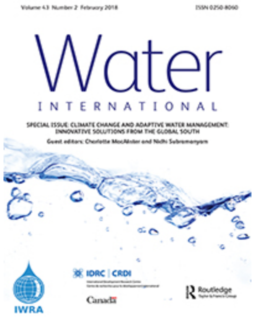

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RESEARCH ARTICLE

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Assessing the economic impact of a low-cost water-saving irrigation technology in Indian Punjab: the tensiometer

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ABSTRACT

This article assesses the impact of the tensiometer on the consumption of groundwater and electric power in paddy cultivation in Indian Punjab, and its subsequent economic benefits. We find that compared to the continuous flooding method, the tensiometer-based application of irrigation reduces water and power consumption by 13%, cutting variable costs by 7% without any yield penalty. If 30% of the paddy area is irrigated following tensiometer-based schedules, then the state could save a total of 0.67 million ha m of water and 1516 million kWh of electric power in 2010–2025, with aggregate economic benefits of US$ 459 million.

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Irrigation scheduling; tensiometer; groundwater conservation; electricity consumption; paddy; economic impact; Punjab; India

Introduction

Over the past five decades, Indian agriculture has undergone significant transformation and experienced remarkable progress, making the country food-sufficient. The adoption of high-yielding seeds, chemical fertilizers, and pesticides on a large scale, coupled with investments in irrigation, infrastructure and markets, have played a key role in this transformation. However, this process has been accompanied by the degradation of natural resources such as land and water. Intensive cultivation has increased farmers' dependence on groundwater for irrigation, especially in the north-western states of Punjab and Haryana, and parts of Uttar Pradesh (Chand, 1999; Mukherjee, 2007; Singh, 2004). The excessive dependence on groundwater has led to its over-extraction, thereby threatening the sustainable development of agriculture (Gandhi & Namboodiri, 2009; Government of Punjab, 2014; Sato, 2010; Sidhu, Vatta, & Dhaliwal, 2010; Singh, 2009).

The over-exploitation of groundwater has been caused by a number of economic and non-economic factors. In the quest to ensure food security, agri-food policy has emphasized the cultivation of staple food crops such as paddy and wheat by providing farmers with incentives like subsidies on fertilizers, electricity, and diesel for irrigation. The policy has also assured the offtake of these commodities at government-

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administered minimum support prices. These agri-food policies and subsidies have encouraged farmers, especially those in irrigated regions, to shift their production portfolio from traditional water-efficient but less remunerative crops such as coarse cereals, pulses and oilseeds towards water-intensive but more remunerative and less risky crops like paddy (Shah, 2012; Vatta, Sidhu, & Kaur, 2013).

Policy makers are well aware of the consequences of over-extraction of groundwater and the need for reversing it through policy reforms in the irrigation and power sectors. For instance, the government of Punjab enacted the Punjab Preservation of Subsoil Water Act in 2009, which prohibits the transplantation of paddy in drier months to regulate groundwater extraction in the state. Available evidence shows that this regulation has been able to arrest the pace of groundwater depletion. Using time-series data from 1985 to 2011, Tripathi, Mishra, and Verma (2016) found an annual improvement of 0.2 cm in the groundwater table after implementation of the act, despite an increase in the area under paddy cultivation. This regulation has also induced the adoption of water-saving technologies and practices, such as laser land levelling and sensor-based application of irrigation (Aryal, Bhatia-Mehrotra, Jat, & Sidhu, 2015; Chahal, Kataria, Abbott, & Gill, 2014; Sidhu & Vatta, 2012). However, state-sponsored tariff-free electric power for agriculture for the past two decades, and the lack of political will to introduce volumetric pricing of irrigation water, are some of the major obstacles to the efforts to reverse groundwater depletion in the state (Shah, 2009, 2012).

Given the political economy of irrigation management in the state, policy makers are seeking technological and institutional solutions that minimize stress on groundwater resources without adverse effects on farm profitability. One such option is the application of soil-moisture-sensor-based scheduling of irrigation using devices like tensiometers. A tensiometer is a simple device that measures the amount of energy required by the plant to pull soil water (water potential) at the current moisture level and guides farmers on when to irrigate. Several studies based on experimental data have reported that the use of tensiometers is a technically feasible option for efficient management of groundwater resources without any yield penalty (Bhatt, Arora, & Chew, 2016; Bhatt & Sharma, 2010; Buttaro et al., 2015; Hodnett, Bell, Ah Koon, Soopramanien, & Batchelor, 1990; Kukal, Hira, & Sidhu, 2005; World Bank, 2010). According to Bhatt et al. (2016), tensiometer-based irrigation application in paddy cultivation in Punjab could save 14–15% of water consumption, thus saving 170–250 kWh of electric power per hectare per season.

The use of tensiometers for irrigation scheduling has been long known, but its application in Indian agriculture is relatively new. Scientists from the Punjab Agricultural University, Ludhiana, modified and developed a low-cost tensiometer,[1] which is being promoted for irrigation scheduling in paddy fields in Punjab (Vatta, Sidhu, & Kaur, 2014). In this article, we assess the technical feasibility of this technology in terms of savings in irrigation water consumption and electric power used to pump groundwater, as well as the associated economic benefits from its wider adoption by farmers in the state of Punjab. We also identify some of the important factors that may influence adoption or non-adoption of this tensiometer, and make a few recommendations to promote its wider adoption.

The article is organized as follows. The next section provides an overview of water and energy use in agriculture in Punjab. The third section provides some background on the development of a low-cost tensiometer, and the efforts being made to promote it in the state. This section also discusses the data used to assess the technical and economic feasibility of tensiometer-based irrigation scheduling, and subsequently projects the economic benefits of its wider adoption. The methods for assessing the impacts of the adoption of tensiometer-based irrigation are discussed in the fourth section, and the fifth section discusses the results of the impact analysis. The last section concludes and discusses the implications of the findings.

An overview of water and energy use in Punjab agriculture

Punjab is one of the leading agricultural states in India. Agriculture and allied activities such as animal husbandry and fisheries contribute 27% to the state's gross domestic product as compared to the national average of 15% (Government of India, 2015). The state has been at the forefront of adoption of modern agricultural technologies and practices. High-yielding varieties of wheat and paddy were introduced in the state in the late 1960s. With assured irrigation and increased use of modern inputs such as chemical fertilizers and pesticides, the adoption of high-yield varieties of these crops led to a significant increase in their productivity. Between 1970–71 and 2014–15, the yield of both wheat and paddy more than doubled. The state shares only 3% of the country's net sown area (4.2 million ha) but contributes 12% to national food grain production, and one-fourth to the wheat and 41% to the paddy procurement by the government of India for public distribution and buffer stocking (Government of India, 2015).

Table 1 traces the key indicators of agricultural development in Punjab. Almost the entire area under agriculture in the state is irrigated and is intensively cultivated, with cropping intensity of 190% and fertilizer use of 460 kg/ha.[2] The average annual rainfall in the state ranges from 250 mm in the south-western region to 1000 mm in the sub-mountainous region or undulating plains (Figure 1). The temperature ranges from −2 °C in winter to over 40 °C in summer.

Groundwater is the main source of irrigation – nearly three-fourths of the total irrigated area in the state is irrigated using groundwater. The dependence on groundwater has increased over time, as reflected in the sharp rise in the number of tube-wells, from 192,000 in 1970–71 to nearly 1.4 million in 2013–14, and the increase in tube-well-irrigated area, from 1.6 million ha to 3 million ha, during the same period (Government of Punjab, 2014).

Table 1. Indicators of intensification of agriculture in Punjab.

Indicator	Initial (year)	Latest (year)
Area under high-yielding varieties of wheat (%)	6 (1967–68)	100 (2013–14)
Area under high-yielding varieties of paddy (%)	35 (1967–68)	100 (2013–14)
Area under high-yielding varieties of maize (%)	5 (1967–68)	96 (2013–14)
Fertilizer use (NPK in kg/ha of net area sown)	12 (1965–66)	413 (2013–14)
Agro-chemical use (technical grade in tonnes)	3200 (1980–81)	8364 (2013–14))
Irrigated area (% of net sown area)	56 (1960–61)	98 (2013–14)
Cropping intensity (%)	126 (1960–61)	190 (2013–14)
Percentage of power-operated tube-wells	47 (1970–71)	87 (2013–14)
Electricity use in agriculture (kWh/ha)	1174 (1967–68)	4878 (2012–13)

Source: Statistical Abstracts of Punjab, various issues.

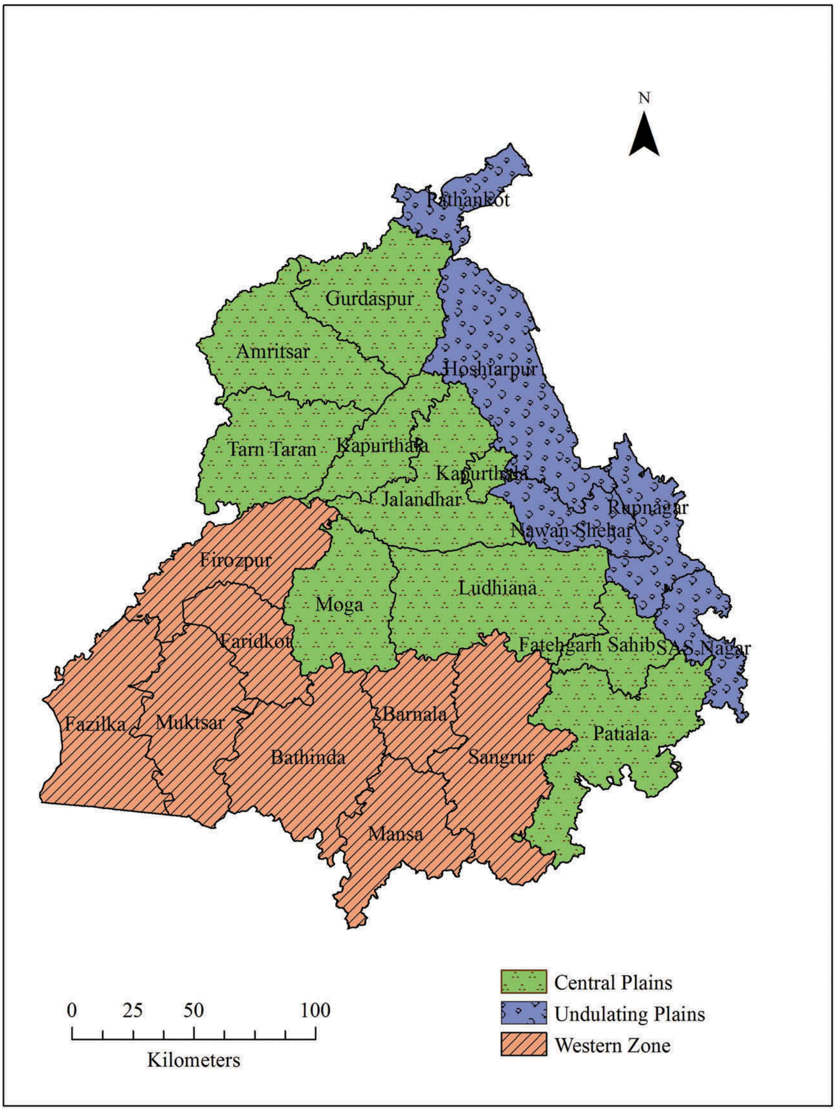

Figure 1. Geographical map of Punjab.

The extensive cultivation of paddy, a water-intensive crop, is one of the main causes of depletion of groundwater in the state. Until the early 1970s, paddy was a minor crop in Punjab, cultivated on about 300,000 hectares. However, the area under paddy has grown significantly and has now reached 2.8 million ha, or about 70% of the cultivated area during the *kharif* or summer season. Cotton (11%) and maize (3%) are the other important crops of this season.

Increased availability of electric power, coupled with the policy of its subsidized or tariff-free provision for agriculture, has resulted in a considerable increase in the number of power-operated tube-wells in the state, leading to over-exploitation of groundwater resources. Figure 2 shows the trend in net groundwater availability in

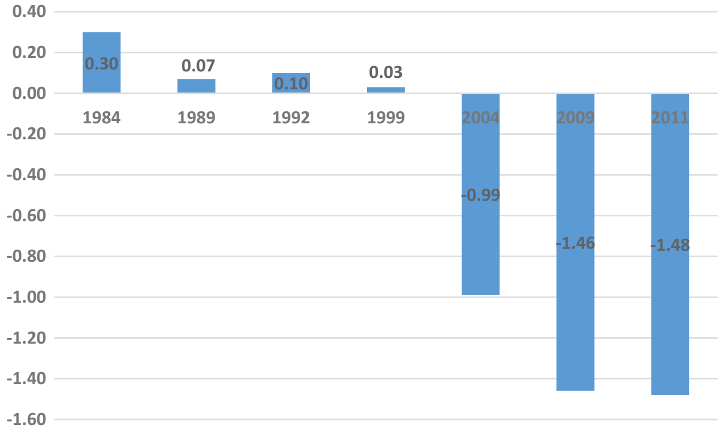

Figure 2. Net groundwater availability in Punjab, 1984–2011 (million ha m).
Source: Central Ground Water Board (2013).

Punjab.[3] Since the late 1990s the demand for groundwater in Punjab has far exceeded its supply, resulting in faster depletion of groundwater. The water table in Punjab registered an average annual decline of 18 cm during 1982–1987; this value increased to 42 cm during 1997–2002, and further to 75 cm during 2002–2006 (Singh, 2009, 2011).[4] A similar picture emerges from an analysis of the trend in the number of over-exploited groundwater blocks in the state (the block is the development unit of a district). The number of blocks experiencing over-exploitation of groundwater has more than doubled, from 53 in 1984 to 110 in 2011 (Table 2). Although the problem of depletion of groundwater is widespread in the state (except in regions which are not fit for irrigation), the central region practising intensive cultivation of paddy and wheat has experienced a faster decline in its water table.

As a result of the pumping of groundwater from a greater depth, the annual electric power consumption in agriculture in the state has more than doubled in the past two decades, from 5105 million kWh in 1990–91 to 10,898 million kWh in 2010–11. Since the supply of electric power to agriculture has been tariff-free or heavily subsidized, the

Table 2. Trends in the exploitation of groundwater resources in Punjab, 1984–2011 (number of blocks).

Degree of exploitation[a]	1984	1989	1999	2004	2011
Over-exploited	53	62	73	103	110
Critical	7	7	11	5	4
Semi-critical	22	20	16	4	2
Safe	36	29	38	25	22
Total number of blocks	118	118	138	137	138

Source: Central Ground Water Board (2013).

[a] An *over-exploited* block is the one where the extraction of groundwater is more than 100% of its availability. Here, future groundwater development is linked with water conservation measures. In a *critical* block, the utilization of groundwater is more than 90% but less than 100% of its availability. Such a situation calls for intensive monitoring and evaluation for groundwater development. A *semi-critical* situation refers to extraction of 70–90% of the available groundwater, and calls for a cautious approach to further development of groundwater. The areas where groundwater extraction is less than 70% of its availability are considered *safe* from the perspective of development of groundwater resources.

quantum of power subsidy in the state has increased nearly nine times during this period (Vatta et al., 2013).

Background and data

The Centers for International Projects Trust (CIPT), India, the Punjab Agricultural University (PAU), Ludhiana, India, and the Columbia Water Center of Columbia University, USA, came together in 2009 to promote innovations for reversing groundwater depletion in Punjab. CIPT and PAU chose to test tensiometers for scheduling irrigation per the water requirement of the crop. The evidence indicates that use of tensiometers can save significant amounts of irrigation water without adversely affecting crop yield (Bhatt & Sharma, 2010; Kukal et al., 2005; World Bank, 2010). The associated benefit is a reduction in the power needed to pump out groundwater. Subsequently, to scale up this innovation, CIPT received financial support from the International Development Research Centre, Canada, and the US Agency for International Development.

CIPT and PAU have been promoting tensiometers for irrigation scheduling in paddy crops in the state of Punjab since 2010. The instrument is installed in the field around a week after paddy transplantation. It is saturated with water before its installation in the field. The water level in the tensiometer indicates whether the crop needs irrigation. There are three colour-bands on the instrument: green, yellow and red. Depending on the moisture in the soil, the water in the tensiometer moves across these bands. Water in the green band indicates that the crop does not require more water. Water in the yellow band indicates that the crop needs irrigation. Water in the red band indicates that the crop is water-stressed and its yield may be adversely affected. Once the water requirement of the crop is fulfilled, the water in the tensiometer reverts to the green band. As paddy is a rainy-season crop in the state and precipitation alters the level of water in the tensiometer, it changes the need and timing of irrigation.

CIPT started promoting the use of tensiometers for irrigation scheduling in paddy fields in 2010. In this article, we restrict our discussion to data generated in 2012–2014. During this period, a total of 7,148 farm households spread over nine districts in the central region of Punjab were persuaded to use tensiometers for irrigation scheduling (Table 3). These farmers were frequently contacted by field staff, who made them aware of the consequences of depleting groundwater, and the use of water-saving technologies and practices. Often, the first meeting with farmers in the study villages was held three months prior to paddy transplantation, and subsequently, at an interval of about

Table 3. Number of tensiometers installed, and districts and villages covered in Punjab.

Year	Tensiometers installed	Districts covered	Villages covered
2010	525	5	51
2011	3700	7	38
2012	981	6	44
2013	1941	7	79
2014	4226	8	136

Source: Centers for International Projects Trust survey.

10–15 days to monitor the use of the tensiometers in the field and collect information to assess their technical and economic feasibility.

Data on key farm and farmer characteristics such as land ownership, cropping pattern, crop yields, irrigation sources, use of tensiometer, and age and education of household-head were collected. We also used data on the cost of cultivation from the reports of the Commission of Agricultural Costs and Prices, Government of India (http://eands.dacnet.nic.in/Cost_of_Cultivation.htm), and on cropping patterns in the state from the Statistical Abstracts of Punjab (Government of Punjab, 2014).

A brief description of the key characteristics of farm households is given in Table 4. On average, a farm household owned 4.35 ha of land, of which over 90% was allocated to paddy cultivation, while the rest was under other crops like maize, cotton, and fodder crops. Sample farm households cultivating between 2 and 4 ha dominated the agrarian structure. These are classified as medium farmers and comprise about 59% of the total farm households. Twenty-three per cent of farm households belong to the large land class (≥4 ha), and the rest have small landholdings of less than 2 ha.

Each surveyed household had installed at least one power-operated bore-well to pump out groundwater. More than half of the farm households had only one bore-well, 29% had two bore-wells, and 20% had three or more bore-wells. Depending on the depth of groundwater, these bore-wells are run on electric motors of varying capacities – 19% on motors of less than 10 hp, 40% on motors of 10–15 hp, 25% on motors of 15–20 hp, and the rest on motors of more than 20 hp.

Of the farm households that were provided a tensiometer in 2012–2014, about 44% discontinued its use after installation or initial experimentation, and 46% continued to use it for irrigation scheduling. The rest could not use it because of faulty devices. On average, those who continued to use it were younger and better educated compared to those households that discontinued its use. They also had a greater portion of their land

Table 4. Means and standard deviations of key characteristics of the surveyed farm households.

Particular	Farmers continued with the use of tensiometers	Farmers discontinued the use of tensiometers	Farmers with technically faulty tensiometers	All
Age of household head (average number of years)	39.7 (11.53)	42.8 (11.88)	42.3 (11.48)	41.3 (11.78)
Years of schooling of household head	10.4 (3.57)	6.55 (4.54)	6.51 (4.65)	8.3 (4.56)
Size of land holding (ha)	4.54 (3.76)	4.35 (3.66)	4.26 (3.56)	4.35 (3.70)
Area under paddy (ha)	4.01 (3.51)	3.98 (3.45)	3.92 (3.42)	3.99 (3.47)
Depth of water table (m)	25.8 (8.50)	25.2 (8.42)	24.7 (28.69)	25.41 (8.49)
Percentage of area laser levelled	57.65 (44.20)	54.78 (44.73)	55.52 (44.73)	56.18 (40.50)
Number of electric motors per household	1.78 (0.93)	1.70 (0.92)	1.72 (0.91)	1.74 (0.92)
Average yield of paddy (100 kg/ha)	72.0 (18.8)	71.5 (7.69)	71.5 (19.45)	71.7 (19.05)

Figures in parentheses are standard errors.
Source: Centers for International Projects Trust survey.

laser-levelled, which is another water-saving innovation. The high rate of non-adoption of tensiometers could be due to high risk aversion among the farmers.

Methods of analysis

Economic surplus approach

Amongst the various approaches to impact assessment, the economic surplus approach is widely used due to its less restrictive assumptions and minimum data requirement (Alston, Norton, & Pardey, 1998). Using certain assumptions, this approach scales up farm-level economic benefits that accrue over a period of time due to the adoption of a technology to a higher-level spatial unit (e.g. the state of Punjab in this study) and provides estimates of the returns on investment in terms of net present value, internal rate of return, and benefit-cost ratio (Maredia, Byerlee, & Anderson, 2001). Another important advantage of this approach is that it allows us to study the distribution of benefits between producers and consumers. In the case of water management in India, Rama Rao, Kareemulla, Nagasree, Venkateswarlu, and Kumar (2010) have applied this approach to estimate returns on investment in soil and water conservation research, and Palanisami et al. (2012) have used it to assess the impact of water management technologies on crop production.

India is the largest producer of rice and has been exporting both basmati (scented) and non-basmati rice in large quantities. Punjab is one of the major rice-growing states in India, with an 11% share of national rice production. So, we assume that Punjab also makes a significant contribution to India's rice exports. To evaluate the economic benefits of the adoption of tensiometers, the state of Punjab is assumed to be a small exporting economy where all the benefits of the adoption of this technology accrue to paddy farmers. We also assume a parallel downward shift in the supply curve due to lower cost of production with use of tensiometers (Figure 3). The supply curve shifts from S_0 to S_1 while the demand curve is assumed to remain unchanged at C_0. Further, the rice price is assumed to be the prevailing world market price P_0, which does not change due to greater domestic production of rice. Thus, the increase in producer surplus in Figure 3 is equal to the area *abcd*.

Mathematically, in a small open economy framework the change in producer surplus can be expressed as:

$$\Delta \mathrm{PS}_t = \Delta \mathrm{TS}_t = P_0 Q_0 (K_t - Z_t)(1 + 0.5\, Z_t\, \eta)$$

where, $\Delta \mathrm{PS}_t$ is the change in producer surplus in the year t; TS_t is the total surplus in the year t; P_0 is the initial price; Q_0 is the initial level of production; Z_t is the reduction in price as a result of increased supply due to adoption of the technology; η is the absolute value of demand elasticity; and K_t is the proportionate supply shift in year t. The value of K_t is obtained as:

$$K_t = \{[E(Y)]/\varepsilon - [E(C)] \ / \ [1 + E(Y)]\} p A_t \ (1 - \delta_t)$$

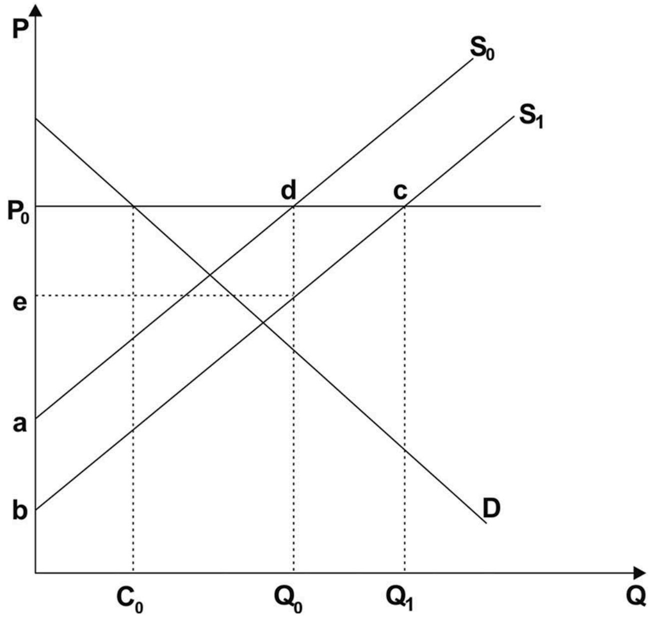

Figure 3. Conceptual framework to estimate economic surplus in an open economy.
Adapted from Alston et al. (1998).

where $E(Y)$ is the change in yield, $E(C)$ is the change in variable cost, ε is the supply elasticity; p is the success rate or probability of success of the technology; A_t is the adoption rate in the year t; and δ_t is the rate of degeneration of the technology.

Logistic regression

To identify the factors influencing the use of tensiometers for irrigation scheduling, we employ a logistic regression model. As discussed above, in our sample, 46% of the farm households continued to use tensiometers and 44% discontinued their use after installation or initial experimentation. Using this data-set, we identify the factors that influence farmers' decision to continue or discontinue the use of tensiometers. The logit model is:

$$Pr(Y = 1|\boldsymbol{x}) = \frac{e^{x'\beta}}{1 + e^{x'\beta}}$$

where Y_i is the status of tensiometer use – 1 for those who continue to use a tensiometer, zero otherwise; and $x'\beta$ is an unobserved index value, which is determined by a set of explanatory variables. We include age and education of household head, landholding size, proportion of land area levelled, depth of the groundwater table in the village, and the number of electric motors per hectare of land area in the set of explanatory variables. It is hypothesized that young and educated farmers are more likely to adopt and to continue to use the sensor-based irrigation application compared to older and less-educated farmers. Similarly, we expect that the technology is scaleneutral, with its adoption and use unlikely to be influenced by landholding size, and that farmers in regions with deeper water tables are more likely to adopt tensiometers.

Results and discussion

Farm-level impacts of the use of tensiometers

The main benefit of the use of a tensiometer for irrigation scheduling is the savings in irrigation water and electric power, and therefore saving in money spent by the state to provide tariff-free or subsidized electricity. Table 5 compares the number of irrigations, quantity of irrigation water used, and electric power consumption on the paddy plots receiving irrigation based on tensiometer readings with those irrigated through the continuous-flood method during the season. The plots irrigated with the continuous-flood method are termed control plots and belong to the same farmer who has adopted tensiometer-based irrigation. Since both the fields belong to the same farmer, the estimated parameters are unbiased, free from the influence of differences in socio-economic characteristics between adopters and non-adopters.

On average, during the season, the paddy plots with tensiometers installed needed three fewer irrigations than the control plots. This resulted in about 13% savings in the total amount of water used for irrigation, and an equal amount of saving in electric power consumption. Fewer irrigations were also associated with a lower requirement for human labour, about 10 hours per hectare of paddy area during the season. On the other hand, we see no significant difference in paddy yield between experimental and control plots. These results are in conformity with those reported by Bhatt et al. (2016). This leads us to conclude that the use of tensiometers can save irrigation water and electric power with no yield penalty.

The savings in electric power and labour use have been converted into their monetary equivalents. The survey did not collect information on the inputs used other than irrigation and the labour used for it. On the assumption that the use of a tensiometer is unlikely to cause any change in the usage of other inputs, we used data

Table 5. Change in water and electric power consumption due to use of tensiometers.

Particular	Tensiometer-installed plots	Control plots	Percentage change over control plots
Number of irrigations per ha	15	18	17
Water usage (1000 L/ha)	7,930	9,110	12.95
Electric power usage (kWh/ha)	1,853	2,120	12.59
Labour use in irrigation (hours/ha)	45	55	18.18
Monetary value (US$/ha)			
Cost of electricity usage	200.11	228.94	12.59
Cost of labour use in irrigation	29.29	35.81	18.21
Other variable costs[a]	406.93	418.08	2.67
Total variable costs	636.33	682.83	6.81
Yield (t/ha)	7.17	7.13	0.56

[a] Other variable costs include the costs of seed, fertilizers, manure, pesticides, machine use, human labour in farm activities other than irrigation, and animal labour. These costs were taken from 'Cost of Cultivation of Major Crops', published by the Ministry of Agriculture and Farmers' Welfare, Government of India (http://eands.dacnet.nic.in/Cost_of_Cultivation.htm). Indian rupees were converted to US$ at the mean exchange rate of US$ 1 = INR 46.30 in 2012–2014.

Source: Centers for International Projects Trust survey.

Table 6. Values of parameters used in estimation of economic surplus.

Parameter	Value	Source
Rice production (1000 t)	11,041.33	GoP (2014)
Producer price (US$/t)	385.71	FAOSTAT
Reduction in variable cost (%)	6.81	CIPT survey
Maximum adoption rate (%)	30	CIPT survey
Time period to achieve maximum adoption	2010–2025	Expert opinion
Supply elasticity of rice	0.24	Kumar (2010)
Demand elasticity of rice	−0.25	Kumar (2010)
Probability of success of tensiometer (%)	100	
Effective life of tensiometer (years)	3	Expert opinion

on the cost of cultivation to calculate the costs of other inputs. On average, the savings in electricity consumed was 268 kWh/ha, which is almost the same as reported by Bhatt et al. (2016). At present, the government of Punjab supplies tariff-free electricity for agricultural uses. We valued electricity at INR 5/kWh, which is nearly equal to the cost of power generation in Punjab. The reduction in irrigation expenditure on electricity resulting from the use of tensiometers is therefore estimated at US$ 28.83/ha, i.e., a 13% savings in irrigation cost in the paddy season. Tensiometers thus help reduce the total variable costs of paddy cultivation by about 7%.

Aggregate economic benefits

The farm-level benefits were aggregated or scaled up to the state level based on certain assumptions and parameters (Table 6). It is assumed that by 2025 about 30% of the area under paddy in Punjab will be brought under sensor-based irrigation management and that the adoption of the technology will follow a sigmoid curve (Figure 4). Further, its increasing adoption is unlikely to alter the observed savings in irrigation, electric power, and labour use, i.e., the savings in cost of paddy cultivation would remain unchanged at around 7%.

The price of rice is taken as the average of the producer price for the period 2008–2010 from FAOSTAT (http://faostat.fao.org), which is estimated at US$ 385.71/

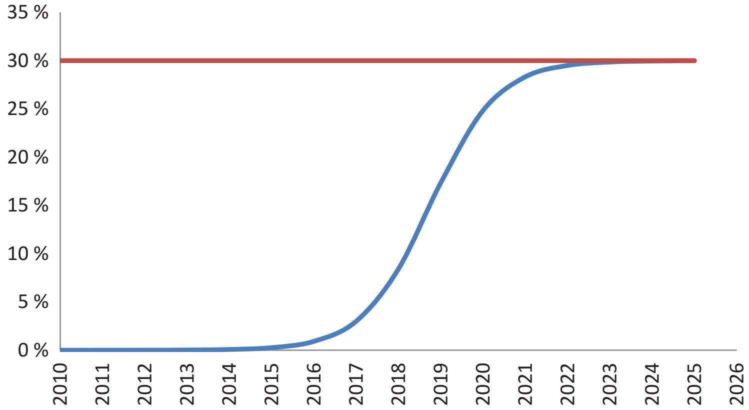

Figure 4. Assumed adoption curve for tensiometers, 2010–2025.

Source: authors' creation.

t. The average annual rice production in Punjab during this period was 11.04 million t. A few more parameters, like elasticity of demand and supply of rice, change in the cost of cultivation due to adoption, effective life of tensiometers, research and development costs and discount rate, are required for estimating the economic surplus due to wider adoption of tensiometers. The supply and demand elasticity of rice were taken from Kumar, Shinoj, Raju, Kumar, and Msangi (2010). Since tensiometers are already in use, the success rate of research is assumed to be 100%.

We also estimated the research and development costs as the sum of the expenditure for the salaries of scientists and other research staff involved in the development and experimentation of tensiometers in proportion of their time allocation to these activities, and the cost of tensiometers to the farmers. The effective life of a tensiometer is three years, and we assume that it will be replaced after three years.

The future stream of benefits needs to be discounted at an appropriate rate. Alston et al. (1998) suggest that in most situations, the real discount factor will fall in the range of 3–5%. In India, Kula (2004) estimated a discount rate of 5.2% for agricultural projects. Alpuerto, Norton, Alwang, and Ismail (2009) and Birthal, Nigam, Narayanan, and Kareem (2012) have applied a discount rate of 5% in the ex-ante assessment of the impact of improved crop varieties in South Asia. Following these studies, we, too, apply a discount rate of 5% in our study.

Table 7 presents the stream of benefits of the use of tensiometers for irrigation scheduling in terms of savings in water and power, and the resultant economic benefits. By 2025, tensiometers are expected to be used for irrigation scheduling on 0.85 million ha of area under paddy in Punjab. Over the period 2010–2025, it would result in cumulative savings of 0.67 million ha m of water and 1516 million kWh of electric power. In terms of economic benefits, the net present value of the adoption of tensiometers on 30% of the paddy area would generate a cumulative surplus of US$ 459 million. The internal rate of return is also quite attractive, at 136%. These findings

Table 7. Potential benefits of adoption of tensiometers.

Year	Paddy area irrigated using tensiometers (million ha)	Irrigation water saved (million ha m)	Electric power saved (million kWh)	Net present value (US$ thousands)
2010	0.00	0.00	0.00	−13.8
2011	0.00	0.00	0.00	−57.8
2012	0.00	0.00	0.00	−44.2
2013	0.00	0.00	0.00	−30.1
2014	0.00	0.00	0.58	−10.6
2015	0.01	0.00	2.01	218.8
2016	0.03	0.00	6.90	1959.3
2017	0.09	0.01	22.47	4435.9
2018	0.24	0.03	63.04	8538.4
2019	0.49	0.06	129.84	44,893.6
2020	0.71	0.08	185.99	44,790.3
2021	0.81	0.09	212.12	35,102.7
2022	0.84	0.10	220.97	93,033.0
2023	0.85	0.10	223.62	65,628.9
2024	0.85	0.10	224.39	45,335.9
2025	0.85	0.10	224.61	115,089.5
Total		0.67	1516.53	458,870.1

Source: estimated by the authors.

Table 8. Sensitivity of benefits to changes in cost of cultivation and adoption rate.

Scenario		Savings			
Adoption rate (%)	Cost reduction (%)	Water (million ha m)	Electricity (million kWh)	Net present value (US$ millions)	Internal rate of return (%)
20	6.81	0.45	1016.71	294.67	120
20	10	0.65	1452.45	435.41	134
25	6.81	0.56	1270.89	376.76	129
25	10	0.81	1815.56	552.74	143
30	6.81	0.67	1516.53	458.87	136
30	10	0.97	2178.15	670.12	164

Source: estimated by the authors.

suggest that sensor-based irrigation management is an economically feasible option to arrest the rapid rate of groundwater depletion.

To test whether these results are sensitive to changes in our assumptions and parameters, particularly the adoption rate of tensiometers and their cost-effectiveness, we conduct a sensitivity analysis of the benefits with respect to changes in adoption rate and cost of cultivation. Table 8 shows the estimated savings in water and electric power use and the resultant economic benefits at 20%, 25% and 30% adoption rate, i.e., the area of paddy under tensiometer-based irrigation, and 7% and 10% reduction in cost of cultivation due to use of tensiometers. The lower cost of cultivation occurs due to lower use of electricity and diesel to operate tube-wells, and also less human labour. As expected, a lower rate of adoption (20%) at the existing level of cost reduction (about 7%) would reduce cumulative saving of water to 0.45 million ha m and of electric power to 1017 million kWh over the period 2010–2025. The associated economic benefits would be US$ 294 million. However, if the cost reduction is 10%, then even at a 20% rate of adoption, the savings in water and electric power and economic benefits would almost parallel those at 30% adoption and at the existing level of cost reduction. At a 10% level of cost reduction with 30% area under sensor-based irrigation management, the benefits would be nearly 1.5 times their original estimates.

Factors influencing the use of tensiometers

Table 9 presents the results of the logistic regression model that examines the factors influencing the use of tensiometers. The model provides a good fit, with chi-squared significant at the 1% level. The dummies for land class to which farmers belong to are not significant, suggesting the scale-neutrality of the sensor-based irrigation management technology. We also control for the influence of other water management interventions, especially laser land levelling, on the adoption of tensiometers. Interestingly, the coefficient for laser land levelling appears positive and significant at better than the 5% level, suggesting that farmers often use tensiometers in conjunction with laser land levelling for efficient use of irrigation water. Further, the probability of continuous adoption of tensiometers is higher in the villages facing greater water scarcity, as indicated by a positive and significant coefficient on the depth of water table in the village.

Table 9. Factors influencing the use of tensiometers.

Variable	Regression coefficient	Marginal effect
Age of the household head (years)	−0.0142 ***	−0.0035***
	(0.0023)	(0.006)
Years of schooling of the household head	0.2237***	0.0552***
	(0.0071)	(0.0017)
Land class (ha)		
<2 ha	0.0179	0.0044
	(0.0744)	(0.0184)
2–4 ha	0.0079	0.0019
	(0.0586)	(0.0145)
Proportion of land laser-levelled	0.1308**	0.0323**
	(0.0594)	(0.0147)
Depth of water table (feet)	0.0033***	0.0008***
	(0.0009)	(0.002)
Constant	−1.8595***	
	(0.1534)	
No. of observations	7143	
Chi-squared	1470.64***	

***$p \le .01$; **$p \le .05$; *$p \le .1$.
Note: Standard errors in parentheses.

The results also indicate that relatively young farmers are more likely to adopt and continue with the use of tensiometers for irrigation scheduling. Educated farmers also have a greater probability of continuing their use. The regression coefficients on these variables are positive and highly significant. These results are expected, as younger and more educated farmers are more aware of the consequences of depleting the water table, and are less risk-averse in adoption of new water conservation technologies and practices.

The marginal effect of education is the largest, suggesting that a 10% improvement in the education level of farmers enhances the probability of continuing with the use of tensiometers by 0.6%. Likewise, the probability of continuation in the use of tensiometers increases by 0.3% with a 10% increase in the adoption of laser land levelling. Surprisingly, although the probability of tensiometer adoption increases with increase in groundwater depletion, the effect is not as strong.

Conclusions and implications

The intensive cultivation of paddy has been causing depletion of groundwater resources in Punjab. This trend needs to be reversed through technological and policy interventions to improve the sustainability of production systems and farm profitability. This article has assessed the impact of a simple and low-cost soil-moisture sensor – the tensiometer – on the use of irrigation water and electric power in paddy cultivation and quantified the economic benefits that would accrue to farmers in the state from its wider adoption.

Our findings clearly show that the use of tensiometers for irrigation scheduling reduces the number of irrigations in paddy cultivation, resulting in about 13% water savings. That also means a saving of about 13% in electric power use in pumping out groundwater, and about 3% in labour use. These savings lower the cost of paddy cultivation by about 7%, without adversely affecting crop yield. If soil-moisture-sensor-based irrigation is practised on 30% of the paddy area, then by 2025, the resultant benefits would be quite large. It would conserve a total of 0.67 million ha m of water and save 1516 million kWh of electric power. The aggregate economic benefits are estimated at US$ 459 million.

For successful adoption of groundwater-saving technologies, one of the critical conditions is to reform policies on irrigation and electric power supply to agriculture. Our results indicate that nearly half the farmers in the state have installed more than one electric-power-operated bore-well, probably because of the provision of tariff-free or heavily subsidized electric power for agriculture. Given the growing water scarcity in the state, the policy of tariff-free or subsidized electric power to agriculture needs rethinking in terms of withdrawal of subsidies and volumetric pricing of electricity. The resultant savings could be used for the promotion of water conservation technologies and practices such as laser levellers and tensiometers, and the development of institutions for efficient management of groundwater resources. The high rate of non-adoption of tensiometers indicates a need to make farmers and other stakeholders aware of the consequences of depleting groundwater and the interventions that could arrest this trend. It also suggests the need for more research on the potential of sensor-based water management instruments to increase water savings. Our results indicate that initial targeting of younger and more educated farmers would have a demonstration effect on other farmers and stakeholders to adopt water conservation technologies and practices.

Notes

1. The price of the tensiometer in Punjab is only US$ 6, as compared to US$ 40–200 in the international market.
2. Net sown area refers to area cultivated only once a year. Cropping intensity is the ratio of total cropped area to net sown area.
3. Net water availability is the difference between groundwater extraction and its natural recharge. A negative value indicates an extraction rate higher than the recharge rate.
4. These figures were estimated from the average depth of the water table in all observation wells in Punjab.

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