rapid decline in Punjabi agricultural income.

Our empirical findings suggest eliminating the 'electricity for irrigation' subsidy leads to double gains: An environmental gain and an economic gain. The environmental gain is a slower rate of aquifer depletion over time relative to a subsidy world. Removing the subsidy discourages production of high water-intensive crops, thus slowing the rate of groundwater extraction. Although removing the subsidy increases agricultural production costs, it makes electricity less expensive for competing sectors, namely manufacturing, which in turn leads, over time, to increased electricity, capital and labor demand from manufacturing. This reallocation of resources to more productive sectors in the economy leads to an increase in Punjabi gross state domestic product, as compared to the case where electricity is subsidized. The empirical results suggest removing Punjabi electricity subsidies entails trade-offs between agricultural and manufacturing income and has implications for long term water use. Empirical results also suggest that correctly calculating the "stock" value of a natural resource requires macroeconomic data and hence, may be impossible to conduct in a partial equilibrium setting.

Keywords: Economic growth; groundwater; capital accumulation; general equilibrium; natural capital valuation.

1. Introduction

The deep alluvial aquifer of the Punjab region of India has made the region one of the most agriculturally productive regions in the world and a leading supplier of food grains (rice and wheat) to India. The provision of essentially free electricity made groundwater extraction for agriculture relatively inexpensive and facilitated Punjab's rise to productive prominence. This prominence, however, is now threatened, because groundwater tables have dropped to the point where concerns with water salinity are being raised and because political pressures are mounting for the government to eliminate, or at least lower the subsidy rates. The energy subsidies are particularly deleterious for two major reasons. First, they have encouraged farmers to withdraw groundwater at — what most would consider — unsustainable rates. The rapid rates of groundwater extraction lowers groundwater tables, which in turn requires more energy to pump water to the surface: This process creating a trap in which eliminating or lowering the subsidy leads to groundwater extraction costs that would make agricultural production unprofitable for many farmers. Second, the excessive use of electricity in water extraction makes electricity more expensive for the non-farm economy, thus inhibiting the non-farm economy's ability to absorb labor from the farm economy and hence, serves as a drag on the country's economic growth potential.

This study investigates the effect of economic policy (here, electricity subsidies) on economic and ecosystem service dynamics (groundwater in the present case). The analysis follows from a dynamic, multisector and general equilibrium model in which both aquifer hydrology dynamics in the Punjab region of India and capital accumulation across India are endogenous. Groundwater management is carefully evaluated in order to understand the links, over time, between Punjab groundwater resources and the broader Indian economy. The model predicts Punjabi aquifer depletion which has distinct regional impacts and spillovers on the rest of the Indian economy. From the Punjab perspective, electricity subsidies encourage higher levels of groundwater extraction than one would observe in the absence of the subsidy. In turn, the higher levels of ground water increase agriculture's ability to compete for labor and other farm inputs. Even with the subsidy, however, as the economy transitions to the long run equilibrium, groundwater tables fall and more electricity is needed to supply the same amount of water used in the previous period. These forces slowly diminish agriculture's ability to compete for resources and the sector eventually loses resources to the rest of the economy and in turn, agricultural income falls over time. These dynamics are accentuated when the subsidy is removed, leading to a more rapid decline in Punjabi agricultural income.

Our empirical findings suggest eliminating the 'electricity for irrigation' subsidy leads to double gains: An environmental gain and an economic gain. The environmental gain is the restoration of the aquifer where water can be withdrawn at rates roughly equal to renewal, while also providing a "hedge" or option to access water at rates that exceed renewal in times of drought. Removing the subsidy discourages production of high water-intensive crops, thus slowing the rate of groundwater extraction. Although removing the subsidy increases agricultural production costs, it makes electricity less expensive for competing sectors, namely manufacturing, which in turn leads, over time, to increased electricity, capital and labor demand from manufacturing. This reallocation of resources to more productive sectors in the economy leads to an increase in Punjabi gross state domestic product, as compared to the case where electricity is subsidized. The empirical results suggest removing Punjabi electricity subsidies entails trade-offs between agricultural and manufacturing income and has implications for long term water use.

The paper proceeds as follows. Section 2 summarizes the literature relevant to this study and highlights key aspects of the economy pertinent to groundwater management and the current economic and policy environment that Punjabi farmers face. Section 3 lays out the structure of the dynamic, general equilibrium model underlying the empirical model, with an emphasis placed on its implications for studying aquifer dynamics in a general equilibrium setting. Section 4 describes the data and methodology, along with its benefits and limitations. The result of this process is a "baseline model" which is solved numerically to provide time-dependent forecasts of the Punjab economy and the broader Indian economy. Section 5 presents the empirical results of the base line model and compares the results with those of a world where electricity subsidies are removed. Then, Section 6 uses the water shadow prices and groundwater extraction levels to calculate the unit shadow price of groundwater in agricultural production, along with the stock value of that water. We conclude by discussing one of the challenges faced when trying to calculate the stock value of water, and suggest directions for possible future research.

2. Background

Punjab, a northwest state of India, is an agriculturally intensive region that relies heavily on groundwater, the extraction of which is causing a steady decline in the region's water table. According to the 2011 Critical Economic Indicator in Punjab (CEIP), the 2007 share of agriculture and allied sectors in total gross state domestic product was 30% for Punjab and 16% for all of India. In particular, relative to its food grain production in the 1960s, Punjabi levels more than quadrupled by the 2000s. In Punjab, the vast majority of farmers grow rice in the summer monsoon season and wheat in the winter season, with about 77% of total cultivated area devoted to the two grains. Between 1970 and 2002, rice area increased from about 0.4 million to 2.48 million hectares, while wheat area increased from about 2.3 million to 3.42 million hectares (Humphreys *et al.* 2010). As a grain surplus state, Punjab contributed to 61% of wheat and 28% of rice of India's central pool of food grains in 2007–2008 (CEIP 2011).

Evidence suggests Punjab's normal precipitation levels are inadequate for its rice–wheat growing cycle (Perveen *et al.* 2011). One of the major factors underlying Punjab's reputation as a leading producer of rice and wheat is access to its rich alluvial aquifers — and the electricity subsidies to extract the resource. Currently, almost all cropped area in Punjab is irrigated. During 2007, gross irrigated area in Punjab is 98% of gross cropped area, while only 45% for all of India (CEIP 2011). Since 1997, free electricity has been provided to famers for irrigation purposes.[1] In 2007, agriculture was responsible for 32% of Punjab's electricity consumption (CEIP 2011). Between 1990 and 2008, the number of tube wells operated by electric pumps almost doubled to slightly over 1 million (Economic Adviser to Government of Punjab 2009).

In a sample of 193 borewells, Punjab groundwater tables vary considerably across the region, with the levels ranging from 0.67 meters below ground (mbg) to 40 mbg (Perveen *et al.* 2011). Among these wells monitored, 36.27% had water tables between 10 mbg to 20 mbg, and 15.54% were between 20 mbg and 40 mbg. The remaining wells were 2 mbg to 10 mbg. Humphreys *et al.* (2010), predicted that 75% of Punjab wells will experience an additional 10 m decline in water table levels by 2020 and that 30% of wells are likely to experience drops by as much as 30 m by 2025.

According to a survey conducted by Columbia Water Center, Punjab farmers are extremely dissatisfied with unreliable electricity supply, the voltage of which fluctuates and damages pumps (Perveen *et al.* 2011). In addition, farmers are allowed to access only limited hours of electricity per day, about 6 h to 7 h (Fishman *et al.* 2011). As water tables continue to fall, farmers face increased pumping costs due to expenditures on larger pumps and the fact that the deeper the water table, the more energy they need to pump a unit of water. So, even if

[1]In Punjab, electricity for pumping was free from 1997 to 2002 and after 2005 (Perveen *et al.* 2011).

electricity is free, an essentially fixed amount of electricity leads to less water pumped as water tables drop. The social cost of electricity subsidies has been relatively high, as such subsidies more than tripled between 1990 and 2002, leading to a situation where over 40% of Punjab's state budget deficit is traced back to subsidizing electricity (Singh *et al.* 2004). Thus, the administrative priority of water allocation to the farmers imposes an extensive economic stress on other parts of the economy and consequently, the process of industrial growth and economic development is adversely affected.

Tsur *et al.* (2004), note the economic literature on groundwater management which is predominantly based on partial equilibrium analysis. For instance, while Balali *et al.* (2011) recognize the important relationship between groundwater dynamics and government subsidies, their analysis is limited to dynamics in the agricultural sector. Consequently, the indirect economic interaction among sectors and the rest of the economy is overlooked. Knapp *et al.* (2003) evaluate the relative efficiency of different groundwater management tools. In their model, groundwater demand is determined by an endogenous price of water, while energy and other factor prices are exogenous and constant over time. Although their implications for sector efficiency gains from establishing water markets would likely hold in a general equilibrium setting, their partial equilibrium analysis tell us nothing about the regional or economy-wide effects of a given policy.

Few studies have focused on water's role as an economy-wide resource. Two exceptions are Diao *et al.* (2008) and Hassan *et al.* (2008), who each use detailed general equilibrium models to analyze the impact of groundwater scarcity on agricultural and non-agricultural sectors, albeit in a static setting. They show that allowing markets to play a more significant role in allocating leads to an increase in gross domestic product (GDP) of 3% to 4% in the case of Morocco (Diao *et al.* 2008) and South Africa (Hassan *et al.* 2008): Large gains when one realizes irrigated agriculture only accounts for 5% to 10% of the respective economies. Although their quantitative simulations have important implications for water management in a macroeconomic setting, the analyses are static and hence, are unable to shed any insight into the effects of water policy on economic growth and sustainable groundwater management. To our knowledge, no studies to date have examined water's role as an economy-wide resource in the process of economic growth.

Diwakara and Chandrakanth (2007) and Reddy (2005) evaluate the costs of alternative recharge mechanisms like watershed development programs and irrigation and percolation tanks to reduce the external environmental costs caused by groundwater extraction. These studies provide important insights into the effects of water scarcity on individual farmer's choice of crops and production techniques, but they provide no insight into the broader regional and economy-wide effects of the groundwater management mechanisms. Thus, they likely underestimate the consequences of policies designed to sustain or deplete groundwater supplies. Moreover, the effects of water policy on the regional and national economy feedback to farmers in terms of changes in wage of labor, capital costs and food prices. These indirect effects can exceed the direct effects measured by partial equilibrium analysis including the literature mentioned above. The study by Bhatia *et al.* (2006) analyzes both direct and indirect effects of the policy changes on the state of Tamil Nadu economy. Using an optimization approach, they suggest if the state shifts from fixed sectoral water allocations to a flexible water allocation scheme, over a 20 year period, total water demand would fall by 15%, with 24% less water pumped from groundwater sources. With exogenously projected output levels, however, the role of input prices — including the shadow prices of water — in allocating resources is not considered in the study.

Comparing two input–output tables, one for 1969–1970 and the other for 1979–1980, Bhalla *et al.* (1990) argue that the rapid growth and structural transformation of the Punjab economy over the 10 year period was primarily the result of technological breakthroughs in agriculture. Industry was dominated by an agriculturally-based industry and the transition to a more diversified economy was rather slow. As an agricultural surplus state, Punjab enjoyed its comparative advantage specializing in producing food grains. Labor emigrated from the neighboring states to Punjab and capital was imported mostly for agricultural purposes. The study did not express any concern with the sustainability of Punjab's groundwater resources. Furthermore, the electricity subsidies were viewed as necessary public spending and considered as an engine of economic growth. Although the study had a regional, general equilibrium learning, water as a factor of production did not factor in the study.

Using time series data from the 1960s and 1980s, McGuirk and Mundlak (1990) conclude that agriculture was the major driver of Punjabi economic growth. Emphasizing modern higher yielding varieties for wheat and rice, they conclude that agriculture would continue prospering as long as irrigation technology and fertilizer use expanded and more productive agricultural techniques were adopted. The authors' concerns for continued economic growth lay more with continued discovery of new crop varieties — not with farmers facing groundwater constraints. Later, Bhalla (1995) argued that expanding the area of irrigated agriculture via groundwater sources was a key determinant of agricultural growth in the region. The study was also one of the first to express concerns that electricity subsidies led to an excess demand for power. However, according to his analysis, the increase in electricity demand was caused not just by pumping groundwater, but also by electrification of Punjab's rural areas. The environmental threat was not viewed as a serious concern for the Punjab economy at that time.

Gulati (2002, 2007) argues that in earlier years, Punjab benefited from producing surplus rice and wheat that was absorbed by grain deficit states in other parts of India. The grain deficit regions, however, eventually improved their productive capacity, leading to a decrease in demand for Punjabi grain in the 2000s. He also suggests free electricity, encouraged excessive groundwater extraction and the annual rate of groundwater table decline and noted the policy dialog started viewing the adverse impact that heavy subsidies to agriculture were having on the Indian economy. Shreedhar *et al.* (2012) fault policy makers with putting Punjab farmers in a position where they relied too much on subsidized production. They suggest that, although it would be difficult to remove the power subsidies completely, the subsidies could be gradually phased out and converted into investments in rural infrastructure and agricultural research.

3. Overview of the Model

The economic model takes as its point of departure, the dynamic three-sector, small open economy model in Chapter 4 of Roe *et al.* (2010): A Ramsey model that uses land, labor and capital to produce two traded goods and a non-traded good. Here, we also employ a dynamic small open economy model, but disaggregate India into six sectors: rice, wheat, other agriculture, manufacturing, services and Punjab electricity. Rice, wheat, other agriculture and manufacturing are each produced in two regions: The Punjab and the rest of India (ROI). We aggregate all service production into a single all-of-India sector. Although electricity is produced throughout India, for reasons of parsimony, we aggregate the ROI electricity in ROI services. The formal mathematical model is presented in the Appendix.

As in Roe, Smith and Saraçoglu (RSS), the mathematical model has two parts. The first part introduces the model primitives (production technologies and household preferences) and defines corresponding indirect objective functions (cost, value-added and expenditure functions). The model has a distinct production technology for each final good produced in Punjab (rice, wheat, other agriculture and manufacturing) and for each final good produced in the ROI (rice, wheat, other agriculture, manufacturing and services). The empirical model represents these primitives with Cobb–Douglas functions. Household preferences are also represented with Cobb–Douglas functions and defined over five final goods (rice, wheat, other agriculture, manufacturing and services). The indirect objective functions derived from the underlying technologies are used to define equilibrium conditions that must hold at each point in time — e.g., profit and utility maximization and factor market and output market clearing conditions — referred to by RSS as *intratemporal equilibrium* conditions. The intratemporal equilibrium conditions defined in the Appendix are "dual" representations of the factor and output market clearing, and agent maximizing behavior captured in a typical computable general equilibrium model.

The second part introduces the groundwater dynamics and derives the households' optimal consumption/savings decision (the economic dynamics). Groundwater dynamics are modeled using a standard "bucket" representation of an aquifer (see Appendix): At each point in time, the groundwater table falls with groundwater extractions and increases with recharge — here water infiltration from precipitation. As the groundwater table falls, pumping water to the surface requires more capital, labor and electricity and hence, extraction costs increase[2] as the groundwater table falls. See the Appendix for details on our modeling of groundwater dynamics. The economic dynamics follow the optimal savings framework of Ramsey (1928): At each point in time the household decides, how much of its instantaneous income (from capital, labor and land and water rent) to use for current consumption and how much to save.

4. Methodology and Data

We link the conceptual model outlined in the Appendix to an empirical analogue in which household preferences and firm production functions are specified as Cobb–Douglas functions.

4.1. *Consumption and non-water using production*

We parametrize the model using data from several sources. The major data source is a social accounting matrix (SAM) for Punjab and the ROI was developed by M. R. Saluja, India's foremost authority on Indian national accounts (Saluja and Yadav 2006). The SAM was aggregated to match the 10 sectors discussed above: Punjab and ROI rice, wheat, other agriculture and manufacturing and all of India's services and Punjab electricity. The second major data source is the World Bank's World Development Indicator (WDI) data on India's gross fixed capital formation, labor force and GDP, with the WDI data used to create a capital stock series. This data, along with the factor account entries in the SAM was used to identify the

[2]In principle, unit extraction costs do not have to increase monotonically: If the extraction technologies are capital and energy intensive and both capital rental rates and unit energy costs fall fast enough relative to the increase in capital and energy demands, unit extraction costs could fall (at a point in time).

Table 1. Consumption Shares

Rice	Wheat	Other Ag.	Industry	Services
0.589	0.656	0.561	0.259	0.583

factor elasticities and initial total factor productivity level for seven of the 10 sectors: Services; the ROI rice and wheat; and Punjab and ROI manufacturing and other agriculture. The consumption shares were also derived directly from the SAM. See Roe *et al.* (2010) for details on this process. The consumption shares are presented in Table 1.

4.2. *Punjab rice and wheat production*

There remains three empirical issues to address: (i) groundwater's (and rain's) contribution to rice and wheat production, (ii) energy's contribution to groundwater extraction and (iii) specification of the equation of motion for the groundwater table. We first note there is a dearth of production data linking Punjabi rice production with water. However, rice production data does exist for Tamil Nadu, an intensive rice producing state having a production and cost structure comparable to Punjab. The state also has similar values of gross value-added as well as yield per hectare for rice production (Agricultural Research Data Book 2011).[3] As such, we use empirical results of rice production from Lundberg *et al.* (2014); Palanisami (2013), the SAM by Saluja and Yadav (2006) and cost of production data from the Agricultural Research Data Book to reapportion Punjabi rice factor account entries across capital, labor, land and a "shadow" water account. This allows us to estimate factor elasticities for capital, labor, land and water in rice production. See Lundberg *et al.* (2014) for a more detailed discussion of this approach. Factor shares for wheat are derived using Palanisami (2013), the Saluja SAM and the Agricultural Research Data Book. The production shares are summarized in Table 2.

4.3. *Groundwater dynamics*

Throughout Punjab region, groundwater tables have been dropping because the rate of groundwater extraction has exceeded the rate of aquifer recharge. Data from monitored wells throughout the region reveals that groundwater head levels range from less than 1 m below ground (mbg) to over 30 mbg throughout the state. As with the spatial differences in groundwater head levels, the rate at which the groundwater tables fall varies across the state. In this study, we characterize the

[3]See Table 5.18 Cost of cultivation of principal crops (2006–2007).

Table 2. Production Factor Shares

	Punjab						ROI				
	Rice	Wheat	Other Ag.	Industry	Energy	Irrigation	Rice	Wheat	Other Ag.	Industry	Services
Labor	0.209	0.139	0.445	0.250	0.865	0.018	0.589	0.656	0.561	0.259	0.583
Capital	0.187	0.177	0.175	0.581	0.135	0.140	0.117	0.078	0.168	0.741	0.417
Land	0.422	0.647	0.380	0.111		0.018	0.293	0.266	0.271		
Water/Rain	0.182	0.037				0.231					
Energy				0.058		0.594					

Punjab aquifer as a single cell "bathtub" and in the empirical analysis, model the depth of the groundwater table, along with its rate of change, as the averages across the districts in Punjab.

In general, the major source of aquifer inflow is precipitation, with a relatively insignificant amount of recharge coming from return flows from irrigation. The main drawdown from the aquifer is water extraction for agricultural irrigation, with a relatively insignificant drawdown from industrial and residential demands.[4] Groundwater response to precipitation recharge depends on a number of factors including soil properties and precipitation characteristics. The Indian Central Ground Water Board (2009), estimates that 22% of rainfall eventually recharges the Punjabi aquifer system.[5] As suggested above, the amount of energy required to transport water from the aquifer to the field increases as the groundwater table falls.

To capture the link between the increasing energy consumption and falling groundwater tables, we follow the convention suggested by hydrologists. Let v represent hydraulic energy consumption in gigawatt hours (GWh), let Y_h represent the amount of groundwater pumped (in million m^3) and D represent the groundwater table depth (in meters, m). Then FAO (Cunningham 2012) and Coker (2007) note $v = \frac{Y_h D}{367\kappa}$. The denominator is a physical constant multiplied by a pumping efficiency parameter, κ ($0 \leq \kappa \leq 1$). This simple hydraulic energy equation has the advantage of being linear in depth, D.

The above discussion leads to the following empirical specification of the groundwater depth dynamics:

$$\dot{D}(t) = \frac{Y_h(t) - \beta \cdot \text{Rain}(t)}{\gamma}.$$

This simplified groundwater model shows the rate of change in the groundwater table, $\dot{D}$ depends on the difference between withdrawal, Y_h and recharge, $\beta \cdot \text{Rain}$. The scalar γ converts the net water volume extraction per period into the corresponding change in the water table level. The parameter β is an infiltration factor.

[4]According to Ground Water Year Book (Central Ground Water Board 2012), total annual groundwater replenished in Punjab in 2009 was 22.56 billion m^3 in which the recharge from monsoon rainfall was 10.57 billion m^3, while recharge from non-monsoon rainfall was 1.34 billion m^3. The difference between the total replenished amount and recharge from annual rainfall was recharge from other sources. Subtracting natural discharge from total annual replenished groundwater, the net annual groundwater availability was 20.35 billion m^3. On the other hand, total annual groundwater draft was 34.66 billion m^3 among which 33.97 billion m^3 was used for irrigation purpose and 0.69 billion m^3 was used for domestic and industrial uses.

[5]The data were provided by Dr. Shashidhar Thathikonda, Indian Institute of Technology, Hyderabad, India in June 2012.

This representation of groundwater dynamics is analogous to the representation of groundwater dynamics in Roumasset and Wada (2012).[6]

5. Empirical Analysis and Simulation Results

Below are the results of two simulations. The baseline simulation examines the economics of unchanged policy, where the unit price of electricity for agriculture is subsidized at 90%.[7] The discussion of results focuses on groundwater extraction and water table dynamics, Punjabi agricultural and manufacturing sector value-added dynamics, and unit electricity price and the shadow value of groundwater. The second simulation removes the subsidy and compares the subsequent groundwater and value-added dynamics with the baseline model results. Perhaps the most important of the variables we discuss is the shadow value of groundwater, which provides a measure of the economic value of groundwater in agricultural GDP, i.e., the flow value of groundwater. After discussing the groundwater and economic dynamics, we then discuss the relationship between the flow value and stock value of groundwater in Punjabi agricultural production.

5.1. *The baseline scenario — subsidized electricity for agriculture*

Table 3 shows that the total amount of groundwater pumped in the initial period is about 39,000 million m^3, but drops to about 25,000 million m^3 by 2037. Although not shown in the table, the long run level of total groundwater extraction drops to about half the initial levels. In Table 1, the groundwater tables begin at 11.3 mbg and drops to 21.7 mbg by 2027. Of course, this continual fall in the water table, albeit at a diminishing rate over time, occurs because the rate of annual groundwater withdrawals exceeds the rate of recharge each period.

The model predictions are consistent with empirical findings to date. For example, between 2002 and 2008, Rodell *et al.* (2009) observe declines in the Punjab

[6]According to CEIP (2011), electricity for irrigation use was 10,022 GWh while that for industry use was 11,354 GWh in the period of 2007–2008.

[7]Although electricity subsidies pervade India, the model focuses only on electricity subsidies in Punjab. Doing so involves a couple of implicit assumptions we are unable to circumvent. First, although water is a factor of production in ROI agriculture, we implicitly move it into the ROI agriculture's constant term and hence, implicitly assume water (productivity and) availability in the ROI remains constant over time. The same is true for electricity in manufacturing. The upshot of this is that Punjab's agriculture and manufacturing sectors' ability to compete for resources is worse than the case where everyone faces evolving (most likely more challenging) factor market conditions. If placed on an equal footing with others, Punjab agriculture and manufacturing output would likely be a little higher than with the case modeled here.

Table 3. Punjab Groundwater and Economic Variables in the Subsidy Scenario

	Groundwater Table		Unit Shadow Prices		Groundwater Extraction		Output Supply ($ Index)			Value-Added Prices	
Year	Depth (mbg)	Change	Water ($/mill m^3)	Energy ($/GWh)	Rice (mill m^3)	Wheat (mill m^3)	Rice	Wheat	Manuf.	Rice	Wheat
2007	11.30	0.66	0.49	3.35	28588.1	10558.3	2592.9	3497.8	1980.2	0.91	0.98
2012	14.39	0.57	0.72	5.00	26315.1	10455.0	2441.7	3463.6	746.2	0.87	0.97
2017	16.99	0.46	1.07	7.30	23257.9	10332.7	2238.4	3423.1	151.3	0.80	0.96
2022	19.02	0.35	1.43	9.32	20249.6	10213.2	2038.3	3383.5	26.5	0.74	0.95
2027	20.57	0.27	1.68	10.43	18096.6	10118.8	1895.1	3352.2	8.3	0.69	0.94
2032	21.80	0.22	1.85	10.99	16592.8	10044.4	1795.1	3327.6	4.3	0.66	0.93
2037	22.80	0.18	1.97	11.28	15497.0	9983.8	1722.2	3307.5	3.0	0.64	0.93

groundwater table ranging between 0.4 m and 0.5 m, Singh (2006) observed that between 2002 and 2006, the groundwater table in central Punjab fell an average of 0.75 m per year. More recently, Palanisami (2013) observed groundwater table declines in excess of 1 m over the past three years.

Table 3 presents the evolution of two factor prices: (i) The shadow rental rate of water, which in equilibrium is equal to the unit cost of extracting groundwater and (ii) the shadow price of electricity. As the groundwater table falls over time, the cost of extracting that water increases due to the increased amount of energy needed to bring a unit of water to the surface. With energy fixed for the region and an increase in the energy needed to extract a unit of water, energy becomes increasingly scarce over time, putting upward pressure on the shadow energy prices. These price pressures hamper Punjabi agriculture's ability to compete for resources as the economy grows. As energy prices increase, the unit cost of extracting groundwater increases. Given the Leontief structure of agricultural production, the price increase directly affects the net price received by farmers and hence profitability: The output price is adjusted for the unit groundwater cost weighted by its input–output coefficient — the resulting unit value is called the "value-added" price.[8] Table 3 presents the value-added prices for rice and wheat, also, which both fall over time.

Roe *et al.* (2010) discuss the link between factor intensity, capital deepening and economic structure, and suggest capital deepening tends to favor the more capital intensive sectors. One of the effects of capital deepening is a downward pressure on rates of return to capital and upward pressure on wages, as labor becomes more scarce than capital over time. Punjabi and ROI manufacturing are the most capital intensive sectors in the economy. As such, we would expect these two sectors' GDP share to increase over time. And although not shown here, ROI manufacturing does garner a larger and larger share of GDP over time — producing 23% of GDP in 2007 and about 35% of GDP by 2057. Hampered by the high cost of electricity, however, Punjabi manufacturing does not fare as well, as its value-added price falls by almost 60% between 2007 and 2057. This precipitous drop in net unit price (relative to manufacturing in the ROI), contributes to Punjab manufacturing's declining GDP share.[9] Effectively, the Punjab economy is

[8]The value-added price of rice is defined as $1 - \sigma_{hi} p_h,\ i = 1, 2$. For a discussion of value-added prices, see Chapter 8 of Roe *et al.* (2010).

[9]This particular result is almost certainly, an artifact of the model ignoring electricity's role in the ROI, and the fact that Punjab manufacturing share a fixed resource — electricity. This combination contributes to an increase in the diminishing returns to the capital and labor used in the region and its concomitant decline in GDP share.

"losing" its comparative advantage with the rest of the Indian economy in competing for economy-wide resources.

5.2. *The no-subsidy scenario*

Table 4 shows the impact of removing the electricity on the Table 3 variables. Not surprisingly, with no subsidy the shadow irrigation water prices increase, the amount of groundwater extracted each period falls, and the groundwater table falls more slowly. By 2017 the groundwater table had only fallen to 14.8 mbg and by 2037 to 18.5 mbg. The economics driving the results are analogous to those driving the subsidy scenario, but here with agriculture paying the full cost of electricity they use less energy, and in turn use less water and produce less output than in a subsidy world. The decrease in energy demand from agriculture triggers a decrease in energy price, which benefits manufacturing in a significant fashion — doubling output in the initial period relative to the case with energy subsidies.

Table 5 summarizes the change in variables useful in describing the economy-wide impact of removing the subsidy. In particular, we observe the following: (i) the level of household saving and the rate of return to capital increases slightly without the subsidy, suggesting the subsidy had a negative impact on the aggregate returns to capital; (ii) service good production and the price index of services both fall a small amount relative to the subsidy, reflecting the fact that an increase in savings leaves — in the short to intermediate run — less income for consumption, and with homothetic preferences less total consumption means less income to spend on all final good categories; (iii) manufacturing in the ROI falls, reflecting Punjab manufacturing's enhanced ability to compete for capital and labor with the ROI; (iv) agricultural production in the ROI increases, reflecting resources released by a non-subsidized Punjab agriculture to the ROI. These adjustments are small in percentage terms, but highlight the link between Punjabi agricultural distortions and the rest of the economy. Finally, Punjabi GDP increases, while ROI GDP and aggregate GDP for India falls slightly when the subsidy is removed. The GDP results, however, are difficult to interpret, as the price of services without the subsidy is lower than with the subsidy — preventing us from using relative GDP levels at a point in time as relative measures of welfare at that time.

6. The Flow and Stock Shadow Values of Water in Punjab Agriculture

Although not stressed in the earlier discussion, the variable p_h is the price farmers pay for a unit of water. Given there is no market for water, in equilibrium, p_h is the shadow value of an additional unit of water: the amount a farmer would be willing

Table 4. Percent Difference in Groundwater and Economic Variables (No-Subsidy Relative to Subsidy Scenarios)

	Groundwater Table		Unit Shadow Prices		Groundwater Extraction		Output Supply ($ Index)			Value-Added Prices	
Year	Depth (mbg)	Change	Water ($/mill m^3)	Energy ($/GWh)	Rice (mill m^3)	Wheat (mill m^3)	Rice	Wheat	Manuf.	Rice	Wheat
2007	−0.02	15.54	−0.24	−0.02	−20.43	−1.45	−14.98	−1.45	172.9	−15.88	−2.96
2012	−0.05	16.02	−0.25	−0.01	−23.69	−1.58	−16.98	−1.58	569.5	−17.98	−3.22
2017	−0.11	10.86	−0.24	−0.01	−22.29	−1.35	−15.40	−1.35	3051.6	−16.32	−2.74
2022	−0.16	4.81	−0.22	0.00	−18.16	−0.98	−12.00	−0.98	17,357.9	−12.72	−1.99
2027	−0.19	1.38	−0.21	0.00	−14.69	−0.72	−9.33	−0.72	54,439.3	−9.91	−1.47
2032	−0.21	−0.49	−0.20	0.00	−12.21	−0.56	−7.51	−0.56	104,788.1	−7.98	−1.14
2037	−0.21	−1.58	−0.20	0.00	−10.39	−0.45	−6.22	−0.45	150,460.5	−6.61	−0.92

Table 5. Percent Difference in the Level of Macroeconomic Variables (No-Subsidy Relative to Subsidy Scenarios)

	GDP			Investment		Services		ROI		
Year	India	Punjab	ROI	Capital	Interest	Price	Output	Manuf.	Rice	Wheat
2007	−0.022	15.536	−0.244	0.000	0.014	−0.018	−0.122	−0.746	0.076	0.096
2012	−0.049	16.022	−0.253	0.045	0.010	−0.012	−0.123	−0.690	0.052	0.065
2017	−0.107	10.861	−0.240	0.078	0.005	−0.007	−0.124	−0.587	0.029	0.036
2022	−0.163	4.812	−0.222	0.090	0.003	−0.004	−0.125	−0.491	0.017	0.021
2027	−0.192	1.375	−0.210	0.089	0.003	−0.003	−0.125	−0.434	0.014	0.018
2032	−0.206	−0.490	−0.203	0.081	0.003	−0.004	−0.123	−0.399	0.017	0.021
2037	−0.212	−1.583	−0.198	0.073	0.004	−0.005	−0.121	−0.377	0.021	0.026

to pay for an additional unit of water. Also, given that p_h embeds the cost of capital, electricity and aquifer rent, it represents the unit gross value of water in agricultural production.

Let $P^h(t)$ represent the shadow "stock price" of water — the amount a farmer would pay to own the water and let $P^z(t)$ represent the purchase price (not rental rate) of land. Given the natural asset stocks Z and $\bar{H}$, the total value of physical and natural asset holdings, denoted $A(t)$ is expressed as

$$A(t) = K(t) + P^z(t)Z + P^h(t)\bar{H}(t).$$

Earlier, we noted $\bar{H}(t)$ represents the period t stock of water. In the empirical application, $\bar{H}$ is the "economically accessible" stock of water, which is defined as $S(t) = H_0 - \int_0^t Y_h(t)dt$, where $H_0 = \int_0^T Y_h(t)dt$, with T being some period sufficiently in the future: In the empirical model used here, $T = 300$.

Assume the natural and physical asset markets are not segmented, and that arbitraging occurs for both types of assets. In such a case, Roe *et al.* (2010) derive the following no-arbitrage condition between r^k and land rents:

$$r^k = \frac{\Pi^a}{P^z} + \frac{\dot{P}^z}{P^z},$$

where $\Pi^a(\cdot, t)$ is time-t agricultural land rent. Smith (2013) derives the following no-arbitrage condition between r^k and the water rent, here interpreted as the gross value of water in agricultural production:

$$r^k = \frac{p_h}{P^h} + \frac{\dot{P}^h}{P^h} + \frac{\dot{\bar{H}}}{\bar{H}}.$$

In this case, if arbitrage conditions hold across natural and physical assets, the time t unit stock price of land is given by

$$P^z(t) = \int_t^\infty e^{-\int_t^\vartheta [r^k(v)-\delta]dv}\Pi^a(\cdot, t)dt.$$

Here, $\Pi^a(\cdot, t) = \sum_{j=1}^2 \sum_{i=1}^3 \Pi^{aij}(\cdot)$ is the total land rent for India (Punjab and ROI, rice, wheat and other agricultural land rent). The time-t unit stock price of water is given by

$$P^h(t) = \int_t^\infty e^{-\int_t^\vartheta [r^k(v)-\delta-\frac{\dot{\bar{H}}}{\bar{H}}]dv} p_h(t)dt.$$

Here, the expression $\frac{\dot{\bar{H}}}{\bar{H}}$, captures the impact of a declining aquifer on its stock price. If negative, then the effective discount rate

$$e^{-\int_t^\vartheta [r^k(v)-\delta-\frac{\dot{\bar{H}}}{\bar{H}}]dv} \qquad (*)$$

Table 6. Stock Value of Land and Shadow Value of Water

	(US$ per million m^3)			(million US$)		Stock of	Stock
Year	"Correct"	No "Depreciation"	Traditional	"Correct"	Traditional	Water (million m^3)	Value of Water
2007	23.0	26.1	5.0	984,476.6	678,755.1	3,678,979	84,553,186
2017	32.0	35.0	10.9	898,900.1	593,479.1	3,448,035	110,390,982
2027	38.8	41.7	18.0	835,666.5	527,967.3	3,321,135	128,798,482
2037	43.0	46.1	21.8	788,964.2	479,499.9	3,220,695	138,547,966
2047	45.6	48.9	24.0	753,956.6	443,168.3	3,126,346	142,491,368
2057	47.4	51.1	25.4	727,383.8	415,596.5	3,033,757	143,732,862
2067	48.6	52.7	26.3	706,989.6	394,452.1	2,941,161	142,890,262
2077	49.4	53.8	27.0	691,183.5	378,085.8	2,847,743	140,725,464
2087	50.0	54.7	27.5	678,825.6	365,314.9	2,753,117	137,658,951
2097	50.4	55.4	27.9	669,086.0	355,279.7	2,657,142	133,830,894
2107	50.6	55.9	28.1	661,349.1	347,348.1	2,559,790	129,442,077

increases, reflecting the loss in value associated with aquifer depreciation. This effect, of course, places a downward pressure on the value of the aquifer.

Table 6 presents the unit (shadow) stock water prices, the corresponding wealth value of water and the stock value of land. Three unit (shadow) stock prices are presented for water. The "correct" unit price is calculated using the discount factor in Eq. ($*$), the "no depreciation" unit price is calculated with the $\frac{\dot{H}}{H}$ term dropped from the discount factor in ($*$), and the "traditional" unit price is calculated using the standard rental rate divided by the interest rate (earnings/price ratio).

Table 6 reveals two significant empirical results. First, when ignoring the price effect of declining groundwater stocks, the "no depreciation" model overestimates groundwater stock values by 8% to 20%. The traditional pricing model underestimates the stock values by 44% to 80%. Similar results are obtained for land rental values. Second, although unit water rental and stock prices increase over time, the rate of change in these values is smaller than the rate at which the groundwater stock declines. The result is, eventually, the Punjab's "wealth" attributed to its water stocks fall. The stock of capital falls, also, as the falling level of water used each period decreases the productivity of capital and labor in agriculture, thus, hampering Punjabi agriculture's ability to compete for capital and labor. Hence, Punjab wealth, as measured by the stock value of physical and natural capital eventually falls over time. The result of relying on the increasingly scarce water resource.

The other point to make is, deriving the "correct" unit stock value of water ***requires*** exploiting a no-arbitrage condition derived from macroeconomic

Table 7. Percent Difference in Stock Values of Water and Land: $(\frac{\text{no subsidy}}{\text{subsidy}} - 1) \times 100$

	(US$ per million m^3)			(million US$)		Stock of Water (million m^3)	
Year	"Correct"	No "Depreciation"	Traditional	"Correct"	Traditional	Stock of Water	Stock Value of Water
2007	38.599	35.273	167.539	−0.533	−0.641	−4.986	31.688
2017	19.679	19.019	75.032	−0.367	−0.676	−3.729	15.217
2027	11.064	11.377	25.689	−0.228	−0.389	−3.825	6.815
2037	6.942	7.588	13.594	−0.158	−0.251	−4.127	2.529
2047	4.744	5.453	8.845	−0.117	−0.179	−4.408	0.127
2057	3.283	3.979	6.329	−0.090	−0.133	−4.689	−1.559
2067	2.310	3.026	4.755	−0.069	−0.102	−4.982	−2.787
2077	1.586	2.371	3.669	−0.054	−0.078	−5.292	−3.790
2087	1.000	1.858	2.875	−0.042	−0.060	−5.622	−4.679
2097	0.539	1.470	2.272	−0.032	−0.046	−5.973	−5.466
2107	0.164	1.170	1.804	−0.025	−0.035	−6.344	−6.191

conditions and variables. It follows that, attempting to calculate the stock value of a natural asset in a (static or dynamic) partial equilibrium setting can lead to potentially biased — or seriously biased unit stock price estimates.

Table 7 shows the percent difference in the unit stock prices of land and stock shadow price of water when removing the electricity subsidy. As with the flow rental values, the unit stock shadow price of water is higher when the subsidy is removed — reflecting the fact that without the subsidy, water is more expensive to extract, the farmer uses less of it, and hence, is more dear to the farmer. Although not shown here, eventually the "correct" no-subsidy stock price of water becomes slightly lower than the corresponding price with the electricity subsidy. The economics of the no-subsidy scenario are quite similar to those in the base line model, and we leave it to the reader to ferret out the similarities.

7. Conclusion

This study develops an empirical methodology for uncovering the flow and stock value of an ecosystem service in an economy-wide setting. The methodology is also designed to evaluate the impact of economic activity and policy (here, electricity subsidies used in groundwater extraction) on natural resource dynamics. The underlying theory takes as its point of departure Roe *et al.* (2010) and Smith (2013), and integrates groundwater dynamics with policy decision making and economic dynamics. The empirical results suggest Punjab agricultural policy and corresponding groundwater dynamics have (slight) economy-wide implications, and significant implications for Punjab. We construct, and fit to data, a dynamic general equilibrium model in which Punjab aquifer hydrology dynamics and capital accumulation across India are endogenous. The analytical framework that follows from the theory and empirics is used to evaluate the effects, over time, of groundwater resource management in Punjab and the potential spillovers on the broader Indian Economy. The model predicts Punjabi aquifer depletion (with or without electricity subsidies) will be accompanied by increased extraction costs — or equivalently, lower levels of groundwater pumped — which eventually lessens Punjabi agriculture's ability to compete for capital and labor. These forces lead to adjustments in both the Punjab and national economy — basically, the Punjab region garners a smaller share of total resources as its groundwater tables fall.

As Punjab food grain production falls, regional food marketing, food processing and ancillary economic activities will likely face problems holding on to labor, with the region as a whole facing the possible out-migration of workers. In recent years, India has been an exporter of wheat and rice, the foreign exchange earnings of which have been used to pay for the imports of machinery and other industrial goods. These goods help the economy to increase the productivity of labor and foster growth in per capita income. The decline in wheat and rice production as the aquifers in the Punjab region are depleted will cause the country to risk the loss of this source of foreign exchange earnings although the projected decline in irrigated crop production in Punjab alone appears not to be significant enough to jeopardize the national economy.

The analysis here merges two disparate literatures: (i) studies using dynamic partial equilibrium models to understand groundwater dynamics and the impact different policy instruments can have on transition dynamics and steady-state levels of groundwater tables and (ii) static, computable, general equilibrium models that examine the equilibrium outcome of water policy on the agricultural sector and whether such policy can have an appreciable impact on aggregate or regional income. The first set of studies suffer from problems like factor prices being constant over time, while the second set of studies suffer from the fact that a static model is invoked to analyze a dynamic question. These models are also not designed to measure the stock value of a natural resource, as neither approach accommodates the requisite no-arbitrage condition. The model presented here links groundwater dynamics (ecosystem services of water) with economic dynamics (capital accumulation), and avoids the pitfalls inherent in the prior studies. More importantly, the no-arbitrage condition is a natural element of the theory and easily accommodated in the empirical methodology.

Our analysis suggests that understanding the fundamental economic issues of groundwater use requires developing a deep understanding of the direct and indirect economic impacts of resource (e.g., water and electricity) linking the irrigated to other sectors of the economy since they compete for economy-wide resources (e.g., labor and capital) and benefit from intermediate resource linkages. Given the current policy of subsidizing electricity to farmers, the analysis focuses on economic and natural resource (ecosystem service) consequences assuming the policy continues and then, examines the potential gains and distribution of those gains if the policy were terminated.

The results suggest once and for all elimination of the subsidy would have undesirable impacts on Punjabi agriculture in that higher electricity costs would likely make energy costs too high for many farmers, driving them out of grain production. The model presented here, provides a point of departure for examining a host of policy and economic/natural resource management issues. For instance, with groundwater, what impact would a more efficient pumping technology have on Punjabi transition dynamics? Is there an optimal way to gradually decrease the level of electricity subsidies? What are the aggregate economic benefits of policies that subsidize adoption of water saving technologies or less water consuming crops? Recognizing environmental concerns for present and future generations, the current study provides a sound basis to evaluate the human activities within sustainability constraints of environmental and economic systems and to formulate more efficient water management options.

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Appendix A. The Mathematical Model

In what follows, let i index final goods, with $i = a1, a2, a3$ representing rice, wheat and other agriculture respectively and with $i = m, s, \varepsilon$ representing manufacturing, services and electricity. Similarly, let j index region with $j = 1$ representing Punjab and $j = 2$ representing the ROI (and all-of-India for the service sector).

The economy is endowed with four factor categories: Capital, labor, land and Punjabi water, denoted K, L, Z and $\bar{\boldsymbol{H}}$, respectively. Of course, the ROI has a water endowment, but is ignored in the analysis below.[10] Letting t represent time, the stock of capital and Punjabi water — $K(t)$ and $\bar{\boldsymbol{H}}(\boldsymbol{t})$ — evolves over time, but the stock of land and labor is constant. The constant labor assumption has one major impact on the empirical results generated by the model: In general, relative to the case where the labor force increases over time, the productivity of capital, land and water over time will be lower. An indirect effect of the constant labor force assumption is (relative to a model with labor force growth) the rate of capital accumulation will be slightly slower and the shadow value of land and water will be slightly lower.

In a small open economy model, the price of traded goods is exogenous, while non-traded good prices are endogenous. The traded goods are rice, wheat, other agriculture and manufacturing while the non-traded goods are services and Punjabi electricity. Denote the endogenous time-t service good price by $p_s(t)$ and the electricity price by $p_\varepsilon(t)$. Any excess supply or demand of the manufactured good trades in international markets at the price p_m, while rice, wheat and other agriculture are traded at respective international prices p_{a1}, p_{a2} and p_{a3}. The agricultural, electricity and service goods are pure consumption goods, while the manufactured good is consumed or saved (augments the capital stock).

Labor services are not traded internationally and domestic residents own the entire stock of domestic assets. Firms in all sectors hire both labor and capital and both factors are mobile across all sectors and regions. Labor earns a time-t wage rate of $w(t)$, while capital earns a rate of return on capital of $r(t)$. Land is region specific, as is Punjab water and electricity. Assume a land rental market among farmers exist in each region, and that land is rented in or out at rate $\varpi_{z,i}$ per acre, $i = 1, 2$. A discussion of water rent and electricity price follows shortly.

The economy uses its factor endowments to produce final goods, with the time-t level of a final good represented by Y_{ij} (t). Thus, we denote the level of Punjab rice produced by $Y_{a11}(t)$, the level of Punjab manufacturing produced by $Y_{m1}(t)$, the level of ROI manufacturing by $Y_{m2}(t)$ and the level of services by $Y_{s2}(t)$. Similarly, sector capital and labor demand is denoted as K_{ij} (t) and L_{ij} (t).

A.1. *Firm behavior — ROI*

Modeling the ROI manufacturing and service sectors is relatively straightforward. Represent the ROI manufacturing and service technology by the production function

$$Y_{i2}(t) = F^{i2}(K_{i2}(t), L_{i2}(t)),$$

[10]This is akin to embedding the ROIs' water contribution to its agricultural land rent and embedding the ROIs' energy contribution in manufacturing and service sector's measure of factor productivity.

where Y_{i2} is ROI manufacturing or all-of-India service output, and K_{i2} and L_{i2} are the corresponding levels of capital and labor employed by the sector, $i = m, s$.[11] Assume the technology $F^{i2} : \mathbb{R}^2_+ \rightarrow \mathbb{R}_+$ satisfies the following *regularity conditions*: It is everywhere continuous and twice differentiable, linearly homogeneous, non-decreasing and strictly concave in inputs and satisfies the Inada conditions. The cost function corresponding to $F^{i2}(\cdot)$ is given by

$$C^{i2}(r^k, w)Y_{i2} \equiv \min_{K_{i2}, L_{i2}} \{r^k K_{i2} + wL_{i2}\colon Y_{i2} \leq F^{i2}(K_{i2}, L_{i2})\}, \quad i = m, s.$$

Here, $r^k(t) = r(t) + \delta$, where δ represents the rate of capital depreciation. Given the properties of $F^{i2}(\cdot)$, the corresponding cost function is linearly homogeneous, concave, differentiable and non-decreasing in input prices, and satisfies Shepard's lemma.[12]

ROI agricultural production is governed by the technology

$$Y_{ai2}(t) = F^{ai2}(K_{ai2}(t), L_{ai2}(t), Z_{i2}),$$

where Z_{i2} is the time invariant amount of land used in producing agricultural good-ai, $i = 1, 2, 3$. The land rent earned by ROI agriculture's sector specific resource Zi_2 is given by the value-added function

$$\begin{aligned}\Pi^{ai2}(p_{ai}, r^k, w, Z_{i2}) &\equiv \max_{K_{ai2}, L_{ai2}} \{p_{ai} F^{ai2}(K_{ai2}, L_{ai2}, Z_{i2}) - r^k K_{ai2} - wL_{ai2}\} \\ &= \pi^{ai2}(p_{ai}, r^k, w)Z_{i2}.\end{aligned}$$

The regularity conditions imposed on $F^{ai2}(\cdot)$ ensure the value-added function is non-decreasing in p_a, non-increasing in w and r^k, homogeneous of degree one and differentiable in input and output prices, convex in input and output prices and satisfies Hotelling's lemma. Here, $\pi^{ai2}(p_{ai}, r^k, w)$ is the rental rate per unit of land per worker required for the rental market among farmers to clear. Assuming differentiability, by Hotelling's lemma the gradients of the value-added yield the sector's partial equilibrium agricultural supply and the derived demands for capital and labor, e.g.,

$$Y^{ai2}(p_{ai}, r^k, w)Z_{i2} = \frac{\partial}{\partial p_{ai}} \pi^{ai2}(p_{ai}, r^k, w)Z_{i2}.$$

[11]In the remainder of this text, we will refrain from explicitly defining subsequent introductions of sector factor demands.

[12]To conserve on space, we assume all production functions satisfy the *regularity conditions* listed above, and cost functions are linearly homogeneous, concave, differentiable and non-decreasing in input prices and satisfies Shepard's lemma.

A.2. *Firm behavior — Punjab manufacturing*

Manufacturing in the Punjab region combines capital and labor with electricity to produce its output, while agriculture combines capital, labor and land with groundwater to produce its three outputs. Furthermore, pumping groundwater to the surface requires the services of capital, labor and electricity. There are several ways to model Punjab's manufacturing and agricultural technologies — our approach is to assume electricity enters manufacturing and groundwater extraction in a Leontief fashion. More explicitly, we represent Punjab's manufacturing technology by the production relation

$$Y_{m1} = \min_{K_{m1}, L_{m1}, Y_{\varepsilon m}} \left\{ F^{m1}(K_{m1}, L_{m1}), \frac{Y_{\varepsilon m}}{\sigma_\varepsilon} \right\}, \tag{A.1}$$

where $Y_{\varepsilon m}(t)$ is the amount of electricity the manufacturing sector demands and σ_ε is the input–output coefficient for electricity used in producing manufactures. As with the ROI manufacturing, given $F^{m1}(\cdot)$ satisfies the regularity conditions, the production structure in (1) does also. The cost function corresponding to (1) is

$$C^{m1}(r^k, w, p_\varepsilon)Y_{m1} = [c^{m1}(r^k, w) + p_\varepsilon(t)\sigma_\varepsilon]Y_{m1},$$

where

$$c^{m1}(r^k, w)Y_{m1} \equiv \min_{K_{i2}, L_{i2}} \{r^k K_{i2} + wL_{i2}\colon Y_{i2} \leq F^{i2}(K_{i2}, L_{i2})\}.$$

A.3. *Firm behavior — Punjab agriculture and groundwater extraction*

Punjab agriculture combines capital, labor, land and water to produce rice, wheat and "other agriculture." Rice and wheat use both groundwater and precipitation, while other agriculture uses only precipitation. Groundwater extraction uses capital, labor and electricity to extract the services of the great Punjabi aquifer.

Represent Punjab agricultural production by

$$Y_{ai1} = \min_{K_{ai1}, L_{ai1}, Y_{\varepsilon ai1}} \left\{ F^{ai1}(K_{ai1}, L_{ai1}, Z_1), \frac{Y_{hi}}{\sigma_{hi}} \right\}, \quad i = 1, 2, 3. \tag{A.2}$$

Here, $Y_{hi}(t)$ is the amount of water used in producing good $ai1$, where, "water" refers to both rainfall and groundwater, and σ_{hi} is the input–output ratio for water and agricultural good i. Let Y_{hgi} denote the amount of water derived from groundwater sources and let $Y_{h\varrho i}$ denote the amount of water derived directly from precipitation.[13]

[13]Anecdotal evidence suggests other agriculture, good-$a3$, does not rely on groundwater, hence, $Y_{hg3} = 0$.

If the amount of rice produced is equal to Y_{a11}, then the total amount of water demanded is equal to $\sigma_{h1} Y_{a11}$. If the amount of precipitation received during rice production is equal to $Y_{h\varrho 1}$, then the total amount of groundwater to pump for rice production is $\sigma_h Y_{a11} - Y_{h\varrho 1i}$.

Let $p_h(t)$ represent the time-t unit (possibly shadow) price of groundwater. Then, the value-added or rent/profit earned by the farmer on agricultural output-*ai* is

$$p_{ai} F^{ai1}(K_{ai1}, L_{ai1}, Z_{i1}) - r^k K_{ai1} - wL_{ai1} - p_h(\sigma_{hi} Y_{ai1} - Y_{h\varrho i}),$$

which yields the value-added function

$$\Pi^{ai1}(p_{vi}, r^k, w, p_h, Z_{i1}, Y_{h\varrho i}) = \pi^{ai1}(p_{vi}, r^k, w) Z_{i1} + p_h Y_{h\varrho i}$$

and

$$\pi^{ai1}(p_{vi}, r^k, w) Z_{i1} \equiv \max_{K_{ai1}, L_{ai1}} \{p_{vi} F^{ai1}(K_{ai1}, L_{ai1}, Z_{i1}) - r^k K_{ai1} - wL_{ai1}\},$$

where $p_{vi}(t) = p_{ai} - \sigma_{hi} p_h(t)$ is the value-added price of agricultural good-*ai*. As with $\pi^{ai2}(\cdot)Z_{i1}$, the function $\pi^{ai1}(\cdot)Z_{i1}$ is non-decreasing in p_{ai}, non-increasing in w and r^k, homogeneous of degree one and differentiable in input and output prices, convex in input and output prices and satisfies Hotelling's lemma. Also, $\pi^{ai1}(\cdot)$ is the rental rate per unit of land per worker required for the land rental market among farmers to clear. Observe the value-added function for Punjab crop-*i* includes the rent to precipitation, $p_h Y_{h\varrho i}$ — a pure rent that accrues to the farmer.

The last issue to address with production is groundwater extraction. Groundwater extraction requires capital, labor, electricity and groundwater. Represent the groundwater extraction technology by

$$Y_h = \min_{K_h, L_h, Y_{\varepsilon h}} \left\{ F^h(K_h, L_h, A), \frac{Y_{\varepsilon h}}{\kappa D} \right\}. \tag{A.3}$$

Here, $Y_h = Y_{hg1} + Y_{hg2} + Y_{hg3}$ is the amount of water moved from the aquifer to the field, $D(t)$ is groundwater table depth and σ_h and $\sigma_{\varepsilon h}$ are the input–output coefficients for aquifer water and electricity. The scalar A represents the fixed aquifer upon which the groundwater is drawn, while the scalar κ is a pumping parameter discussed later. While each input–output coefficient encountered thus far is assumed constant, the input–output coefficient for electricity is not, and is related to how far below the surface the aquifer water is. The deeper the water table, the more electricity it takes to pull a unit of water to the surface. At this point, we simply note the groundwater extraction function's input–output coefficient for electricity is given by $\kappa D > 0$.

Given (A.3) and κD, the aquifer rent function is given by

$$\pi^h(p_{vh}(D), r^k, w)A \equiv \max_{K_h, L_h}\{p_{vh}(D)F^h(K_h, L_h, A) - r^k K_h - wL_h\},$$

where $p_{vh}(D(t)) = p_h(t) - \kappa D(t)p_\varepsilon(t)$ is the value-added price of groundwater (i.e., unit value of water in agricultural production less unit electricity cost of moving that water to the surface). The properties of $\pi^h(\cdot)A$ are identical to the value-added functions introduced above.

A.4. *Groundwater dynamics*

The depth of the aquifer water table decreases as farmers extract groundwater, and increases with precipitation and other sources of aquifer recharge. Represent groundwater table evolution as

$$\dot{D}(t) = g(Y_h(t), \mathrm{Rain}(t)),$$

where *Rain* is precipitation during period t. The function $g(\cdot)$ is increasing (groundwater table gets lower) with groundwater extraction and is decreasing in precipitation. We provide more details on the equation of motion for groundwater in the data section below.

A.5. *Household preferences*

At each instant in time, households provide labor services in exchange for a wage $w(t)$ and earn income on capital assets at rate $r^k(t)$ per unit of the asset. Households also earn rent on Punjab and ROI land and on the Punjab aquifer. Income is used to purchase final goods and services and save for future consumption. Let $Q_j(t)$ represent the level of final good j, $j = a1, a2, a3, m$, s and represent household preferences by the time-separable utility function

$$\int_0^\infty \frac{U(Q_{a1}(t), Q_{a2}(t), Q_{a3}(t), Q_m(t), Q_s(t))^{1-\theta}}{1-\theta} e^{-\rho t}dt.$$

We assume the felicity function $U(\cdot)$ is homothetic, everywhere continuous and twice continuously differentiable, non-decreasing and strictly concave in each argument. The parameter $\rho > 0$ is the rate of time preference and $\theta > 0$ is the inverse of the elasticity of inter-temporal substitution. In the empirical application that follows, we use the standard representation of felicity — the Cobb–Douglas function

$$U(Q_{a1}, Q_{a2}, Q_{a3}, Q_m, Q_s) = (Q_{a1})^{\lambda_{a1}}(Q_{a2})^{\lambda_{a2}}(Q_{a3})^{\lambda_{a3}}(Q_m)^{\lambda_m}(Q_s)^{\lambda_s},$$

where λ_j is the share of expenditures spent on good j and $\sum_j \lambda_j = 1$.

Let Q represent an index of household consumption (i.e., utility). Then given homothetic preferences, household expenditure at an instant in time is defined as

$$E(p_{a1}, p_{a2}, p_{a3}, p_m, p_s)Q = \min_{Q_j}\left\{\sum_j p_j Q_j : Q \le U(Q_{a1}, Q_{a2}, Q_{a3}, Q_m, Q_s)\right\}.$$

Here, the expenditure function, $E(\cdot)Q$, is the minimum cost of achieving Q. Given the properties of $U(\cdot)$ the expenditure function is linearly homogeneous, concave, differentiable, and non-decreasing in prices, and satisfies Shepard's lemma.

Suppressing the time and function arguments, the household's *flow budget constraint* is given by

$$\dot{K} = (r^k - \delta)K + wL + \pi^h(\cdot)A + \sum_{j=1}^{2}\sum_{i=1}^{3}\Pi^{aij}(\cdot) - E(\cdot)Q,$$

where δ is the rate of capital depreciation. The flow budget constraint tells us households earn income from wages (wL), capital rent ($r^k K$) and natural resource rent (the various Π^{aij}). With this income, they purchase goods and services, with the value of those purchases equal to $E(\cdot)Q$.

The household's problem is to choose the sequence of consumption levels $\{Q(t)\}_{t\in[0,\infty)}$ to maximize

$$\int_0^\infty \frac{Q(t)^{1-\theta} - 1}{1-\theta} e^{-\rho t} dt,$$

subject to initial conditions, $K(0),\ D(0)$, the flow budget constraint at each t and the transversality condition on borrowing

$$\lim_{t\to\infty}\{K(t)e^{-\int_0^t r(v)dv}\} = 0.$$

We assume agents behave myopically with respect to groundwater extraction and hence, groundwater depth does not factor directly into the household's optimizing behavior. The implication here is, although the groundwater table impacts the farmer (the deeper the table level, the more expensive it is to bring a unit of water to the surface), we do not assign a costate variable to the differential equation governing its dynamics. The present-value Hamiltonian for this problem — normalized in labor efficiency units — is[14]

$$\Delta = \frac{q^{1-\theta} - 1}{1-\theta} e^{-\rho t} + \xi \left[(r^k - \delta)k + w + \pi^h(\cdot)a + \sum_{j=1}^{2} \sum_{i=1}^{3} \Pi^{aij}(\cdot) - E(\cdot)q \right],$$

where the co-state variable $\xi(t)$ is the present value shadow price of capital. The lower case variables are defined as:

$$q(t) = \frac{Q(t)}{L}, \quad k(t) = \frac{K(t)}{L}, \quad z_{i1}(t) = \frac{Z_{ij}(t)}{L}, \quad y_{h\varrho i}(t) = \frac{Y_{h\varrho i}(t)}{L}, \quad a(t) = \frac{A}{L}.$$

The Euler condition for this problem is

$$\frac{\dot{q}}{\hat{q}} = \frac{1}{\theta}\left[r - \rho - \lambda_s \frac{\dot{p}_s}{p_s} \right],$$

where $\lambda_s = \frac{\partial E(\cdot)q}{\partial p_s} p_s / E(\cdot)q$ is the share of income spent on the non-traded service good.

A.6. *Equilibrium*

We next define a competitive equilibrium using the cost, revenue and expenditure functions introduced above, along with the groundwater dynamics and household's consumption and savings behavior.

Given: (i) firm technologies, household preferences, (ii) exogenous traded good prices, $(p_{a1}, p_{a2}, p_{a3}, p_m)$, (iii) initial service price, energy price, groundwater price, $(p_\varepsilon(0), p_h(0), p_s(0))$, (iv) labor force endowment, initial capital stock and groundwater depth levels $(L, K(0), D(0))$. Then a competitive equilibrium is a trajectory of: (i) endogenous output and factor prices and (ii) capital stock and groundwater depth levels

$$\{p_\varepsilon(t), p_h(t), p_s(t), w(t), r^k(t), K(t), D(t)\}_{t\in[0,\infty)},$$

such that:

(1) Firms maximize profit.

[14]Note, there is no costate variable associated with groundwater dynamics. Myopic behavior here implies, farmers do not consider the impact water withdrawals today have on future groundwater table levels and the corresponding extraction costs. As such, the absence of a costate variable for groundwater. Myopic behavior of Punjab farmers, however, does not imply the shadow rental rate of groundwater is zero — even if electricity is free: When extracting groundwater farmers need capital and labor (please see Eq. (A.3) on page 19 of the Appendix) and hence, face capital rental and labor costs.

(2) Households maximize utility.
(3) The capital, labor and Punjab electricity and water markets clear.
(4) The service good market clears.

The reader is directed to Smith (2013) for a guide to deriving a mathematical characterization of the equilibrium.

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