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Drivers of Change in Groundwater Resources: A Case Study of the Indian Punjab

Authors: Sukhwinder Singh[1], Julian Park[2]

[1] Postdoctoral Fellow, School for Environment and Sustainability, University of Michigan, Ann Arbor, USA;

Corresponding author: (sukhrec@yahoo.com); ORCID ID: 0000-0003-3681-5511

[2] Professor and Head, School of Agriculture, Policy and Development, University of Reading, UK

1. Introduction

The Indian Punjab, a strategically important region from India's national food security standpoint, produces 19% and 11% of India's total wheat and rice production respectively, and has been contributing about 25-50% of rice and 38-75% of wheat to India's central pool of food grains for the last four decades (PSFC 2013). To note, from the central pool, food is distributed to the poorest across India through the national public distribution system.

Punjab's agro-climatic conditions allow its farmers to cultivate their land at least twice a year i.e. during the *Rabi* (winter) and the *Kharif* (summer) seasons[1] (Pede et al. 2012). Wheat and rice are the major *Rabi* and *Kharif* crops of Punjab respectively. However, despite Punjab having higher productivity levels than the respective national averages[2], many of its farmers are facing various socio-economic challenges associated with a slowdown in agricultural growth, thus, resulting in reduced net farm incomes. Increased cost of cultivation, particularly related to seeds, fertilizers, pesticides, diesel and labor, is one of the major drivers of this falling trend in farm incomes (Kalkat et al. 2006; Singh 2012). Additionally, Singh (2012a) and Sarkar and Das (2014) argued that the current farming systems are depleting the groundwater reservoirs, leading to long-term ecological implications for the overall sustainability of farming enterprises in Punjab.

Nearly 100% of Punjab's farmed area is irrigated, of which, 73% is irrigated through groundwater resources (GoP 2012). Most of the canal-irrigated areas lie in the south-western zone of Punjab where the groundwater is brackish and unfit for irrigational purposes although in some regions, the groundwater is used in conjunction with canal water (Tiwana et al. 2007; Sidhu et al. 2011).

Looking at the recent demand and supply equation (as on 2009), the net annual groundwater demand (irrigation, domestic and industrial use) in Punjab was 34.66 billion cubic metres against an availability of 20.35 billion cubic

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[1] The *Rabi* (winter) growing season runs from November/December through April with the major crops being wheat, barley, oilseeds and millet. The *Kharif* season refers to the summer growing period from May to November with rice, corn, and cotton as the major crops.

[2] Punjab's average yield of wheat and rice in 2010-11 was 4.7 and 3.7 tonnes/ha compared with 2.9 and 3.2 at national level respectively. However, the respective world averages were 3.1 and 4.3 (GoP 2012).

metres. The deficit of 14.31 billion cubic metres is essentially met through the overwithdrawal of groundwater resources (CGWB 2013). About 2.95 million hectares (ha) out of Punjab's net sown area of 4.07 million ha, is irrigated via 1.38 million tubewells, of which, 82% are electricity operated utilizing approximately 31% of Punjab's total electricity consumption (GoP 2012). In 2010-11, Punjab's farm sector received Rs 32.6 billion (INR) as electricity subsidy, which was approximately 7.4% of Punjab's total Net State Domestic Product (NSDP) from agriculture and allied activities at current prices (Singh 2012a; GoP 2012). Further, Punjab government has recently decided to release permissions for a further 0.11 million tubewell connections in a phased manner, that will place an additional burden of INR 6.7 billion on the state exchequer (Sood 2014).

According to the latest groundwater report by the CGWB (2014), the stage of groundwater development[3] was assessed as 172% in Punjab (higher than all Indian states) compared with 133% and 137% in the adjoining states of Haryana and Rajasthan respectively, and 62% at the national level. The percentage of over-exploited blocks[4] increased from 53% in 2000 to 80% in 2011 (Table 1).

Table 1 Number of development blocks (%) under different categories of groundwater exploitation in Punjab: 2000 to 2011

Category	2000	2004	2011
Over-exploited	53	75	80
Critical	7	3	3
Semi-critical	12	3	1
Safe	28	19	16

Sources: Tiwana et al. (2007); CGWB (2006; 2014)

In particular, the level of groundwater in central zone is depleting relatively faster than in the other two zones[5]. For instance, nine districts in this zone have a majority of blocks in the over-exploited category. The annual rate of groundwater depletion in the nine central districts is 75 cm compared with 55 cm across Punjab as a whole (Tiwana

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[3] Stage of groundwater development = Existing gross draft for all uses/Net annual availability *100 (CGWB 2011).

[4] Block is an administrative unit used for rural planning in India. A block covers several villages. In 2009, Punjab had 20 districts, 141 blocks and 12,278 inhabited villages (GoP 2009).

[5] Punjab can be broadly divided into three agro climatic regions, sub-mountainous (zone I), central (zone II), and south-western (zone III) covering 17%, 47%, and 36% of the land area respectively (Sidhu and Vatta nd).

et al., 2007; Singh, 2012a). Further, this zone covers more than half of the land area of Punjab and contains 70% of total tubewells. Here, 72% of the land area is under rice, of which, about 80% is irrigated using groundwater resources (GoP, 2012a). In fact, Rodell et al. (2009) estimated that the groundwater in Punjab depleted at a mean rate of 4.0 ± 1.0 cm annually between 2002 and 2008, and termed this phenomenon 'as the largest mining of water on earth.' However, the phenomenon of over-exploitation of groundwater resources is not only limited to Indian Punjab but also common in many parts of the world as it is really difficult to regulate the pumping of groundwater resources and realize its equitable distribution across all users (De Fraiture and Giordanob 2013; Hoogesteger and Wester 2015).

When considering the crop water requirements within both the cropping seasons, the relative water requirements of wheat are comparable to other *Rabi* crops. However, rice (including basmati[6]) is the most water-intensive crop of the *Kharif* season[7] (Singh 2012a), which is cultivated on 68% of Punjab's net sown area (GoP 2013) using a mixture of surface and groundwater sources[8]. Most rice growers use conventional irrigation techniques such as flood irrigation and puddling[9] (Singh 2009a; Larson et al. 2013). In India, only 22% of the total water saving technologies released in the last 40 years has been successfully transferred to farmers and their success rate (adopted and approaved by farmers) was only 12% (Palanisami et al. 2015). In Punjab, which is one of the agriculturally advanced states of India with high levels of subsidies on water saving technologies, the adoption of these technologies is limited. For instance, the laser leveler, which is the water saving technology most widely available on rent, was used by only one-seventh of the farmers in Punjab (Larson et al. 2013) and the adoption of other precision technologies, e.g. drip irrigation, SRI (System of Rice Intensification), direct seeding, zero-tillage is also limited.

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[6] Here, rice refers to an ordinary variety of rice whereas basmati is a premium variety of long-grain Indian rice with a delicate fragrance.

[7] Over the *Kharif* season, rice and basmati, on average, require 22 and 15 irrigations respectively when compared to other popular *Kharif* crops such as cotton, sugarcane and maize which, on average, need 6, 14 and 5 irrigations respectively. In the *Rabi* season, wheat requires 5 irrigations compared to 4, 8 and 12 irrigations for mustard, winter maize and spring maize respectively (Singh 2012a).

[8] To note, surface water sources cover the south-western region and some parts of the central region only.

[9] Puddling is a process of making the upper surface of the rice field hard enough to keep the water standing in the rice field (Singh and Kaur 2012).

Considering the supply side, amount of rainfall and land area irrigated by canals have declined in Punjab by 14% and 27%, respectively between 1990 and 2010 (GoP 2012). For instance, the annual rainfall was 754 mm, 392 mm and 472 mm in 1990, 2000 and 2010, respectively, whereas the net area irrigated by surface water resources (e.g. canals) came down from 1,660 to 1,113 thousand hectare between 1990-91 and 2010-11 in Punjab. As Srivastava et al. (2015) argued that unlike India, rainfall in Punjab has a limited role to play in recharging the groundwater due to low annual precipitation. Moreover, rainfall in Punjab recharges only 32% of replenishable groundwater against 74% at national level. In Punjab, other sources, e.g. return flow from irrigation, seepage from canal, recharge from tanks, ponds and water conservation structures, supply the remaining groundwater recharge. Thus, artificial groundwater recharging and integrated water resources management can play a decisive role in improving groundwater supply. The CGWB (2013a) reported that about 86% of the land area (43,340 out of 50,362 sq. km) in Punjab is feasible for artificial recharge and planned 4,54,924 artificial recharge structures (rural and urban) for the state. However, Srivastava et al. (2015) argue that artificial groundwater recharge alone cannot help much in sorting out Punjab's groundwater sustainability crisis as the CGWB (2013a) estimated that the quantity of non-committed surplus surface water in Punjab for artificial recharge is 1201 million cubic metres (MCM) against the requirement of 70,071 MCM. Further, integrated water resources management has a limited scope as interlinked nature of groundwater and surface water is not recognized in India. For instance, more than 60% tube wells were constructed outside the command area of surface irrigation and less than 1% of the total wells were used for augmenting groundwater supplies. Thus, there is a limited scope of augmenting groundwater supplies through artificial groundwater recharge and integrated water resource use, withdrawal of groundwater for agricultural use should be curtailed as agriculture sector consumes about 98% of groundwater in Punjab (Srivastava et al. 2015).

In fact, the groundwater withdrawal could depend on a range of socio-economic factors in addition to the crops grown and their cultivation methods. These are in part shaped in response to the policy framework, especially the Minimum Support Price and Assured Purchase (MSPAP) and provision of free electricity to the farm sector. However, there is a general consensus that an expansion of the area under rice has largely contributed to the depletion of groundwater in Punjab (Singh 2009; 2012a; Sarkar and Das 2014). The MSPAP policy and input subsidy regime, especially unlicensed groundwater availability and free-of-cost electricity to pump it out, are encouraging farmers to adopt simple wheat-rice rotations to the exclusion of other more diversified options (Singh 2013; 2016). For instance, between

1980-81 and 2011-12, the proportion of land area under wheat and rice in Punjab increased from 59% to 80% (GoP 2012).

The consistent use of this rotation for the last four decades has gradually led to a reduction in crop diversity[10] in most regions of Punjab (Singh and Sidhu, 2004; Sidhu and Vatta, n.d.; Singh and Benbi 2016). Although the State government has been encouraging farmers to diversify to high-value crops since 1986, it has had little success (Sarkar and Das 2014) because wheat and rice are more effectively priced and have a lower productivity risk compared with alternative crops that have been suggested under various diversification plans to-date (Singh 2013; Shergill 2013). Another driver could be a poor performance of agricultural research and development institutions, both at the national and state levels, as they have failed to prescribe an alternative set of crops with similar or lower productivity risks to wheat and rice to farmers (Singh 2016).

Punjab government had enacted and implimented "The Punjab Preservation of Sub Soil Water Act, 2009" in 2009 which forbids farmers to transplant rice before 10th June (Singh 2009), which has now been extended to 15th June. Recently, the national government's Ministry of Water Resources has advised the Indian states to enact the Ground Water Legislation to regulate and control the development of groundwater (Kulkarni and Shah 2013) but the Punjab government has not done anything in this regard although a neighboring state of Himachal Pradesh had already enacted and implemented it (see www.cgwb.gov.in).

Concerns regarding the socio-economic, environmental and food security impacts of current farm related trends in the Indian Punjab suggest a nuanced understanding of groundwater resources and socio-economic drivers for its use is needed. The theoretical framework of this study is underpinned around the fact that the existing research explains the groundwater depletion in Punjab from two perspectives only:

(a) Policy perspective i.e. Centre and State government policies, particularly related to production oriented subsidies and marketing and procurement of crops;
(b) Technological perspective i.e. relative water requirements of existing and suggested crops, and adoption and efficiency of water conservation technologies.

[10] Crop diversification index dropped from 0.75 in 1975-76 (Sidhu et al., 2010) to 0.42 in 2009-10 (Singh and Benbi 2016)

However, no study in the existing literature has discussed the socio-economic factors affecting farmers' decisions about 'which crops to cultivate and how they are to be grown' that eventually affect the groundwater withdrawal. Against this backdrop, this paper evaluates the current situation in Punjab using data collected through a field survey of 120 farmers spread across three agro-climatic zones of Punjab, and outlines the major socio-economic (farm-and farmer-specific) factors (*cause*) that have a significant association with the change in the level of groundwater (*effect*) in this region.

2. Material and Methods

In October-November 2010 (Singh and Benbi 2016[11]), a survey of 120 farmers was conducted across three districts, namely Gurdaspur, Barnala and Ferozepur, of the Indian Punjab. A multistage cluster sampling technique was used to select districts, blocks and then farmers. To start with, a Farming Intensity Index (FII) was calculated (Table 2) for each of the 20 districts of Punjab using the major indicators of agricultural sustainability in Punjab, e.g., per hectare agricultural production in value terms, condition of the underground water resources, state of soil health and Crop-Diversification Index (CDI). The data used to realize the FII components (Table 2) were largely calculated using secondary resources. For instance, agricultural production/hectare (in Rs) and Crop Diversification Index (CDI) were calculated from Statistical Abstract of Punjab (GoP 2012) whereas groundwater development data was taken from CGWG (2012). The district-wise data on Soil Organic Carbon were calculated under the guidance of Professor Dinesh Benbi using the soil unit database available at the Department of Soil Science, Punjab Agricultural University, Ludhiana.

The CDI was calculated using 1-H, where H is Hirschman-Herfindahl Index (HHI)[12] measured as:

$$H = \sum_{i=1}^{N} s_i^2$$

where

[11] This paper is based on the same field survey that I, as the first author, used in my paper Singh and Benbi (2016). Thus, some contents of this paper, e.g. Material and methods, and farmer profile, might look identical to Singh and Benbi (2016).

[12] This index takes a value of 1 when there is complete concentration and approaches zero when diversification is 'perfect'. A higher CDI indicates greater crop diversity in production patterns (Singh and Sidhu 2004).

N is the total number of crops

Si represents area proportion of the i-th crop in total cropped area

Table 2 Calculation of a district-wise Farming Intensity Index (FII) using major agricultural sustainability indicators for the Indian Punjab

Sr. No	District	Production / Hectare (in Rs)			Groundwater Development (%)				Crop Diversification Index (CDI)			Soil Organic Carbon (%)			Farming Intensity Index (FII)	Overall Ranking
		X†	X-x̄	(X-x̄) /SD	X	X-x̄	(X-x̄) /SD	Inverse §	X	X-x̄	(X-x̄) /SD	X	X-x̄	(X-x̄) /SD		
				A				B			C			D	A+B+C+D	
1	Sangrur	65002	8586	1.11	183	36	0.71	-0.71	0.60	-0.05	-1.09	0.44	0.02	0.43	-0.26	13
2	Patiala	60818	4402	0.57	165	18	0.36	-0.36	0.59	-0.06	-1.16	0.47	0.05	1.13	0.18	9
3	Ludhiana	69145	12729	1.65	144	-3	-0.05	0.05	0.61	-0.03	-0.69	0.49	0.07	1.54	2.55	3
4	Moga	62821	6405	0.83	178	31	0.61	-0.61	0.58	-0.07	-1.47	0.40	-0.02	-0.48	-1.73	17
5	**Ferozpur**	**58604**	2188	0.28	**105**	-42	-0.81	**0.81**	**0.68**	0.03	0.56	**0.47**	0.05	1.06	**2.71**	**2**
6	Amritsar	48385	-8031	-1.04	152	5	0.10	-0.10	0.60	-0.04	-0.90	0.52	0.10	2.16	0.12	10
7	Kapurthala	61381	4965	0.64	204	57	1.12	-1.12	0.65	0.00	0.03	0.38	-0.04	-0.93	-1.37	16
8	Jalandhar	53572	-2844	-0.37	254	107	2.09	-2.09	0.68	0.03	0.66	0.42	-0.01	-0.14	-1.94	18
9	**Gurdaspur**	**45015**	-11401	-1.47	**107**	-40	-0.77	**0.77**	**0.63**	-0.02	-0.47	**0.42**	0.00	0.05	**-1.12**	**15**
10	Taran Taran	48385	-8031	-1.04	200	53	1.04	-1.04	0.59	-0.06	-1.20	0.39	-0.03	-0.62	-3.90	20
11	**Barnala**	**65002**	8586	1.11	**202**	55	1.08	**-1.08**	**0.61**	-0.04	-0.72	**0.35**	-0.07	-1.54	**-2.22**	**19**
12	Faridkot	58046	1630	0.21	106	-41	-0.79	0.79	0.63	-0.02	-0.46	0.40	-0.02	-0.48	0.06	11
13	Mohali	44593	-11823	-1.53	88	-59	-1.14	1.14	0.69	0.04	0.87	0.40	-0.02	-0.48	0.00	12
14	Fatehgarh Sahib	63515	7099	0.92	161	14	0.28	-0.28	0.61	-0.04	-0.83	0.49	0.07	1.50	1.31	4
15	Mansa	58906	2490	0.32	175	28	0.55	-0.55	0.69	0.04	0.83	0.37	-0.05	-1.16	-0.56	14
16	Bathinda	57613	1197	0.15	93	-54	-1.04	1.04	0.70	0.05	1.03	0.38	-0.04	-0.97	1.26	5
17	Muktsar	60394	3978	0.51	62	-85	-1.64	1.64	0.70	0.05	0.96	0.41	-0.01	-0.20	2.92	1
18	Hoshairpur	45722	-10694	-1.38	85	-62	-1.20	1.20	0.73	0.08	1.74	0.40	-0.03	-0.59	0.96	6
19	Nawanshehar	56807	391	0.05	175	28	0.55	-0.55	0.71	0.06	1.33	0.41	-0.01	-0.25	0.57	7
20	Ropar	44593	-11823	-1.53	93	-54	-1.04	1.04	0.70	0.05	0.98	0.42	0.00	-0.03	0.47	8
	x̄‡	**56415.95**			**147**				**0.65**			**0.42**				
	SD¶	7735.64			51				0.05			0.04				

Notes:

† X= A set of actual values of the variable considered.

‡ x̄ = Mean of X.

§ Groundwater Development (%) had an inverse relationship with agricultural sustainability, thus, the Figures were multiplied with -1 to get their respective inverse values.

¶ SD = Standard Deviation

Source: Singh and Benbi (2016)

To calculate the FII, the values of each of the indicators for each of the 20 districts were normalised (X- x̄)/SD), and then all the realised values were added to obtain a composite score for each of the districts using the formula devised by Singh and Benbi (2016):

$$FII = \sum_{i=1}^{n} \frac{X - \bar{x}}{SD}$$

where

X = a set of actual values of the variable considered,

$\bar{x}$ = Mean of X,

SD = Standard Deviation of X,

n = Number of variables.

In relation to the 20 districts, Muktsar had the highest FII scoring 2.92 whereas Tarantaran was ranked 20th with the lowest FII of -3.90, where a higher score represents a greater intensity. All 20 districts were divided into three groups based on their overall ranking. The first group had six districts having an FII between 2.92 and 0.92 whereas the second group was formed of eight districts with an FII between 0.57 and -1.12. The third group was formed from the remainder six districts having an FII between -1.37 and -3.90 (Table 2). Then, three districts were chosen: one from each of the three groups considering their relative ranking within the group in combination with agro-climatic condition. Gurdaspur, Barnala and Ferozepur (Fig. 1), which represented the sub-mountainous, central and south-western agro-climatic zones of Punjab, respectively were selected for the field survey (Singh and Benbi 2016).

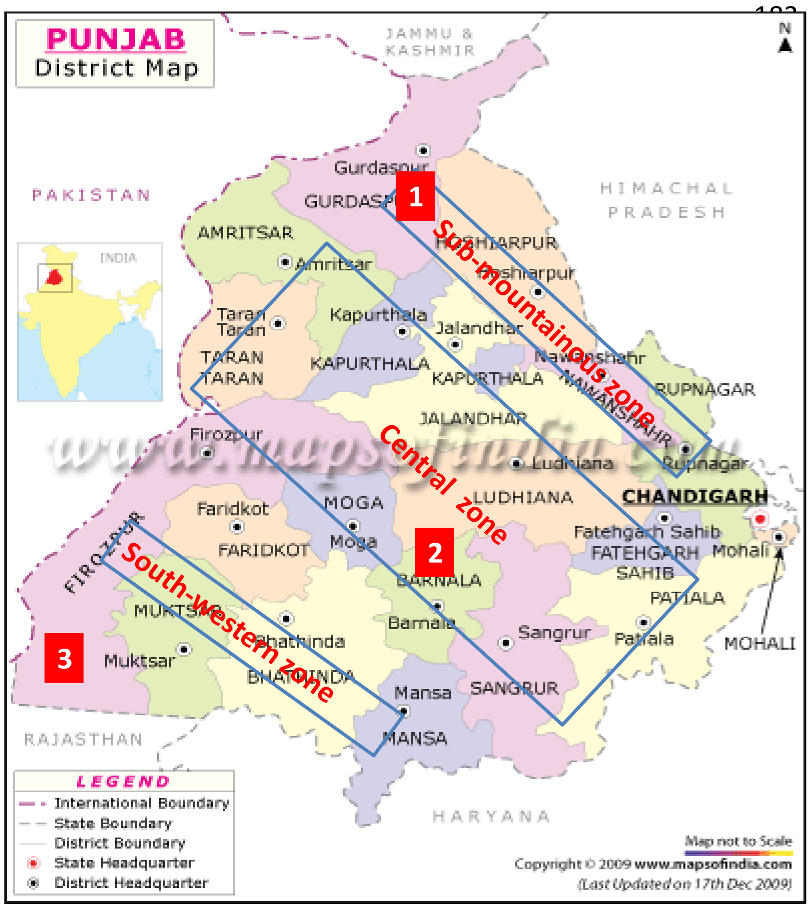

Fig. 1 District map of Punjab showing research regions chosen for field survey

Source: Singh and Benbi (2016)

To maintain consistency, the same sampling technique and sustainability indicators were used to select blocks. However, due to unavailability of block level production data, the other three indicators of agricultural sustainability were used. One block (a cluster of villages within a district) from each district was selected. Three blocks, Gurdaspur, Sehna and Fazilika were selected in Gurdaspur, Barnala and Ferozepur districts respectively. Then, owing to unavailability of secondary data on sustainability indicators at village level, the extension workers of the block concerned were consulted to identify two divergent (i.e., one relatively more and one relatively less intensively farmed) villages from each of the selected blocks.

As used by Singh and Benbi (2016), after identifying the villages, 20 farmers were selected from each of the six villages using a stratified sampling technique. In total, 120 farmers were selected across three districts/blocks. The selected group of farmers in each village represented the range of landholding sizes, i.e., small, medium and large, of the village concerned. Taking into consideration the current landholding distribution in Punjab[13], 30% small, 60% medium and 10% large farmers were selected in each of the villages.

A semi-structured interview schedule was used to collect a range of socio economic data. The interview schedule was translated into Punjabi, the local language of Punjab, to minimise the communication gaps during the field survey. To ensure anonymity, a unique code was allotted to each of the respondents. All the interviews were digitally recorded with the consent of the interviewee concerned. The Statistical Package for Social Sciences (SPSS) was used to realize all the descriptive tables and analyze the data. For regressions, a general ANOVA model, which adjusts the predicted means of dependent variable with respect to each independent variable for the effect of all the independent factors, was used. Correlation values across all independent variables used in the regressions were examined using bivariate corrleation and Chi-sqaure tests and no variable showed a siginificant association with each other.

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13 As per the latest available data on landholding distribution in Punjab (GoP 2012), about 32%, 60% and 8% of farmers are marked as small (less than 2 ha), medium (2-10 ha) and large (more than 10 ha) landholders.

3. Results

3.1 Farmers' profiles, cropping patterns and tubewell density

The average size of landholding cultivated was 4.8 ha (*Min* = 0.4 ha, *Max* = 36 ha, *SD* = 5.45). About four-fifth of the total 120 farmers surveyed were above 36 years of age, of which, one-third were more than 55-year old. Only 20% of farmers were younger than 36 years of age. Levels of technology were relatively high with 75% and 95% of the farmers having a tractor and a tube well respectively. In terms of their educational attainments, about 90% of the farmers were senior secondary school (12 Grade) literate, of which 11% had graduated while the remaining 10% were illiterate i.e. unable to read and write. About 91% of the land area was cultivated by the medium and large holders, who accounted for 70% of the farmer population whereas the smallholders (cultivating less than 2 ha), who comprised of 30% of the farmer population, were left with only 9% of the total land area (Singh and Benbi 2016).

All 120 farmers surveyed across the three agro-climatic regions of Punjab grew at least two crops in a given year. Thus, the average cropping intensity was over 200% with significant intra-zone variations ($X^2(4, 120) = 16.1$ $p < .01$). Farmers in the central (Barnala) and south-western (Ferozpur) zones had a combined average cropping intensity of 202%. In other words, 82% of farmers[14] cultivated their land more than twice a year whereas the remaining 18% of them grew at least two crops a year. An average crop diversity (CDI) across all three zones was 0.61[15] (*Min* = 0.50, *Max* = 0.75) with no significant regional variations. However, cropping patterns in the *Kharif* season were slightly more diverse than in the *Rabi* season. Wheat and rice occupied about 83% and 73% of the net sown area in the *Rabi* and *Kharif* seasons respectively. Overall, the current cropping patterns can be termed as highly intensive with limited crop diversity (Singh and Benbi 2016).

Of the 120 farmers interviewed, 114[16] farmers had 211 tubewells in total (1.8 tube wells per farmer; one tube well per 2.7 ha), out of which 82% were electric-operated submersible pumps specially designed to extract water from deeper

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[14] Punjab can be divided into three agro-climatic zones i.e. sub-mountainous, central and south-western zones covering 18%, 51% and 31% of the land area respectively (Singh 2011).

[15] Crop diversity for each farmer was calculated using the Hirschman-Herfindahl Index (HHI) explained in the Material and Methods section.

[16] Six farmers did not own tube wells and were asked to record the groundwater level estimates of their neighboring tube well. Further, as about 44% of the farmers had more than one tube well, data was used for the first tube well they reported.

levels. Further, 83% of the total tubewells and 86% of the total electric-operated tubewells were situated on medium and large holdings. In contrast, half of the smallholders irrigated their farms with diesel engine-based pumps, thus, not receiving any benefits from the subsidized power provided to those using electricity-run tubewells.

3.2 Current groundwater level

The average level of groundwater was 14 metres (*SD* = 8.30, *N* = 120) ranging between 1 and 30 metre across all 120 farms spread across all three agro-climatic zones. It was the deepest in Barnala (*Mean* = 22 metre, *SD* = 5.11, *N* = 40) followed by Gurdaspur (*Mean* = 12 metre, *SD* = 6.21, *N* = 40) and Ferozpur (*Mean* = 7 metre, *SD* = 4.43, *N* = 40). In the central zone (Barnala) where all the 40 sampled farmers were withdrawing from deeper than 11 metres, of which, 55% were extracting beyond 20 metres (Table 3). In contrast, only 7% of the farmers in the sub-mountainous (Gurdaspur) zone had groundwater deeper than 20 metres whereas all the farmers in the south-western zone were able to access water within 20 metres. Across all zones, for 72% of the farmers, groundwater was deeper than 11 metres, 12% had it between 4 and 10 metres, which can be classed as “a normal level”[17]. Only 16% of the farmers actually reported a problem with water-logging. The reason for water-logging[18] is quite localized and based on agro-climatic conditions.

Table 3 Average Groundwater Level (AGL in metres) across all three zones reported by farmers

Water table level	Number of farmers (%)			Overall
	Gurdaspur	Barnala	Ferozpur	
≤3 metres	8		42	16
4-10 metres	18		18	12
11-20 metres	67	45	40	51
> 20 metres	7	55		21
n	40	40	40	120

Source: Survey data

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[17] According to the Ministry of Water Resources (MWR, 1991), the area is treated as safe from water logging if the groundwater level is 3 metre below the land surface while an ordinary diesel engine operated tube well can pump out the groundwater from up to 10 metres. Thus, between 4 and 10 metres was considered as “a normal level”.

[18] According to the Planning Commission of India (2013), “an area is said to be waterlogged when the groundwater level rises to such an extent that the soil pores in the root zone of a crop become saturated, resulting in restriction of normal circulation of air, decline in the level of oxygen and increase in the level of carbon dioxide. The harmful depth of groundwater would depend on the type of crop, type of soil and quality of water.”

Analyzing the long-term trends in groundwater depth (Fig. 2), fifty-eight per cent of the farmers reported a fall of 3-15 metres between 2000 and 2010, of which, 30% had a groundwater fall of 6-15 metres. Region-wise, the groundwater fall was found to be the greatest in the central zone (Barnala) where 66% of the farmers reported a decline of 6-15 metres and another 26% farmers suggested a depletion of more than 15 metres.

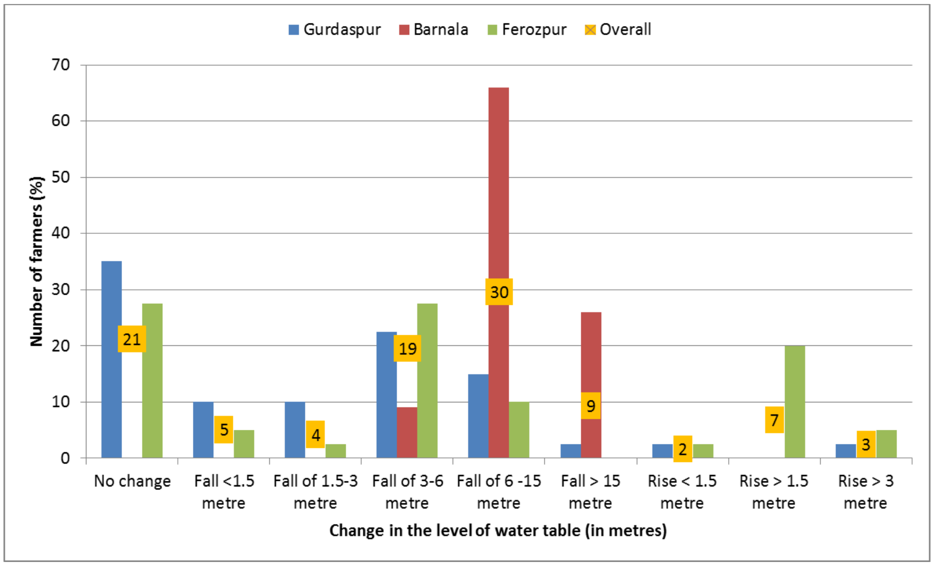

Fig. 2 Change in the groundwater level (in metres) experienced by farmers across different agro-climatic zones between 2000 and 2010

On the other hand, in the sub-mountainous zone (Gurdaspur), only 20% of the farmers experienced groundwater depletion of greater than 3 metres. In the south-western zone (Ferozpur), only 10% of the farmers experienced a fall in the groundwater level of between 6 and 15 metres, while the remaining 90% of the farmers saw either a fall of between 3 and 6 metres or a rise. Note that the groundwater of this region is often not fit for irrigation; it is brackish and needs to be used in combination with surface water. Overall, the data suggests that groundwater resources in Punjab are continuously depleting, especially in the central region where the depletion rate between 2000 and 2010 had been relatively very high.

3.3 Socio-economic factors affecting the groundwater depth

In addition to agro-climatic conditions and regional topography, groundwater level (*effect*) is affected by a range of socio-economic (farmer-and farm-specific) factors (*cause*). Table 4 shows that the groundwater depth varied significantly with respect to agro-climatic region, farmers' educational level, and crop diversity whereas the other factors e.g. size of landholding, farmer age, tractor ownership, cropping intensity, and farmers' connectivity to extension had no significant association with the groundwater level.

Table 4 A general ANOVA model showing the level of variation in the Average Groundwater Level (AGL in metres) with respect to various socio-economic factors

Tests of Between-Subjects Effects

Dependent Variable: Average Groundwater Level (in metres)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5449.642[a]	14	389.260	14.901	.000
Intercept	3142.387	1	3142.387	120.290	.000
Agro-climatic region	**3490.463**	**2**	**1745.231**	**66.807**	**.000**
Landholding size	34.768	2	17.384	.665	.516
Farmer age	10.887	2	5.444	.208	.812
Farmer education	**183.000**	**2**	**91.500**	**3.503**	**.034**
Tractor ownership	15.404	1	15.404	.590	.444
Cropping intensity	62.120	2	31.060	1.189	.309
Crop diversity	**251.723**	**2**	**125.862**	**4.818**	**.010**
Connectivity to extension	5.974	1	5.974	.229	.633
Error	2742.949	105	26.123		
Total	31239.000	120			
Corrected Total	8192.592	119			

a. R Squared = .665 (Adjusted R Squared = .621)

Source: Model results

The groundwater depth varied significantly ($F(2, 105) = 66.807$, $p < .001$)) across agro-climatic regions with the deepest being Barnala, followed by Gurdaspur and the highest being Ferozpur. These Figures are in agreement with the state-level estimates (Fig. 3). The post-hoc comparisons suggested that the groundwater level was significantly deeper in Barnala (*Mean difference* = 10 metres, *SE* = 1.143, $p < .001$) than in Gurdaspur as well as (*Mean difference* = 15 metres, *SE* = 1.143, $p < .001$) in Ferozpur. Further, it was also significantly deeper in Gurdaspur (*Mean difference* = 5 metres, *SE* = 1.143, $p < .001$) than in Ferozpur. Most farmers in Barnala were facing low groundwater levels whereas, in Gurdaspur and Ferozpur, some of them reported waterlogging resulting in damaged crops. Further, the standard error Figures suggest wide variations within the regions as well.

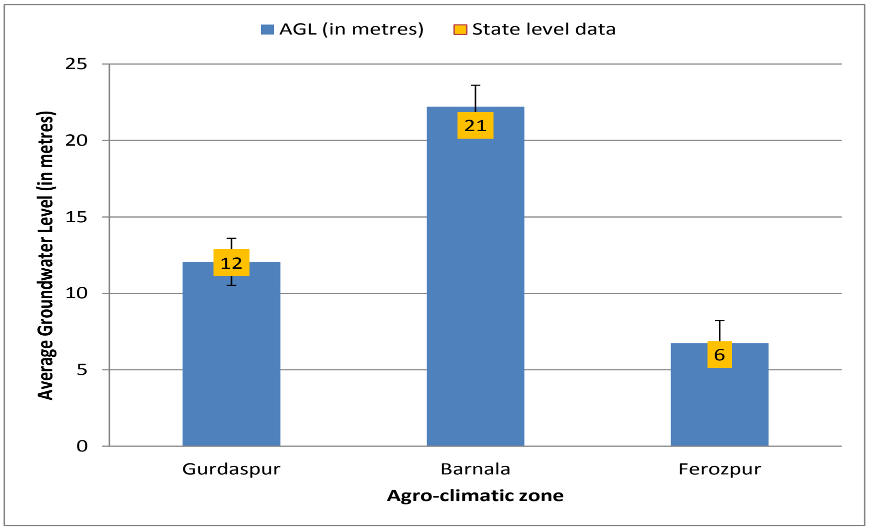

Fig. 3 Average Groundwater Level (AGL in metres) across all three agro-climatic zones

Notes: The State level data are the average of minimum and maximum levels of groundwater in June 2010

Source: Survey data; GoP (2012)

Further, the association between farmer education and groundwater level was significant (F (2, 105) = 3.503, $p < .05$)). Fig. 4 suggests that both the illiterate and graduate farmers, although constituting only 22% of the total farmer population, were withdrawing the groundwater from deeper levels (15 metres) than other farmers (12 metres). However, the post-hoc comparisons suggest that illiterate and graduate farmers had a significantly deeper levels of groundwater (*Mean difference* = 3 metres, SE = 1.465, $p < .01$) than other farmers who made up 78% of the total.

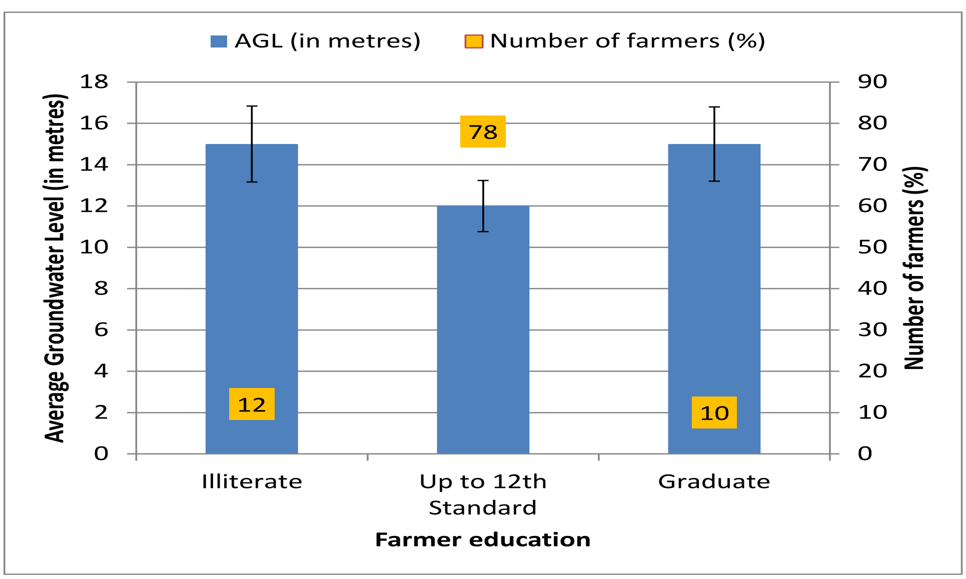

Fig. 4 Average Groundwater Level (AGL in metres) with respect to educational attainments among farmers

Source: Survey data

Results suggest a direct relationship between crop diversity and groundwater depth. For instance, farmers with a higher crop diversity (> 0.70) had significantly (F (1, 105) = 4.818, p < .05) shallower groundwater depth (10 metres) compared with those who chose to concentrate on fewer crops (14-16 metres) (Fig. 5). This specialized group (with crop diversity below 0.70) accounted for 93% of the total farmer population. Thus, the mono-cropping could be one of the reasons for the depletion of sub-soil water in Punjab. The post-hoc comparisons suggest that farmers with crop diversity index of more than 0.70 had significantly (*Mean difference* = 5 metres, *SE* = 1.946, p < .05) shallower groundwater levels than those whose level of diversity was less than 0.60. However, farmers having diversity level of 0.60-0.70 and more than 0.70 were withdrawing the groundwater from similar levels.

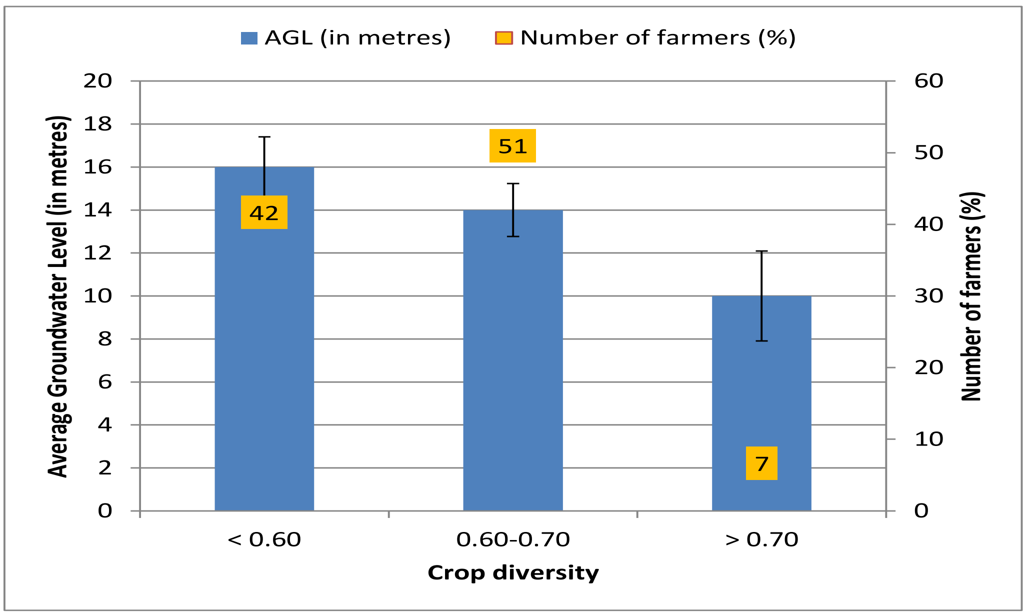

Fig. 5 Average Groundwater Level (AGL in metres) with respect to varying levels of crop diversity

Source: Survey data

As the level of groundwater across Punjab varied mainly due to agro-climatic conditions, statistical comparisons were also made within each of the three regions. In Gurdaspur, the groundwater level varied significantly with respect to farmer education (F(2, 28) = 3.694, p = .05), cropping intensity (F(1, 28) = 7.484, p = .05), and crop diversity (F(2, 28) = 4.196, p = .05) whereas, in Barnala and Ferozpur, it had a significant association with farmer education (F(2, 28) = 4.740, p = .05) and crop diversity (F(2, 28) = 4.641, p = .05) respectively (Table 5).

Table 5 A general ANOVA model showing a district-wise level of variation in the Average Groundwater Level (AGL in metres) with respect to various socio-economic factors

Tests of Between-Subjects Effects						
Dependent Variable: Average Groundwater Level (in metres) in Gurdaspur, Barnala and Ferozpur						
	Gurdaspur		Barnala		Ferozpur	
Source	**F**	**Sig.**	**F**	**Sig.**	**F**	**Sig.**
Corrected Model	2.008	.067	1.258	.298	1.994	.067
Intercept	24.283	.000	104.290	.000	5.965	.021
Landholding size	2.355	.113	.196	.823	.261	.772
Farmer age	.374	.691	.060	.942	.573	.571
Farmer education	**3.694**	**.038**	**4.740**	**.017**	.873	.429
Tractor ownership	1.515	.229	.217	.645	.094	.761
Cropping intensity	**7.484**	**.011**	.577	.454	.810	.455
Crop diversity	**4.196**	**.025**	.401	.673	**4.641**	**.019**
Connectivity to extension	.286	.597	.689	.414	.051	.823
Error	841.254	28	682.410	28	405.463	27
Total	7337.000	40	21135.000	40	2767.000	40
Corrected Total	1504.775	39	1019.775	39	764.775	39
R Squared: Gurdaspur=.441; Barnala=.331; Ferozpur=.470 (Adjusted R Squared: Gurdaspur=.221; Barnala=.068; Ferozpur=.234)						

Source: Model results

In relation to farmer education (Fig. 6), graduate farmers in Gurdaspur and Barnala were extracting water from deeper levels (19 and 27 metres) than the school-educated farmers (11 and 19 metres) who accounted for 82% and 73% of the total farmer population respectively. However, illiterate farmers in Gurdaspur had shallower groundwater levels (4 metres) but at the same time, in Barnala, they experienced much deeper levels of groundwater (26 metres) than the majority of farmers (19 metres). Post-hoc comparisons showed a significant groundwater level variation (*Mean difference* = 5 metres, *SE* = 1.884, $p < .05$) between illiterate and other farmers in Barnala while, in Gurdaspur, they did not suggest a significant variation with respect to farmer education.

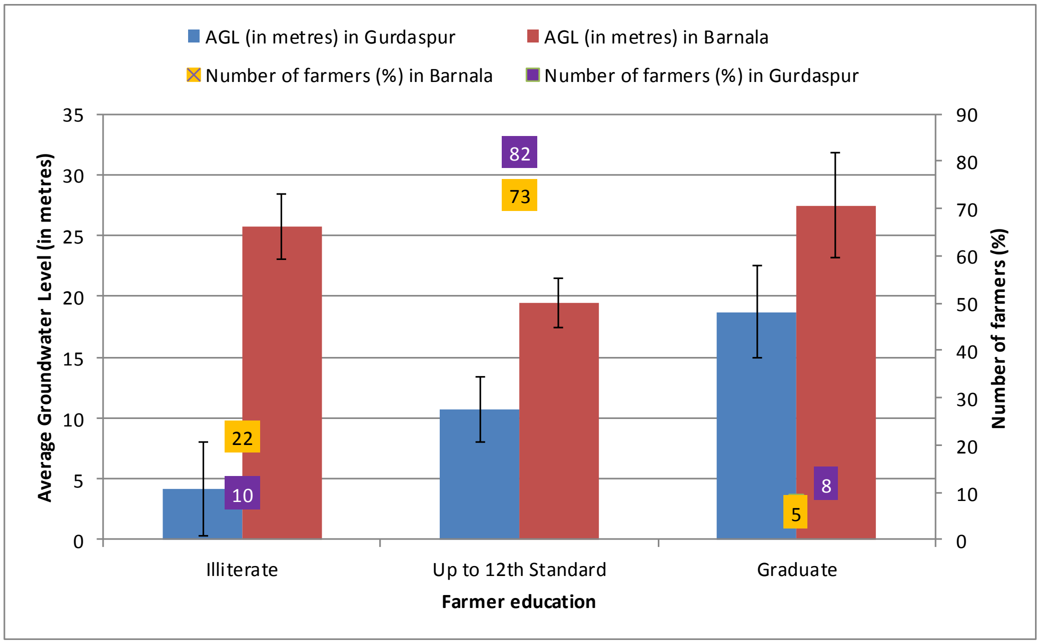

Fig. 6 Average Groundwater Level (AGL in metres) with respect to farmer education in Gurdaspur and Barnala

Source: Survey data

Compared with the respective overall averages, school-passed farmers in Gurdaspur and Barnala had much shallower water level (11 and 19 metre) than the respective overall averages (12 and 22 metres) while the graduate farmers in both regions had deeper groundwater levels (19 and 27 metres) than the respective overall averages. Overall, farmer education in Gurdaspur presents a clear association (direct relationship) with groundwater level whereas in Barnala, this relationship provides no trend.

In relation to cropping intensity (Fig. 7), farmers growing less than two crops in a year (200%) in Gurdaspur had deeper groundwater (16 metres) than those who grew just two crops (6 metre). However, no farmer here grew more than two crops in a given year. Fig. 7 illustrates clearly that farmers concentrating on fewer crops (less than 0.60) both in Gurdaspur (sub-mountainous) and Ferozpur (south-western zones) were withdrawing groundwater from significantly deeper levels (16 and 10 meters) compared with (4 meters) those who decided to grow a variety of crops (more than 0.70) although the proportionate number of such farmers in both the regions was only 8%. Other farmers, who had a crop diversity between 0.60 and 0.70, had groundwater levels of 14 and 5 metres and such farmers constituted about half of the total farmer population in both the regions.

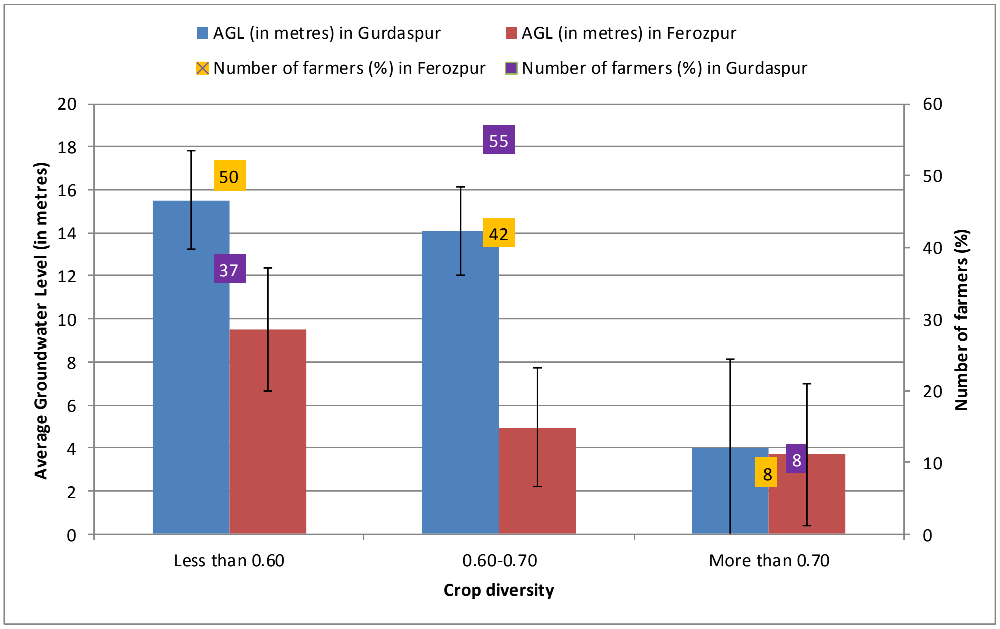

Fig. 7 Average Groundwater Level (AGL in metres) with respect to the level of crop diversity in Gurdaspur and Ferozpur

Source: Survey data

The post-hoc comparisons suggested that farmers in Ferozpur with a lower crop diversity (less than 0.60) had extract from significantly deeper than those who had a crop diversity of 0.60-0.70 (*Mean difference* = 4 metres, *SE* = 1.278, $p < .01$) and more than 0.70 (*Mean difference* = 7 metres, *SE* = 2.399, $p < .05$). However, groundwater level did not vary significantly between farmers having a crop diversity of 0.60-0.70, and beyond 0.70. For Gurdaspur, these variations were insignifcant.

Farmers were asked to comment on some policy related questions, particularly on crop diversification and free electricity to the farm sector. Seventy percent of the farmers felt that lower crop diversity due to an expansion of area under rice has led to a mining of sub-soil water resources in Punjab although only one-third of them would consider stopping rice cultivation. Probably, that is why no farmer suggested stopping of free electricity to farm sector as it helps them bring irrigation costs down to almost zero. However, 82% farmers, who responded to these questions, were ready to pay for electricity if government ensures a regular supply. One-fifth of the farmers would consider delaying rice planting further until 30th June (which is currently 15th June).

4. Discussion

Groundwater depletion in Punjab is a general phenomenon although more serious in the central zone where the average groundwater depth was reported as 22 metres compared with 12 metres in sub-mountainous (Gurdaspur) and 7 metres in south-western (Ferozpur) zone. Further, a wider variation within the zones suggests that not only the agro-climatic conditions but a range of other factors also affect the withdrawal of groundwater resources.

Two-third of the farmers witnessed an annual fall ranging from between 50 cm and 1.5 metres. These findings are almost similar to the findings of CGWB (2012) using data from 361 monitored wells across Punjab. In the central zone, where the problem of groundwater depletion is more severe than the other regions, only 5% of the farmers were accessing groundwater at a depth shallower than 11 metres. More than 65% of the sampled farmers reported that the groundwater level had declined more than 60 cm annually and another 26% found this depletion beyond 1.5 m. However, the groundwater depletion in the sub-mountainous region is not currently that serious. However, continuously expanding rice cultivation and shrinking canal irrigation base in the south-western region, which is traditionally known as the cotton belt of Punjab, could create further implications for the ecological balance of this region. Thus, both the existing literature (CGWB 2012; Singh 2012a) and results of this study are in agreement and suggest that Punjab is facing a serious crisis regarding its groundwater resources, creating a range of long-term implications for the next generation.

In terms of major drivers of change in the groundwater level, besides agro-climatic conditions, farmer education and low crop diversity had a significant association with it. However, the relationship between farmer education and groundwater level does not provide a clear picture as both highly educated (graduate) and illiterate farmers had deeper groundwater levels than other farmers. Therefore, farmer education cannot be directly linked to groundwater depletion in Punjab.

A clear linear relationship between crop diversity (i.e. high rice intensification) and groundwater level across the regions as well as within the regions (Gurdaspur and Ferozpur), suggests that if water conservation is to increase, the culture of mono-cropping focused around rice cultivation needs to be discouraged or more sustainable ways of rice cultivation are to be found and disseminated to farmers. However, despite State government's efforts to increase crop diversity, the area under wheat and rice is constantly expanding (PSFC 2013). In fact, wheat and rice make the best crop combination in terms of economic returns and productivity related risks (Shergill, 2013; Sarkar and Das, 2014). Further, based on the instability indices calculated for major crops in Punjab from 1970-71 to 2006-07; instability indices of wheat and rice were 0.06 and 0.08 respectively, while for cotton, sugarcane and maize, the major crops suggested by the Punjab government in its recent policy draft (PSFC 2013), the respective Figures were 0.27, 0.07 and 0.18 (Sidhu and Vatta n.d.). Therefore, farmers in Punjab lack a set of alternative crops which not only could compete with wheat and rice in terms of economic returns and productivity related risks but also consume less water and allow seepage for groundwater recharging. In fact, it is a clarion call for the agricultural researcher, scientists and policy makers to provide a sustainable crop-mix to farmers.

However, here, it is essential to understand that the problem is the over-withdrawal of groundwater not rice cultivation *per se*. Therefore, technical diversification could be one of the potential solutions rather than compelling farmers to diversify in the absence of economically viable alternative crops to wheat and rice. If farmers are educated to cultivate rice using more sustainable farming techniques in addition to widely establishing more efficient rain harvesting techniques, both the economic and environmental goals of agricultural sustainability could possibly be achieved. Here, it is to be noted that various water saving techniques except SRI (System of Rice Intensification) and direct seeding cannot be effectively used in rice cultivation.

While looking at a continuous lowering of crop diversity in Punjab, it could be a manifestation of provision of free electricity to farm sector as the area under rice increased steeply in 1997 when the state government introduced this policy (Sarkar and Das 2014). Thus, it could be a major catalyst which encourages farmers to grow wheat and rice and discourages them from using water conservation technologies despite heavy government subsidies. However, Singh (2012a) argued that even if the electricity subsidy were withdrawn, wheat and rice would still remain the best crop mix in terms of net economic returns. Further, with the current productivity levels and pricing mechanism in the state, saving electricity through crop diversification is not economically feasible as it will bring monetary losses to farmers and, eventually they will return to wheat-rice rotation unless they don't get financial incentives from the government. It is estimated that the amount of financial support required to make a shift in the current cropping pattern, especially shifting of one-fourth of the area under rice to maize, is much higher than the total electricity subsidy saved in the next 10 years alongside continuous groundwater depletion (Sarkar and Das 2014). Thus, the past and the present crop diversification plans are not economically feasible without a robust financial backup plan from the central government as the state government is already facing financial straits[19].

In terms of association of groundwater level with socio-economic factors within the agro-climatic regions, graduate farmers in Gurdaspur and Barnala had been over-exploiting the groundwater resources more randomly than the poorly-educated farmers. However, at the same time, poorly-educated farmers in Barnala were withdrawing water from shallower levels than the illiterate and graduate farmers. Although the results don't provide any clearer relationship between farmer education and groundwater resources, it provides ample opportunities to the State extension agencies (Department of Agriculture, Punjab and Punjab Agricultural University Ludhiana) to educate farmers about the ecological implications of a declining groundwater level and trying to convince them to adopt more sustainable farming techniques that save water without reducing their net profitability. This involves some challenges as only a limited number of farmers are currently connected to public extension services in India (NSSO 2005) and it is also not certain whether the currently employed public extensionists have an updated and correct knowledge and the required skill set to deal with sustainable agriculture related issues.

5. Conclusions

This research suggests that groundwater depletion in Punjab, in general, and in the central zone, in particular, is a serious concern in relation to the environmental sustainability of farm enterprises in Punjab. Both the results of this study and literature suggest that, in the central zone, the groundwater level on 92% of the farms had depleted by more than 0.60 metres annually between 2000 and 2010. While, the current state of groundwater resources in the other two regions is not too serious and manageable for the time being. However, if the existing policy framework for groundwater resources in the state, which allows the state government to release 0.11 million more connections to

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[19] The militant movement (1980-1992) aimed at creating a separate Independent State for Sikhs along with other economic and political issues jeopardized Punjab's economy. Punjab has been borrowing continuously from national and international financial institutions including the Union government since the mid-1980s (Kaur 2010). Punjab's present debt is Rs 7,75,850 million (GoP 2012).

farmers putting much pressure not only on the groundwater resources but also burdening the state exchequer, continues, Punjab can end up losing much of its groundwater resources.

Further, crop diversity emerged as the main driver of change in the groundwater level not only across regions but also within the regions except the central zone (Barnala) where the crop diversity was the lowest and had very little variation within the region. Education among farmers across regions as well as in the sub-mountainous (Gurdaspur) and the south-western (Ferozpur) zones had an unclear relationship with groundwater levels.

Given that the groundwater depletion in Punjab is a complex problem with a range of policy, economic, attitudinal, social and political dimensions, a multidimensional approach will be required to overcome further over-abstraction. The following measures could form the basis of such an approach:

1. As the results suggest a significant association between the level of crop diversity and groundwater resources, and the literature hits at the failure of past crop diversification policies in Punjab, future crop diversification policies and programs need to be more practical and pragmatic bearing in mind the agro-climatic conditions and market potential of different agro-climatic regions. It will need a close synchronization of policy, research and extension agencies so that whatever is planned by the policy makers and endorsed by the researchers, the same should be disseminated to farmers with no communication gap. Crop-diversification plans should address the productivity and marketing-related risks so that farmers feel convinced and can have enough confidence to experiment with alterative cropping patterns.
2. Policy makers should be aware that wheat-rice makes the best crop combination in terms of lower productivity risks and higher economic returns, therefore, the future policies can also target technical diversification in terms of reducing water use in wheat-rice cultivation. As the adoption of water conservation technologies is low in Punjab, government could initiate more pragmatic programs to disseminate these technologies. However, researchers should evaluate the success rate and economic rate of return of all the technologies before prescribing them to farmer.
3. Farmers can sow a third (preferably non-irrigated) crop in between wheat and rice, i.e. mungbean (a legume), during May-June, as the cropping intensity did not show any negative effect on the groundwater resources and soil health. It will not only bring higher returns to farmers but also

improve soil health. Additionally, scientists have to provide short-duration crop varieties to facilitate cultivation of three crops in a year and extensionists might need to update their knowledge on new crops and their cultivation methods as they have specialized around wheat-rice production systems for decades.

4. "The Punjab Preservation of Sub Soil Water Act, 2009" which currently forbids farmers to transplant rice before 15th June, needs reviewing as one-fifth of the farmers surveyed agreed to delay sowing of rice by another two weeks. Additionally, as monsoons reach Punjab by the first or second week of July, June 15th could be extended to June 30th that would help save water used for rice cultivation without compromising the productivity levels.

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Conflict of Interest' statement

The authors declare that they have no conflict of interest.

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