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Bailout with White Revolution or Sink Deeper? Groundwater Depletion and Impacts in the Moga District of Punjab, India

Upali A, Amarasinghe, Vladimir Smakhtin, Bharat R. Sharma and Nishadi Eriyagama

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IWMI Research Report 138

Bailout with White Revolution or Sink Deeper? Groundwater Depletion and Impacts in the Moga District of Punjab, India

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Cover photograph shows groundwater pumping; and livestock population in the Moga District (inset) (photo credits: Bharat Sharma).

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Summary

This report assesses water depletion from the consumptive water use (CWU) of agricultural production in the Moga District of the State of Punjab in India. In particular, it focuses on the growth in agricultural production and stress on water resources induced by groundwater irrigation.

Forage crops, wheat and rice comprise more than 99% of the annual cropped area in Moga, making milk-wheat-rice the dominant production system. The CWU of milk, wheat and rice production is estimated to be 940, 554 and 1,380 cubic meters per tonne (m^3/tonne), respectively. The contribution of groundwater to the total annual irrigation CWU — 94% of 1,461 million cubic meters (MCM) — is so large that groundwater embedded in the surplus production over the local consumption of rice, wheat and milk alone exceeds the estimated groundwater recharge in the District. The groundwater CWU in rice production is 1.7 to 2 times higher than those of milk and wheat. This suggests that a reduction in rice cultivation throughout Moga is the key to lowering the groundwater CWU.

The financial value of the output of the rice-wheat-milk production system is 10 and 27% lower than that of the milk-wheat and milk-only production systems, respectively. Thus, the intensification of dairy production, with a calculated reduction in the rice area to compensate for increasing requirements for green fodder, can bring the groundwater depletion to sustainable limits, while producing a surplus of rice for export. The optimum combination is to reduce the rice area from 90 to 62% of the net irrigated area (NIA) and increase the green fodder area from 10 to 20% of NIA in the *Kharif* (summer) season; allocate 90 and 10% of the NIA for wheat and green fodder in the *Rabi* (winter) season; and double the lactating dairy animals from 4 to 8 per 6 hectares (ha) of land.

Moga is only one microcosm example of the prevailing precarious situation. Reduction of the rice area and intensification of dairy production with more green fodder may be a viable solution throughout the entire State of Punjab. Many other regions in India also suffer from similar unsustainable groundwater use. A measured change in agricultural production patterns is a possible way out for these regions from this precarious situation of groundwater depletion.

Bailout with White Revolution or Sink Deeper? *Groundwater Depletion and Impacts in the Moga District of Punjab, India*

Upali A. Amarasinghe, Vladimir Smakhtin, Bharat R. Sharma and Nishadi Eriyagama

Introduction

Moga, a district in the State of Punjab in India, is a microcosm of the twin story of irrigation-induced growth and stress. Irrigation was a major catalyst for (a) the successful green revolution resulting in increases in wheat and rice productivity (Dhawan 1988), and (b) the white revolution by providing fodder crops for animal feed resulting in increases in milk production. Growth in agricultural productivity was the major driver behind the economic growth in Moga. However, extensive groundwater irrigation that revolutionized agricultural production is also the cause for severe water stress (Shah 2009).

Considered as the seat of the Green Revolution in South Asia, the State of Punjab, with only 1.5% of the land area, contributes 12% of the total food grain production — 230 million tonnes (Mt) — of India in 2007/2008 (GoI 2009). Punjab also offers 60 and 40% of its total production of wheat and rice, respectively, each year to the national pool for maintaining stocks and operating public distribution systems for the poor and food-deficit states (GoP 2010).

Almost the entire cultivable area of the State of Punjab is irrigated by canals and groundwater (GoI 2009). Irrigation was the major catalyst for the green revolution, fuelling the use of high-yielding varieties and better management of other inputs. As a result, the crop productivity in Punjab is one of the highest in the country. The average yield of all important food grain crops is the highest (about 4.2 t/ha), and is 2.3 times the national average (GoI 2009). However, extensive irrigation development, especially groundwater, also brought severe water stress.

Almost all the area of the State is experiencing physical water scarcity, meaning that no more water resources are available for further development without endangering the environment or other uses (Amarasinghe et al. 2007). The groundwater development is so extensive that 79% of the groundwater assessment divisions (“blocks”) in the State are now considered ‘overexploited’ and ‘critical’ (CGWB 2010). The water stress has, therefore, become the limiting factor for sustainable agricultural growth and overall development of the State.

Many interventions have been proposed recently to reduce groundwater overabstraction. These include the recently enacted “Punjab Preservation of Subsoil Water Act of 2009” for delaying paddy transplantation, laser land leveling, resource conservation technologies, introducing low water consuming crop varieties, and agriculture diversification (Singh 2009). However, the impacts of such measures on sustainable agricultural production are not well understood.

This report assesses the water depletion and its impacts caused by the production of milk, rice and wheat within the boundaries of the Moga District. Rice and wheat, mainly for food, and forage crops for animal feed occupy more than 99% of the cropped area in Moga. This report focuses, in particular, on the growth in agricultural production and the stress on water resources induced by groundwater irrigation. The major objectives of this study are to:

- Assess water depletion in the process of agricultural production in the Moga District of the State of Punjab,
- Examine the impacts of water depletion - in various agricultural production systems - on groundwater use, and
- Propose improved water management practices that farmers can use to reduce water depletion and enhance water productivity.

This report is based on secondary and primary data collected in the Moga District. The primary data are from the questionnaire survey of 300 households that were interviewed between October and December of 2009.

After a brief profile of Moga in the section, *Moga District and its Groundwater Development*, the concept and methodology used in the assessment of water depletion of milk, rice and wheat production in Moga are presented in the section, *Methodology, Data and Assumptions*. The water depletion of milk, rice and wheat production are presented in the section, *Estimates of Consumptive Water Use*. This is followed by the analysis of total water depleted and its impacts on water resources of Moga in the section, *Total Consumptive Water Use and Impacts*. Various interventions and their impacts on water use are discussed in the section, *Interventions for Reducing Internal Water Consumption*. The final section, *Conclusions and Policy Recommendations*, concludes the report with a discussion of options available for policymakers and farmers for achieving sustainable water use in Moga and similar agroecologies elsewhere.

Moga District and its Groundwater Development

Moga District: A Brief Profile

The Moga District, with an area of 2,235 square kilometers (km^2), is the eleventh largest of the 20 districts in the State of Punjab in India. It consists of 5 administrative blocks (Figure 1) with a total of 330 villages. Average annual rainfall is 498 millimeters (mm). Average daily temperatures vary from 5 to 48 °C.

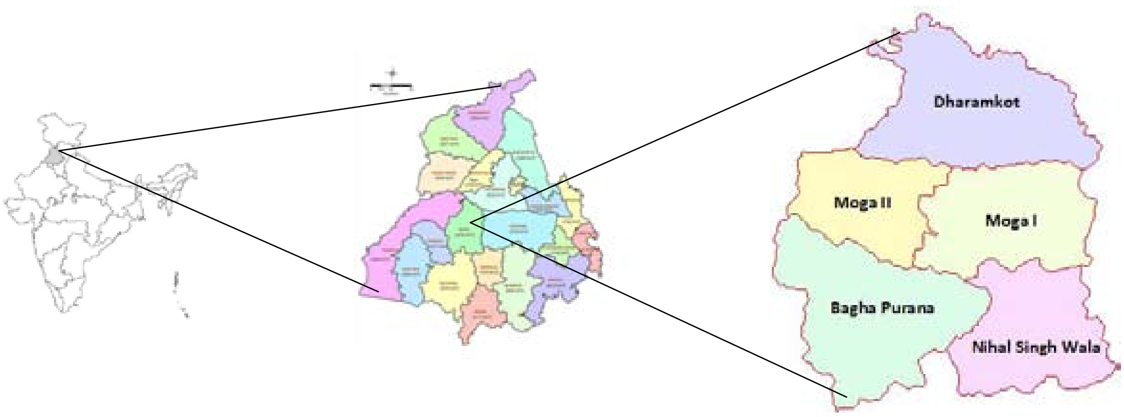

FIGURE 1. Block boundaries of the Moga District in the State of Punjab. *Source*: Punjab Remote Sensing Center, Ludhiana. Maps available at the Punjab Environmental Information System web portal: http://punenvis.nic.in/index.htm

A large part of the population lives in rural areas (Table 1) and they depend on agriculture for their livelihoods. Rice in the *Kharif* season (June/July to September/October) and wheat in the *Rabi* season (October/November to March/April) are the dominant food crops. A substantial area under fodder crops, such as sorghum (jowar), maize, millet, barley, berseem and oats, provide year-round green fodder feed for large cattle and buffalo populations and for a small population of other animals (goats, sheep, horses, etc.). Small areas are also under cotton and maize in the *Kharif* season, and gram and potatoes in the *Rabi* season.

With a very high level of per capita consumption, a substantial part of the milk produced is consumed locally. The surplus milk is procured by local vendors, milk contractors and the dairy companies such as Nestlé. Nestlé, a major food and beverage company, started its operations in Moga in 1961 with 180 farmers and 511 liters of milk procured daily through four collection centers (Nestlé 2010). By 2009, Nestlé has linked with about 85,000 farmers and is now handling 500,000 to 1.3 million liters of milk collected daily through 2,800 collection centers in the Moga and neighboring districts.

Groundwater Stress

Monitoring of the groundwater table carried out by the Central Ground Water Board shows excessive groundwater abstraction throughout the state (CGWB 2010). This is corroborated by the information derived through satellite data for the northwestern India (Rodell et al. 2009). All the cultivated area, covering 90% of the land in the Moga District, is irrigated (DoAAD 2009). Of the NIA, only 2.4% is canal irrigated, and 53.5% is groundwater irrigated. The remaining area is under conjunctive irrigation from canals and tube wells.

TABLE 1. Area, demography and water availability of blocks in the Moga District.

Block name (Figure 1)	Land area	Number of villages	Population		Number of families	Net irrigated area	Net groundwater recharge	Groundwater withdrawals	
			Total	Rural				For irrigation	For all uses
	(1,000 ha)	(#)	(1,000s)	(1,000s)	(1,000s)	(1,000 ha)	(MCM)	(MCM)	(MCM)
Bagha Purana	57.3	47	220	176	30	49.6	257	444	447
Dharamkot	54.9	150	212	169	29	48.9	365	502	506
Moga I	39.8	48	167	134	23	33.4	209	422	428
Moga II	33.3	46	126	101	17	29.0	208	386	391
Nihal Singh Wala	38.2	39	170	136	24	33.9	181	392	394
Moga	223.5	330	895	716	123	194.8	1,220	2,146	2,166

Source: DoAAD 2009

Groundwater is provisioned through 49,662 electric motor pumps and 20,108 diesel pumps (CGB-NWR 2009). Annual groundwater withdrawals for irrigation (ninth column in Table 1) far exceed the sustainable level of groundwater supply (eighth column in Table 1). All administrative blocks in Moga, therefore, have a negative groundwater balance. This results in a declining rate in the water table that varies between the block from 7 to 20 meters (m) per decade in the last decade (Figure 2). The groundwater overexploitation is a serious concern for sustainable agricultural production.

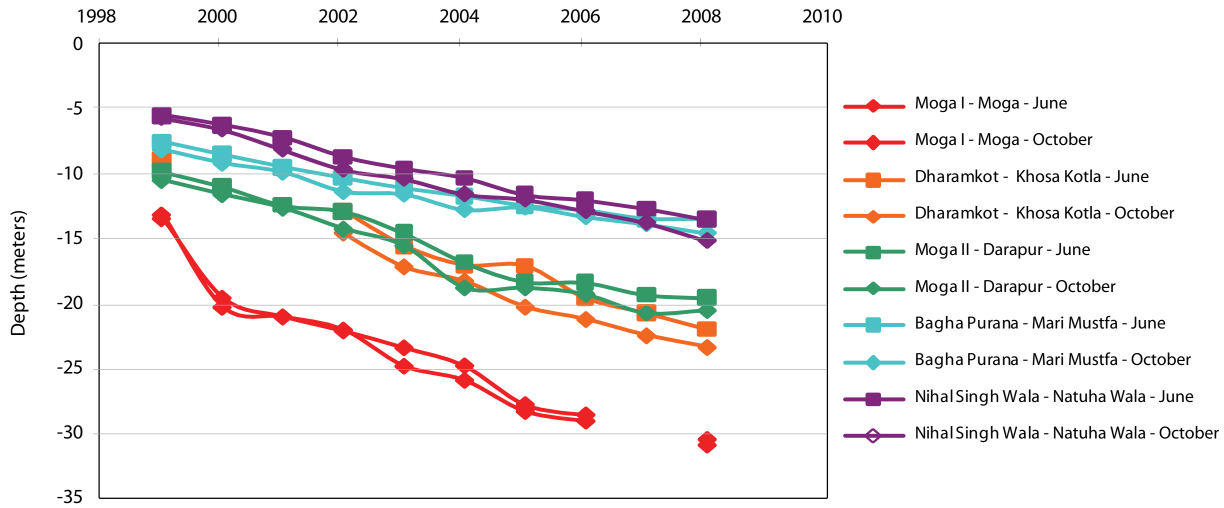

FIGURE 2. Depth to groundwater table at the start (June) and end (October) of the *Kharif* season in five observational wells in the blocks of Moga. *Source*: Department of Agriculture, State of Punjab (unpublished data).

Methodology, Data and Assumptions

Internal and External Water Depletion

The water accounting framework of Molden (1997) is the basis for assessing different components of water depletion. Water depletion during a crop or milk production process can be accounted through *CWU*, which is the depletion through evapotranspiration; or *non-consumptive water use*, which is the return flow that may or may not be captured for further use. A *beneficial* component of the CWU is the evapotranspiration directly from the production process of milk and crops. The other component, called *non-process CWU*, is the evapotranspiration from areas outside the production process, which includes evapotranspiration from water bodies, bare surface, other vegetation, etc. A part of the non-process CWU can be beneficial.

The total water depletion in the production process has two components (Figure 3), namely: i) water depleted within the production area, and ii) water embedded in other inputs used in the production process. These are also often referred to as 'internal' and 'external' water footprints (Hoekstra 2003). The latter ('external water footprint') is also called 'virtual water' (Allan 1998); The internal depletions when aggregated over all commodities such as fodder, rice, wheat, and other crops and services (drinking, bathing and servicing of animals) indicates the extent of depletion of available water resources within the boundaries of the district.

Components of Internal and External Depletion

Both internal and external components account for three aspects of water depletion: consumptive water use (CWU) from effective rainfall ($CWU^{Effective\ rain}$) and from irrigation ($CWU^{Irrigation}$); and the water depletion that occurs due to pollution ($DEP^{Pollution}$) (Equation 1). These three components are also called 'green', 'blue' and 'grey' water footprints in some literature sources (Hoekstra 2003; Chapagain and Hoekstra 2004; Chapagain and Orr 2009).

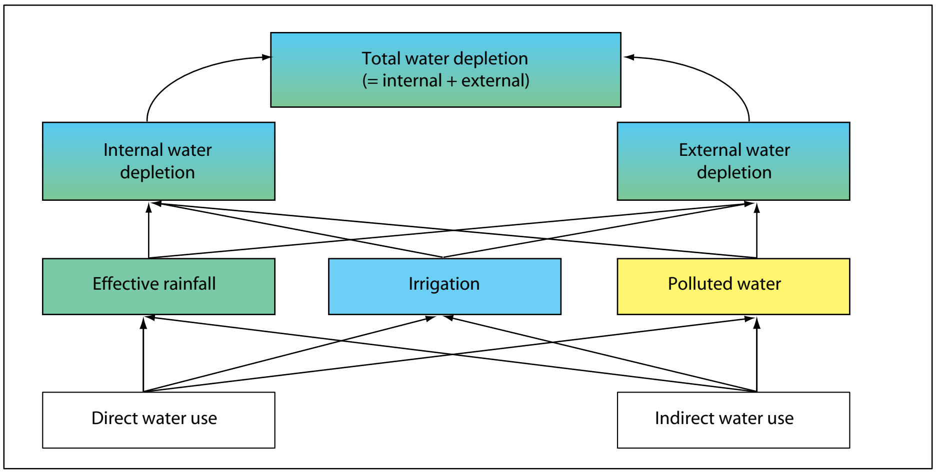

FIGURE 3. Process of estimation of water depletion.

$$\left.\begin{array}{r} \textit{Internal water depletion} \\ \textit{External water depletion} \end{array}\right\} = CWU^{\textit{Effective rain}} + CWU^{\textit{Irrigation}} + DEP^{\textit{Pollution}} \qquad (1)$$

The total (internal or external) depletion includes water depleted *directly or indirectly* in the production process. Milk production has a significant indirect water use component (Table 2). Water used for drinking and bathing of animals is a direct water use. Green and dry fodder production is a direct water use. But these are indirect water uses in the context of milk production. Rice and wheat production mainly have a direct water use. Indirect water use through seeds and other inputs, in general, is much smaller and hence can safely be assumed to be negligible for computational purposes.

TABLE 2. Contributions from direct and indirect water use to components of water depletion.

Depletion in the production of:	Direct water use			+	Indirect water use
Milk	Effective rain	=	N/A	+	CWU from soil moisture in fodder and other feed crops
	Irrigation	=	Drinking/servicing of animals	+	CWU from irrigation in fodder and other feed crops
	Pollution	=	Water required where its quality deteriorates below drinking water standards due to manure	+	Water required where its quality deteriorates below drinking water standards through input use or in by-products
Crop[1]	Effective rain	=	CWU from soil moisture in crop production	+	N/A
	Irrigation	=	CWU from irrigation water in crop production	+	N/A
	Pollution	=	Water required where its quality deteriorated below drinking water standards from input use or in by-products	+	N/A

Notes: [1] Crops are rice, wheat, green fodder (sorghum, maize, berseem, oats, etc.); N/A = not applicable

Methodology

This report mainly deals with estimation of the first two components in Equation 1, which are important for physical water accounting in the production processes. The third component indicates the extent of water pollution due to various input uses and wastewater generated during the production processes. This component is sometimes estimated as the quantity of freshwater that is required if the polluted water is to be brought to ambient (drinking) water quality standards (Hoekstra et al. 2009). However, the wastewater generated from many irrigated areas is often reused downstream. Some of the polluted water may contain nutrients beneficial to crops. Many of the parameters for estimating the third component is not easy to collect. While it is acknowledged that this component has a role to play, its estimation is beyond the scope of this report.

If rainfall meets the full crop water requirement, then CWU from effective rainfall ($CWU^{Effective\ rain}$) equals actual evapotranspiration (ETa) in four crop growth periods (initial, development, mid- and late stage) (Allen et al. 1998). If rainfall is insufficient to meet full crop water requirement, the $CWU^{Effective\ rain}$ equals the effective part of rainfall at the root zone (P_{eff}):

$$CWU^{Effective\ rain} = Min\ (ETa,\ P_{eff}) \qquad (2)$$

where:

$$ETa = \sum_{i=1}^{4} k_i \times \sum_{month\ j\ in\ i^{th} growth\ period} d_{ij}\ ETp^{ij} \qquad (3)$$

$$P_{eff} = \sum_{i=1}^{4} \sum_{month\ j\ in\ i^{th}\ growth\ period} \frac{d_{ij}}{n_{ij}} P_{eff}^{ij} \qquad (4)$$

and k_i is the crop coefficient of the i^{th} growth period, and d^{ij} and ETp^{ij} are the number of days and daily potential evapotranspiration of the j^{th} month in the i^{th} crop growth period, respectively. P_{eff} is calculated as:

$$P_{eff}^{ij} = \begin{cases} P75^{ij} \times (125 - .2 \times P75^{ij}) \\ \quad if\ P75^{ij} \leq 250\ mm \\ 125 + 0.1 \times P75^{ij} \\ \quad if\ P75^{ij} > 250\ mm \end{cases} \qquad (5)$$

where: $P75^{ij}$, and n_{ij} are the daily 75% exceedence probability of rainfall and total number of days in the j^{th} month of the i^{th} crop growth period, respectively.

When irrigation meets part of the deficit crop water requirement, the net evapotranspiration (NET) from irrigation water is the irrigation CWU (Equation 6).

$$CWU^{Irrigation} = NET = ETa - P_{eff} \qquad (6)$$

Total water depletion in the production process is estimated in terms of CWU per unit of product (m^3/tonne/year), and total CWU for the production system per year (m^3/year).

Irrigation water withdrawals (Q, m^3) include both surface water and groundwater, and are estimated as:

$$Q = \{A_{canal}\ x\ NI_{canal}\ x\ d_{canal}\ x + (pd_{gw}\ x\ NI_{gw}\ x\ h_{gw})\}\ x\ 10^4 \qquad (7)$$

where: A_{canal} is the canal irrigated area (ha); NI_{canal} and NIgw are the number of irrigation applications from canal and groundwater resources; d_{canal} is average depth of a canal irrigation application (m); h_{gw} is the average time of groundwater pumping per irrigation (hours); and pd_{gw} is pump discharge (m^3/hours). In conjunctive irrigation, A_{canal} and groundwater irrigated area are the same (Michael 2001). The ratio of $CWU_{Irrigation}$ (Equation 6) to Q (Equation 7) shows the water use efficiency.

Data and Assumptions

The information required for estimating CWU in terms of water depletion per unit of production (m^3/tonne) of milk and other crops in Moga were not available in published databases, so it was necessary to conduct a household questionnaire survey. The primary data collected in the questionnaire survey include milk productivity and feed supply patterns for lactating cows and buffaloes, the cropping and land use patterns of fodder and other crops (irrigated area under canal water, groundwater and conjunctive use), crop growth periods, crop productivity, water withdrawals (number of irrigations and duration of each withdrawal), tube well details, and fertilizer and other input use for food crops and green fodder at the farm level.

A sample of 300 farmers in 10 villages from 5 blocks was selected for the survey. Primary data, collected between October and December 2009, relates to the 2008/2009 *Rabi* and *Kharif* seasons.

Survey data are used to estimate all components of CWU in terms of water depletion per unit of production (m^3/tonne) across farms. The weighted averages of CWU and other data across farms from the sample survey are then combined with secondary data of the total number of lactating cows and buffaloes (DoDL 2009) and total crop production in Moga (DoAAD 2009) to estimate the total CWU (m^3/year) components in Moga.

IWMI's World Water and Climate Atlas (IWMI 2000) was the source of ETp and P75 data. The crop coefficients and lengths of the growing periods (initial, development, mid-season and late season) of rice, wheat and green fodder crops (sorghum, maize, berseem and oats) are taken from the Food and Agriculture Organization of the United Nations (FAO) AQUASTAT database (FAO 2010). These details are given in Annex 2.

The following assumptions are made when calculating the CWU:

- Drinking and bathing water requirements of lactating cattle or buffaloes is assumed to be 100 liters/day/animal and is fully provided by groundwater (Singh et al. 2004);
- Average monthly ETp and P75 of five blocks are used for estimating the farm level crop water requirements. Thus, variations of only the starting date of the cropping calendar, duration and crop area reflect the variations of ETa and NET across farms;
- Non-process non-beneficial evaporation is assumed to be 10% of the difference between irrigation withdrawals and NET (in cubic meters);
- Crop yields for fodder crops were not available from the questionnaire survey. The green-matter yields of major fodder crops, sorghum, maize, berseem and oats are assumed to have ranges of 35-70, 35-45, 100-120 and 45-55 tonnes/ha, respectively, for estimating the range of production possibilities from current cropping patterns (ICAR 2009);
- Green and dry fodder mainly contributes to internal CWU of milk production. If, for an area of interest, the production of green or dry fodder exceeds the total consumption of the lactating animals, then external CWU of green and dry fodder are assumed to be zero (discussions with the farmers during field visits also supported this assumption as most of their fodder requirements were met from within the village/district). In cases where there is a fodder deficit, the external CWU is estimated at the rate of internal CWU. Since, irrigation barely meets the net evaporation requirement of green fodder, the non-consumptive depletion in green fodder is also assumed to be zero.

Feed concentrate contributes to both internal and external CWU. A typical feed concentrate formula is given in Table 3. Since part of the demand for feed concentrate is met by imports from outside Moga boundaries, feed concentrate always has an external CWU. The composition of the feed concentrate shows that about 40% of the cost of different components used in the feed concentrate formula is from within Moga, while the other 60% consists of imports to Moga. This report assumed similar percentages of water consumption within Moga and virtual water imports from outside Moga. The CWU of the feed concentrate is assessed at 1.24 cubic meters per kilogram (m^3/kg).

TABLE 3. Main components of a typical feed concentrate.

	Component	Quantity (%)	Origin
1	Rice bran	17	Punjab
2	Mustard cake	20	South Punjab/Rajasthan
3	Maize crushed	20	Punjab (30%), Uttar Pradesh (70%), Bihar, Karnataka
4	Wheat	2	Punjab
5	Wheat bran	15	Punjab
6	Rice broken	4	Punjab
7	Bajra	5	Rajasthan
9	Barley	3	Rajasthan
10	Molasses	5	Uttar Pradesh
11	Cotton seed cake	7	South Punjab/Rajasthan
12	Gram husk	2	Rajasthan

Source: Feed companies (pers. comm.)

Estimates of Consumptive Water Use

Consumptive Water Use of Rice and Wheat

The average CWU of rice and wheat production are 1,380 and 554 m^3/tonne, respectively (Figure 4). Groundwater contributes 95 and 92% of the irrigation CWU of rice and wheat, respectively. The factors contributing to these estimates are shown in Table 4.

The total and irrigation CWU of rice are 2.5 and 1.9 times, respectively, more than those of wheat. Since there are no significant differences in crop yields, the differences of CWU are mainly due to the variation of irrigation water requirements (Table 4). This shows that rice production is the primary driver of groundwater overabstraction and CWU in the Moga District.

Estimated irrigation water use efficiency (the ratio of irrigation CWU to withdrawals) is significantly lower for rice (42%) than for wheat (79%) (Annex 2, Table A2.2). As a result, rice production also has a significant non-process non-beneficial evaporation, estimated to be in the order of 143 m^3/tonne for rice against 23 m^3/tonne for wheat.

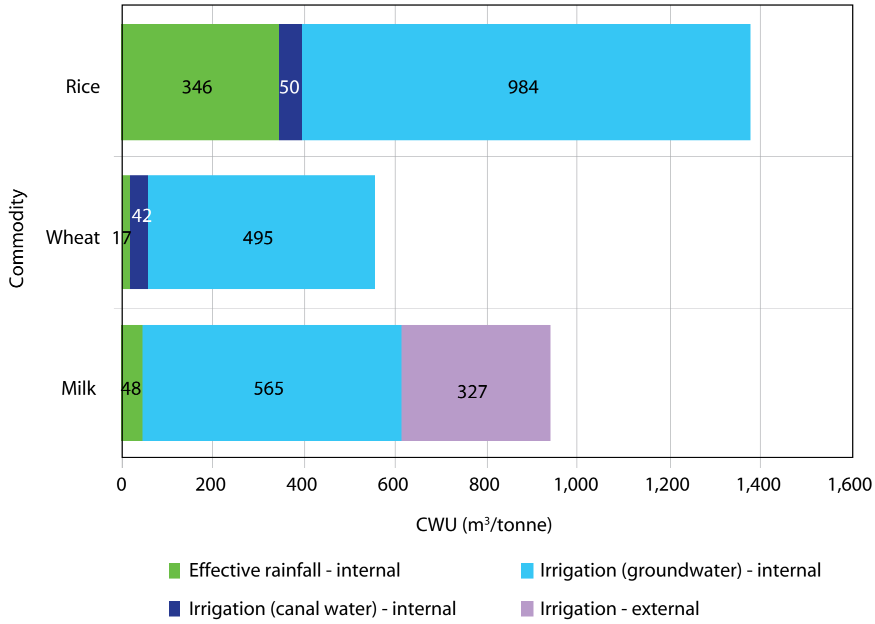

FIGURE 4. Consumptive water use of rice, wheat and milk production. *Source*: Authors' estimates using the sample survey in the Moga District.

TABLE 4. Factors of rice, wheat and fodder production in Moga.

Factor	Crops		
	Rice	Wheat	Fodder[1]
Area (% of net irrigated area)	91.2	89.5	8.10
Productivity (tonnes/ha) – Average	4.96	4.77	124-199
- Standard deviation	(0.66)	(0.52)	
ETa (mm)	671	268	727
Effective rainfall (mm)	167	8	132
NET (mm)	504	260	595
Share of irrigation CWU (%)			
- Only canal irrigation	29	30	0
- Only groundwater irrigation	24	23	100
- Both canal and groundwater irrigation	46	47	0

Source: Sample survey in Moga
Note: [1]Weighted average of all fodder crops grown year-around.

Consumptive Water Use in Milk Production

The total CWU of milk production is 940 m^3/tonne, and the internal and external components are 613 and 327 m^3/tonne, respectively (Figure 4). A major contribution to the internal component is from indirect water use through feed consumption (Table 5). Drinking/servicing water use of animals is only 2% of the total CWU.

TABLE 5. CWU of feed and drinking/servicing water requirements of lactating animals.

Factor	Feed consumption			Drinking/ servicing
	Green fodder	Dry fodder	Concentrates	
Consumption (tonne/animal/year)	9.7	3.5	1.7	36.5[1]
Internal CWU (m^3/tonne)	196	184	218	15
External CWU (m^3/tonne)	-	-	327	-

Source: Sample survey
Note: [1]Estimated at 100 liters/animal/day

Green fodder, dry fodder and feed concentrates are the main types of feed for indigenous and crossbred cows and buffaloes, constituting 1, 28 and 71%, respectively, of the milking animal population. Water consumption in feed accounts for 98% of the internal CWU (Table 5). Only feed concentrate contributes to external CWU, which accounts for 34.8% of the total CWU in milk.

The total CWU in milk production in Moga is significantly lower than the average estimate (1,369 m^3/tonne) at the national level estimated by Chapagain and Hoekstra (2004). High milk productivity is the main reason for lower water depletion in Moga. Average milk productivity estimates of 10.4 and 6.5 liters/day/animal for cows and buffaloes, respectively, are significantly higher than the national average of 6.5 and 2.2 liters/day/animal. On the other hand, fodder crops and crops that contribute to feed concentrate in Moga are fully irrigated. Thus, the irrigation component of water use in milk in Moga could be significantly higher than in many other areas in India.

Green fodder cropping systems have a considerable influence on the internal CWU of milk production. Among the fodder cropping patterns, *sorghum+berseem+oats* is the most prevalent and this also has the lowest total CWU (941 m^3/tonnes - with 581 m^3/tonne of internal contribution). The *sorghum+berseem* system has the highest yield. With 798 m^3/tonne of water depleted internally, it is also the most irrigation-intensive water use system. The *sorghum+maize+berseem+oats* and *sorghum+maize+berseem* are the other two fodder cropping patterns with slightly higher CWU.

Total Consumptive Water Use and Impacts

Groundwater Consumptive Water Use

Rice-wheat-milk is the dominant production system of over 80% of the farmers in Moga. On average, about 90% of the NIA is under rice in the *Kharif* season and under wheat in the *Rabi* season. About 10% of NIA is under year-round green fodder production. In addition to food grains, wheat straw provides almost all the dry fodder feed requirements of dairy animals, while both rice and wheat production contribute to the preparation of feed concentrates. Although, about 5% of the farmers grow wheat and raise livestock for milk production and 2% of the farmers only raise livestock for milk, the rice, wheat and green fodder cropping patterns are an integral part of the major production system in Moga.

Overall, the total groundwater CWU of rice, wheat and milk production is 13% over the annual natural recharge of groundwater resources in Moga (Table 6). The total CWU (MCM/year) is estimated by multiplying the internal CWU (m^3/

tonne) of the product by the total production (million tonnes). The main arguments supporting this are given below.

Irrigation water depleted internally in milk production is estimated to be 565 m^3/tonne (Figure 4). However, dry fodder (wheat straw) also contributes to part of this estimate. To avoid double counting in the estimation of the total CWU in the irrigation component of dry fodder - 178 m^3/tonne (the sum of 37 and 141 m^3/tonne of effective rainfall and irrigation, respectively) is deducted from the internal CWU. The total groundwater irrigation CWU of milk production, contributed by the groundwater resources of Moga, is estimated to be 113 MCM/year (Table 6).

Internal groundwater irrigation CWU of rice and wheat are 984 and 495 m^3/tonne (Table 6), leading to total groundwater CWU of 854 and 415 MCM/year in rice and wheat production, respectively.

Thus, the total groundwater CWU of milk, wheat and rice is 1,382 MCM/year, which is 162 MCM/year over the annual groundwater recharge limit. Overexploitation of groundwater is more critical in Bagha Purana, Nihal Singh Wala and Moga I blocks, where groundwater depletion exceeds the annual recharge limit by 38, 26 and 16%, respectively.

Value of Production

The 'milk-only' production system generates a higher value of output than other systems including rice and wheat (Figure 5). Three main production systems: *milk-wheat-rice*; *milk-wheat* and *milk-only* are considered for this comparative analysis. The first set of three bars indicates the contribution of rice, wheat and milk to the gross value of production per hectare of NIA (US$/ha). The second set of three bars indicates the contribution of rice, wheat and milk to the gross value per cubic meter of groundwater irrigation CWU (US$/$m^3$).

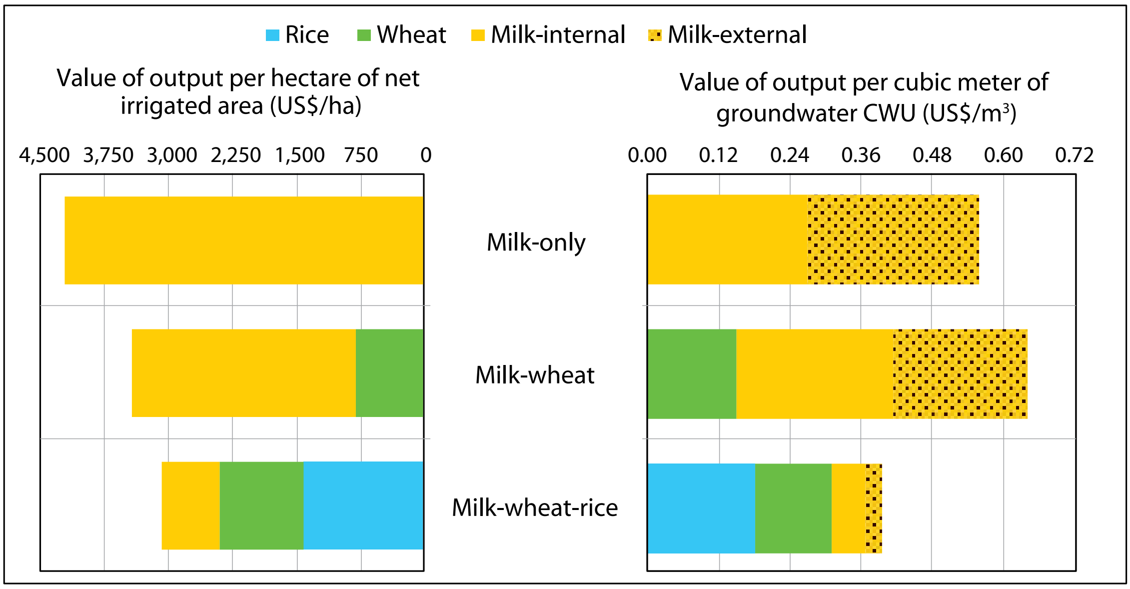

FIGURE 5. Gross value of production per unit of land used and per unit of groundwater irrigation CWU across production systems.
Source: Authors' estimates using the sample survey in the Moga District.

Table 6. Rice, wheat and milk production and groundwater use.

Block name	Crop irrigated area (% of net irrigated area) (%)			Total production in 2008/2009 (1,000 tonnes)			Groundwater irrigation CWU (m^3/tonnes)			Groundwater contribution in internal irrigation CWU (MCM)				Groundwater Overutilization (MCM)
	Rice	Wheat	Fodder	Rice	Wheat	Milk[1]	Rice	Wheat	Milk[1]	Rice	Wheat	Milk	Total	
Bagha Purana	92	92	7.8	241	222	74	902	497	350	217	110	26	353	96
Dharamkot	89	86	8.1	201	201	85	1,028	493	401	206	99	34	340	-25
Moga I	92	90	7.0	149	147	50	973	493	470	145	73	23	241	33
Moga II	92	92	7.0	126	133	35	1,067	478	464	134	64	16	214	5
Nihal Singh Wala	89	86	10.8	152	134	47	953	517	306	145	69	15	229	48
Moga District[3]	91	90	8.1	868	838	292	984	495	387	854[2]	415[2]	113[2]	1,382[2]	162[2]

Sources: Net groundwater resources and net irrigated area (DoAAD 2009); milk production is estimated by combining the milk cattle and buffalo population figures of the 17th Livestock Census (DoDL 2009), with the milk productivity estimated from the Moga sample survey.

Notes: [1] CWU of milk is the average of the upper and lower CWU and excludes the internal CWU of dry fodder.
[2] Totals for the Moga District, estimated using weighted average, may not be equal to the sum of the block totals.
[3] The total of the blocks may be different from the value of Moga District due to errors in rounding off.

The gross value of output per land use of *milk-only* or *milk-wheat* production systems, 4,220 and 3,422 US$/ha, respectively, is far superior to the gross value of output of 3,080 US$/ha for the most common production system, *milk-wheat-rice*. However, due to a higher cost of production, the relative differences of net value of outputs[1] may vary.

Between blocks, fodder area varies from 7 to 11% of the NIA, but the share of the value of milk production varies from 21 to 28% (Table 7). The value of milk production – if estimated per hectare of fodder area – could be 6 to 8 times more than the value of production of rice and wheat per hectare of cultivated area. However, the entire value of milk production cannot be attributed to the green fodder area, as it masks the indirect contribution of dry fodder from wheat production to milk production.

While green fodder accounts for two-thirds of the biomass of feed for lactating animals, wheat straw contributes to 26% of the biomass of total feed. Feed concentrate accounts for 8% of the remaining feed biomass. Thus, although the value of production per unit of irrigated area is a good indicator for comparison of benefits of rice and wheat production, the value of production per hectare of fodder area masks the indirect benefits accrued from the wheat dry fodder. This anomaly in value estimation per hectare can be eliminated by considering the aggregate value of output per unit of NIA and per unit of water consumed, as indicated in Figure 5.

In terms of gross value per groundwater consumptive use, *milk-wheat* or *milk-only* production systems are superior to the production system including rice. The gross value per CWU of the *milk-wheat-rice* production system of 0.40 US$/m^3 is only 62% of the value of *milk-wheat* (0.64 US$/m^3) or *milk-only* (0.56 US$/m^3) production systems. The water used in dry fodder is already included in wheat production. Thus, *milk-wheat* production systems have a higher value of output with respect to groundwater CWU than *milk-only* production systems.

A strong implication of these estimates is that farmers in Moga can diversify their agricultural production systems without significant loss of the value in production while reducing pressure on scarce groundwater resources. As wheat is an important source for dry fodder, a proper combination of wheat and fodder area can optimize the returns to land as well as water depleted. However, rice production is also contributing to the food security of a large population outside Moga. Thus, the intensification of dairy production, with a calculated reduction in rice area to compensate for increasing requirements for green fodder, can bring the groundwater depletion to sustainable limits, while producing a surplus of rice for exports. The trade-off of these scenarios will be assessed later.

Virtual Water Export

The level of production of rice and wheat far exceeds the demand for local consumption by the Moga population (Tables 6 and 7). At present, the local demand for rice, wheat and milk are only 0.3, 11.2 and 43.3%, respectively, of total production. Since groundwater is the dominant source of irrigation, most of the groundwater CWU in agricultural production accounts for the virtual water exports from Moga. A substantial part of the CWU, especially from groundwater, is exported as virtual water from Moga to other regions.

The virtual groundwater content in rice, wheat and milk surpluses are 852, 368 and 64 MCM/year, respectively. The total net virtual groundwater

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[1]The net value of output is the difference between the gross value of output and the cost of production. This study did not estimate the cost of production at the farm level. However, secondary data shows that the average cost of rice and wheat production in the State of Punjab are US$753 (INR 33,885)/ha and US$603 (INR 27,149)/ha, respectively (See GOI 2007a for estimation explanation). Also, Hemme et al. (2003) estimated that the cost of milk production of farms growing crops and forage in the State of Haryana, India, in 2001 was around US$150/tonne. As wheat production is the only source for dry fodder feed, it is assumed that cost of milk production in farms not growing wheat is 25% higher. With a 4.2% annual rate of increase in the cost of production, the cost of milk production in 2008/2009 is estimated as US$200 for wheat and green fodder growing farms, and US$250 for farms only growing green fodder. Based on these data of average costs of production, the net value of output of the milk-wheat production systems (1,822 US$/ha) is the highest, followed by milk-only production systems (1,714 US$/ha) and milk-wheat-rice production systems (1,540 US$/ha).

TABLE 7. Water embedded in the surplus production of rice, wheat and milk over local consumption.

Block name	Population[1] (1,000s)		Value of production[1] (% of total)			Total consumption[2] (1,000 tonnes)			Production surplus/ deficit (1,000 tonnes)			Virtual water[1] content of the surplus (MCM)			Virtual groundwater content (MCM)		
	Rural	Urban	Rice	Wheat	Milk	Rice	Wheat	Milk	Rice	Wheat	Milk	Rice	Wheat	Milk	Rice	Wheat	Milk
Bagha Purana	175.9	43.9	47	31	22	0.7	23.0	31	240	199	43	310	113	17	217	99	15
Dharamkot	169.5	42.3	42	30	28	0.7	22.2	30	200	179	56	292	97	25	206	88	22
Moga I	133.9	33.4	45	31	24	0.5	17.5	24	148	130	26	205	71	14	144	64	12
Moga II	100.7	25.1	45	34	21	0.4	13.2	18	125	120	18	184	64	9	134	57	8
Nihal Singh Wala	136.2	34.0	48	30	23	0.5	17.8	24	152	116	23	203	68	8	145	60	7
Moga District[3]	716.2	178.6	45	31	24	2.8	93.6	126	865	744	165	1,194	412	72	852	368	64

Sources: Population figures (DoAAD 2009); Consumption figures (GoI 2007b); CWU estimates (Moga sample survey)

Notes: [1] Value of production is estimated at INR 14 and INR 10/kg of rice and wheat, and INR 17.50 and INR 24.00/kg of cattle and buffalo milk, respectively

[2] Average per capita consumption figures of the State of Punjab are used for estimating total consumption. Per capita consumption of rice, wheat and milk are 0.0755, 8.94 and 11.875 kg/month in rural areas and 1.023, 7.792, 11.358 kg/month in urban areas, respectively.

[3] The total of the blocks may be different from the value of Moga District due to errors in rounding off.

export through rice, wheat and milk from Moga is 1,284 MCM/year, which is 64 MCM more than the natural groundwater recharge. Rice contributes to two-thirds of the virtual groundwater exports, while wheat and milk exports contribute to 29 and 4%, respectively, of the virtual groundwater exports.

Given the differences of value of production and virtual water exports, it is clear that reducing surplus agricultural production offers the greatest opportunity for keeping the water depletion within the natural groundwater recharge levels. This can be done either by reducing the surpluses of rice, wheat or milk production individually or as a combination.

If a reduction in water depletion is to be achieved only by reducing rice exports, it means reducing the virtual groundwater export of rice by at least 162 MCM, or reducing the production surpluses of rice by 165,596 tonnes. At the current rate of rice yields, this reduction is equivalent to 19% of total rice production. In contrast, if wheat surpluses are to reduce in order to bring groundwater depletion under natural recharge limits, the total wheat production has to be reduced by 16% and milk production has to be reduced by 36%, which in value terms could have a big impact for the farmers of Moga.

The combination of milk, wheat and rice production for making agricultural production financially and hydrologically viable in Moga is assessed next.

Interventions for Reducing Internal Water Consumption

Agricultural Diversification

Many of the physical interventions practiced in Moga intended to reducing irrigation water withdrawals, but not the total CWU. However, a major reduction of CWU cannot be achieved without changing the production patterns. In Moga, the internal groundwater depletion of rice production is the highest and the value of output of rice dominating production systems is the lowest. Thus, a smaller rice area and larger milk production system, with adequate wheat and green fodder, will reduce groundwater depletion. This is the most expedient way of achieving sustainable agricultural production in Moga.

Under the present level of crop and milk productivities, the optimum choice of cropping and animal husbandry pattern for an average farm holding size of 6 ha that maintains the total groundwater CWU below the annual supply is to:

- Reduce rice area to 62% of the NIA and increase green fodder crops to 20% of the NIA in the *Kharif* season;
- Raise 5 and 3 lactating crossbred cows and buffaloes, respectively, with a provision of 50% more non-milk crossbred cows; and
- Allocate 10 and 90% of the area for green fodder and wheat, respectively, in the *Rabi* season.

The main arguments supporting the estimation of the above optimum production system are illustrated below.

The average gross and net value of outputs of crop and milk production under the present conditions (base scenario) are 3,124 and 1,566 US$/ha, but it depletes 162 MCM of groundwater over the natural recharge limits.

The 'base scenario' shows the present average conditions. These are:

- 90% of the NIA is under rice and wheat in the *Kharif* and *Rabi* season, respectively, and 10% of the NIA is under year-round fodder crops.
- The number of lactating dairy animals raised on a 6 ha area of land is four, comprising 1 crossbred cow and 3 buffaloes. Along with

them, 50% more non-lactating dairy animals are also raised.

- Land productivity of rice and wheat are 4.96 and 4.77 tonnes/ha, respectively; green fodder productivity is 110 tonnes/ha; the dry fodder weight of wheat is 1.75 times that of the primary product; and milk productivity of cattle and buffaloes are 10.3 and 6.5 liters/day/animal, respectively.
- Groundwater CWU of rice and wheat are 984 and 494 m^3/tonne and groundwater irrigation depth on the fodder area is 304 and 191 mm/ha in *Kharif* and *Rabi* seasons, respectively.
- Drinking water of lactating animals is assumed to be 100 liters/day/animal. Per capita consumption of green, dry fodder and concentrate is 9.7, 3.5 and 1.7 tonnes/year/animal, respectively.

Alternative scenarios of cropping and animal husbandry patterns and their implications on the value of output and groundwater CWU are developed next (Table 8). The alternative scenarios assume that there are no production deficits of green or dry fodder for feeding the dairy animals.

Alternative scenarios are:

- *A1: No rice area*

Complete elimination of rice area can bring the total CWU of groundwater to well within the natural recharge level, but this also reduces the value of output by 1,372 US$/ha. Although hydrologically attractive, this is not a realistic scenario at the ground level. This scenario over a large area will result in huge financial losses and have larger food security implications outside the Moga area.

- *A2: No rice area and more lactating animals*

Increasing the number of crossbred cows to eight per 6 ha of NIA can offset the loss of output as a result of no rice cultivation. Under this scenario, Moga will have to support close to two dairy animals in milk production and one not in milk production per hectare of NIA to the present level of 0.66 in milk and 0.33 not in milk production, which means more than doubling the dairy animal population in the region. Although increased forage area in the *Kharif* season can meet the increased green fodder requirement, this scenario will result in large deficits of dry fodder and requires significant increases in feed concentrate from outside Moga.

- *A3: Reduce rice area and more lactating animals*

This scenario optimizes the value of output by decreasing the rice area and increasing the number of crossbred cattle, while maintaining green and dry fodder surpluses for feed and groundwater CWU below natural recharge limits (See Annex 1 for specification of the linear programming model).

Under the given constraints, the value of output is optimized with at least 8 dairy animals (5 crossbred cows and 3 buffaloes) in milk production and another four animals not in milk production in a 6 ha area of land. This requires reducing rice production by 28.4% and raising the green fodder area to 19.9% from the base scenario in the *Kharif* season. Altogether this scenario has a land use intensity of 81 and 100% for the *Kharif* and *Rabi* seasons, it provides a gross value of output of US$589 per hectare (and US$277 per hectare of net value of output), which is higher than the base scenario and reduces groundwater CWU below 1,220 MCM.

- *A4: Reduce rice area and more lactating animals with higher milk productivity*

This scenario has the same constraints and assumptions as explained in scenario A3, but it increases the milk productivity of crossbred cows to 15 liters/animal/day, from the present level of 10.3 liters/animal/day.

This scenario has equal hydrological benefits to that of scenario A3, but generates US$567 more value of output than in scenario A3. At present, only 16% of the total crossbred cows have an average milk productivity more than or equal to 15 liters/animal/day. However, they contribute to 24% of the daily milk production. Thus, improving milk productivity with more scientific animal husbandry methods could bring huge additional financial benefits.

- *A5: Lower limit of groundwater CWU*

This scenario has the same assumptions and constraints as explained in scenario A4, except that the upper limit of groundwater CWU is now set at 100 MCM below the sustainable use limit.

This scenario further reduces the rice area to 56.5% of the NIA. However, the gross value of output is still higher than the base scenario by US$459/ha.

Opportunities and Threats

A reduction in the rice area and intensification of dairy farming can bring significant hydrological and financial benefits to Moga, while still ensuring substantial production surpluses for meeting rice demand outside Moga. Although these changes in production patterns will certainly reduce the water depletion in Moga, it is clear that the total external water depletion will also increase. What is not clear from this analysis, however, is how Moga can reduce its external water depletion in the import of components of feed concentrates. At present, the import of various components of cattle feed concentrate contributes to much of the occurring external depletion. Some of these imports are from irrigated production areas while others are from rainfed production areas.

Places like Moga are the classic cases in India where the virtual water trade can become an effective management practice. With significantly high productivities and low CWU, Moga has a large comparative advantage for diversifying agriculture from water-intensive rice-wheat-milk production systems to less water-intensive milk-wheat production systems. Corresponding increases in demand for feed concentrate and dry fodder within Moga offers significant opportunities for areas outside Moga to increase trade. In fact, various components of feed crops require less water and can be cultivated in rainfed areas. Thus, many rainfed areas can also benefit from this virtual water trade with Moga.

Managing waste should be an integral component of the intensification of dairy farming. Increasing the number of dairy animals will generate a large amount of cow manure, and if not properly managed could be a threat to local water resources. At present, a part of the cow manure is used as fertilizer and part as fuelwood in rural areas. Excessive use of manure as fertilizer can be harmful to the soil and will deteriorate water quality (Beynon et al. 2002). A dairy cow weighing 500 kg produces, on average, 40 kg of manure (6 kg/day of dry matter) consisting of 0.5, 0.06 and 0.3% of nitrogen, phosphorous and potassium, respectively (Beynon et al. 2002). The proposed plan would entail raising only 2 animals (milking and non-milking) per hectare. Two cows could produce 146, 18 and 78 kg of nitrogen, phosphorous and potassium manure per year. Proper management of such a quantity of manure as fertilizer can, in fact, enrich the soil with nutrient and reduce the pollution of local water resources. Excess manure can be traded in areas where fertilizer use is significantly lower at present, or can be used as a source for energy generation.

TABLE 8. Changes in value of production and groundwater CWU under various cropping and dairy animal rearing patterns.

Scenario	*Kharif* season		*Rabi* season		Number of lactating animals/6 ha land area		Annual gross value of output		Groundwater CWU	
	Rice	Fodder	Wheat	Fodder	Total	Crossbred cows	Per hectare of NIA	Change from base	Total	Change from base
	(%)	(%)	(%)	(%)	#	#	(US$/ha)	(US$/ha)	(MCM)	(MCM)
Baseline	90.0	10.0	90.0	10.0	4	1	3,124	-	1,382	-
A1: No rice area	0.0	10.0	90.0	10.0	4	1	1,752	-1,372	541	-841
A2: No rice area and more lactating animals	0.0	31.5	90.0	10.0	11	8	3,294	170	711	-671
A3: Reduce rice area and more lactating animals	61.6	19.9	90.0	10.0	8.6	5.6	3,713	589	1,220	-162
A4: Reduce rice area and more lactating animals with higher milk productivity	61.6	19.9	90.0	10.0	8.6	5.6	4,280	1,156	1,220	-162
A5: Lower limit of groundwater CWU	53.5	19.9	90.0	10.0	8.6	5.6	3,583	459	1,120	-262

Source: Authors' estimates.

Conclusions and Policy Recommendations

Milk-wheat-rice is the dominant production system of 80% of the farmers in Moga. The CWU of milk is about 940 m^3/tonne, which is relatively smaller than rice (1,380 m^3/tonne) but larger than wheat (554 m^3/tonne). Unlike rice and wheat, milk has a substantial component of external CWU.

In Moga, green fodder (sorghum and maize) and rice occupies more than 99% of the crop area in the *Kharif* season, while green fodder (berseem and oats) and wheat occupy more than 99% of the NIA in the *Rabi* season. The process of production of these crops contributes to almost all annual groundwater CWU, which at present is 162 MCM more than the natural recharge limits. Three blocks have significantly high levels of overabstraction. *Decreasing internal groundwater CWU is the only solution for long-term sustainable agricultural production*.

Rice production has the highest internal CWU. The contribution of groundwater alone to CWU of rice production is 854 MCM/year, and most of this is virtually exported from Moga at present. In fact, the total virtual water content of the production surpluses of milk, wheat and rice is more than the level of natural groundwater recharge. *Given the differences in value of outputs and groundwater CWUs, a reduction in the rice area and intensifying dairy production with a calculated increase in fodder area is the most expedient way of controlling groundwater overexploitation.*

The value of output of *milk-wheat* production systems per unit of NIA and unit of CWU is 11 and 32%, respectively, higher than that of milk-wheat-rice production systems. *Small farmers should be encouraged to take up agriculture patterns that are dominated by dairy farming. As wheat provides dry fodder for feed, milk-wheat production systems should be the preferred system for them. If the area is too small for both wheat and fodder production, "milk-only" is the preferred production system, where output per internal CWU is still higher than the milk-wheat-rice system. Additional care should be taken to introduce crossbred cows with higher milk productivity than at present.*

However, shifting to dairy-intensive production systems requires an initial investment on procuring dairy animals, preparing animal sheds, etc. Yet, the differences in the gross value of outputs of US$342 or 1,140 per hectare of NIA between milk-wheat-rice production systems and milk-wheat or milk-only production systems (Figure 5) are an incentive for the farmers for this initial investment. *The government and private sector could come forth and provide credit facilities for small farmers to make the changes of agriculture production systems financially feasible.*

At present, virtual groundwater exports in milk, wheat and rice itself is higher than the natural groundwater recharge. Given the large differences of internal CWU of milk, wheat and rice, changes in production and cropping pattern throughout Moga is vital for reducing the internal groundwater CWU. Intensifying dairy production *by introducing at least two times more lactating animals with 10% more green fodder area is the most economical choice*. However, the rice surplus, which is about 99% of the current production, contributes to food security of the large population outside Moga. *Therefore, only a partial reduction in rice area is preferred among medium and large farmers. The rice area of these farmers should be reduced so that the overall rice area can be at most 62% of the NIA to make agriculture in Moga a financially viable and hydrologically sustainable enterprise.*

At present, net irrigation requirement for rice is only 42% of the irrigation withdrawals. Overall, total groundwater irrigation withdrawals in Moga are more than twice the natural recharge. Thus, it is imperative that Moga reduces its groundwater withdrawals, which leads to a smaller CWU from the non-beneficial consumptive use.

The above recommendation of reducing the rice area and intensifying milk production is based purely on the magnitude of agricultural water use and depletion with respect to groundwater recharge. However, the real choices of options will also depend on a range of economic and social factors including prices, labor inputs, fear of innovation and others.

As per State legislature, all farmers have delayed paddy sowing until the 10th of June. *Strict adhering to delayed transplanting until the 10th of June is vital for reducing irrigation withdrawals for rice. This can bring down the non-beneficial evaporation of rice irrigation*.

A large scope still exists for reducing irrigation withdrawals through laser land leveling throughout Moga. At present, only 17% of the land area is laser leveled. *Laser land leveling should be expanded to all irrigated areas. The government should explore possibilities of bringing down the cost of laser leveling per unit area*.

The hydrological and economic cost and benefits of other interventions tested elsewhere can also be explored in Moga. Some of these are: *multi-cut fodder production with high efficiency irrigation technologies such as sprinkler irrigation; adoption of reduced or zero tillage in wheat sowing with about 50 mm irrigation application in each growth periods; intermittent irrigation of rice after 2-3 days of lands drying out after the submergence of rice fields in the initial two weeks and terminating the last irrigation two weeks before the harvest; direct seeding of rice instead of transplanting; raising the bund to a height of 22 centimeters around the rice fields to capture the rainfall in the monsoon periods; system of rice intensification, aerobic rice and regulating farm power supply by separating the power lines to agriculture and the domestic sector.*

Dairy farming is an integral part of the agricultural production system in rural India. A part of the milk production is used for home consumption, and it is the main source of daily protein and other nutritional requirements for rural households. Milk production also generates daily income and it is a strong line of defense for mitigating the impacts in times of droughts and damages to crop production. Changing food consumption patterns, with increasing income and lifestyle changes, show an increasing demand for milk. Increasing variability of rainfall associated with climate change often impacts crop production. Thus, dairy production may, and most likely will, feature even more prominently in rural livelihoods in the future. It requires a better understanding of feed demand and production and their water use patterns. This is even more important in the presence of varying cropping patterns and production of by-products, such as dry fodder, in different locations. A systematic evaluation of the consumptive use and withdrawals of water for crops and milk production and their impacts across all districts, and, in particular, in regions with substantial groundwater stress, is a priority area for future research.

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Annex 1. Specification of Linear Programming Optimization.

The linear programming technique is used to assess the optimal cropping pattern (percentage of rice, wheat and fodder area in the *Kharif* and *Rabi* seasons) and livestock combination (minimum number of crossbred cattle and buffaloes to raise in a 6 ha area of land) for maximizing the value of gross agricultural output while maintaining total groundwater CWU below the sustainable groundwater supply limit. This analysis considers only rice and forage crops in the *Kharif* season and wheat and forage crops in the *Rabi* season. The variables used in the analysis are shown in Table A1.

TABLE A1. Variables used in the analysis.

Variable	Description
VOUP	Value of gross output (million US$)
TGCWU	Total groundwater CWU (MCM/year)
TGFCON	Total green fodder consumption (Mt/year)
TDFCON	Total dry fodder consumption (Mt/year)
A	Net irrigated area (Mha)
$\%A_r$, $\%A_w$, $\%A_{fk}$, $\%A_{fr}$	Percentage area under rice, wheat and green fodder crops in the *Kharif* and *Rabi* seasons (%)
Yr, Y_w, Y_{fk}, Y_{fr}	Yield of rice and wheat, and average yield of green fodder crops in the *Kharif* and *Rabi* seasons (tonnes/ha)
CWU_r, CWU_w	Groundwater CWU of rice and wheat (m^3/tonne)
NET_{fk}, NET_{fr}	Average net irrigation requirement of fodder crops in the *Kharif* and *Rabi* seasons (mm)
N_c, N_b	Minimum number of crossbred cattle and buffaloes in milk to be raised in a **6 ha area of** land
M_c, M_c	Milk productivity of cattle and buffaloes (tonnes/animal/year)
C_{gf}, C_{df}, C_{co}	Consumption of green fodder, dry fodder and concentrates of cows and buffaloes (tonnes/animal/year)
P_r, P_w, P_{mc}, P_{mb}	Prices of rice, wheat and milk of crossbred cattle and buffaloes (US$/tonne)
CP_r, CP_w, CP_m	Cost of production of rice, wheat (US$/ha) and cost of production of milk (US$/tonne)
DW	Drinking and servicing water requirement of cattle and buffaloes (liters/day)

The objective here is to estimate $\%A_r$, $\%A_w$, $\%A_{fk}$, $\%A_{fr}$ and N_c, N_b to maximize the value of gross output (VOUP) and is given by

$$VOUP = A \times (A_r \times Y_r \times P_r + A_w \times Y_w \times P_w)/1000 + (N_c \times M_c \times P_c + N_b \times M_b \times P_b) \times 365/1000 \qquad (A1.1)$$

Subject to three main constraints, namely the total groundwater CWU (TGCWU) should be, at most, the sustainable limit of 1,220 MCM, and sufficient green fodder (TGFCON) and dry fodder (TDFCON) should be available for feeding the total cattle and buffaloe population. It is assumed that only two-thirds of the cattle and buffaloe population provide milk in a given year. Constraints are given by

$$TGWFP = A((\% A_r \times Y_r \times CWU_r + \% A_w \times Y_w \times CWU_w) (\% A_{fK} \times NET_{fK} + \% A_{fR} \times NET_{fR})) \times 10) < 1,220 \qquad (A1.2)$$

$$TDFCON = A \times (N_c + N_b)/6 \times 1.5 \times C_{gf} \leq A \times \% A_w \times Y_w \times 1.75 \qquad (A1.3)$$

$$TGFCON = A \times (N_c + N_b)/6 \times 1.5 \times C_{df} \leq A \times (\% A_{fK} \times Y_{fK} + \% A_{fR} \times Y_{fR}) \qquad (A1.4)$$

where: multiplier 1.5 on the left side of equations (A1.3) and (A1.4) show that the total population of cows and buffaloes is 50% more than the animals providing milk. The multiplier 1.75 in equation (A1.3) indicates that dry fodder production from wheat is 1.75 times the production of wheat grains.

Other conditions in the maximization problem are:

$\%A_r > 0$, $80\% < \%A_w < 100\%$, $\%A_{fR} > 0\%$, $\%A_{fK} > 0$, $N_c > 0$ and $N_b >= 3$

The minimum percentage of wheat area is set at 80% (the current level) as the production of dry fodder is barely sufficient for the current level of livestock population. The minimum number of buffaloes is set at the current level as the milk production from this buffaloe population is sufficient for meeting the preferred milk consumption of the local people.

Annex 2. Data and Information Used to Calculate Components of CWU.

Potential Crop Evaporation and Effective Rainfall Estimates

The estimates of daily potential evapotranspiration (ETp) and effective rainfall (P75) of irrigation blocks in Moga are given in Table A2.1. The crop coefficients, duration of four crop growth periods, the potential crop evapotranspiration (ETa) and net irrigation requirement of different crops are shown in Table A2.2?

TABLE A2.1. Estimates of average daily potential evapotranspiration (ETp) and effective rainfall (P75).

Irrigation blocks	January	February	March	April	May	June	July	August	September	October	November	December
						ETp (mm/day)						
Bagha Purana	1.5	2.4	3.7	5.5	6.8	6.9	5.1	4.7	4.5	3.3	2.0	1.4
Dharamkot	1.4	2.3	3.5	5.3	6.6	6.7	5.0	4.6	4.3	3.2	2.0	1.3
Moga I	1.5	2.3	3.6	5.5	6.7	6.7	5.0	4.6	4.4	3.3	2.0	1.4
Moga II	1.4	2.3	3.6	5.4	6.7	6.8	5.1	4.6	4.4	3.3	2.0	1.4
Nihal Singh Wala	1.5	2.4	3.6	5.5	6.8	6.8	5.0	4.6	4.4	3.3	2.0	1.4
						P75 (mm/day)						
Bagha Purana	0.0	0.1	0.1	0.0	0.1	0.2	2.5	2.5	0.5	0.0	0.0	0.0
Dharamkot	0.1	0.1	0.2	0.0	0.1	0.3	3.2	3.0	0.6	0.0	0.0	0.0
Moga I	0.1	0.1	0.1	0.0	0.1	0.2	2.9	2.9	0.5	0.0	0.0	0.0
Moga II	0.1	0.1	0.1	0.0	0.1	0.2	2.8	2.7	0.5	0.0	0.0	0.0
Nihal Singh Wala	0.1	0.1	0.1	0.0	0.1	0.2	2.7	2.7	0.6	0.0	0.0	0.0

Source: Authors' estimates based on IWMI 2000

TABLE A2.2. Length and crop coefficients of four crop growth periods.

Crop[1]	Length of growth periods (percentage of total number of days of the season)				Crop coefficients in growth periods				ETa (mm)	NET (mm)
	Initial	Development	Mid-season	Late season	Initial	Development	Mid-season	Late season		
Rice[1]	20	20	40	20	1.20	1.15	1.10	0.80	673	268
Wheat[2]	13	21	42	25	0.40	0.78	1.15	0.30	268	259
Sorghum[1]	16	27	34	23	0.40	0.70	1.00	0.90	414	92
Maize[1]	20	20	40	20	0.40	0.70	1.00	0.90	388	90
Berseem[2]	13	21	42	24	0.40	0.70	1.00	0.90	268	7
Oats[2]	13	21	42	24	0.40	0.70	1.00	0.90	203	4

Source: Length of growth periods and crop coefficients (FAO 2010). Total length of the crop growth is estimated from the Moga sample survey.

Notes: [1]Rice, sorghum and maize are *Kharif* (summer) season crops and wheat and berseen are *Rabi* (winter) season crops.

Irrigation Withdrawals

More than half the paddy and wheat crop area receives water from conjunctive irrigation, i.e., both canal water and groundwater (Table A2.3). Conjunctive water use is significantly higher in Bagha Purana (69%) and Nihal Singh Wala (73%) blocks. However, almost all the fodder crop area is groundwater irrigated.

Table A2.3. Land and water use patterns.

Land use pattern of different crops	Percentage of households	Percentage of irrigated area	Water withdrawals Percentage of total			ETa	NET	Ratio of WD to NET
			Groundwater only	Conjunctive use				
				Canal water	Groundwater			
	(%)	(%)	(%)	(%)	(%)	(mm)	(mm)	(%)
Rice								
Groundwater only	38	29	100	0	0	671	499	43
Groundwater+conjunctive use[1]	16	24	47	4	49	676	510	43
Conjunctive use[1] only	47	46	0	8	92	676	512	41
Wheat								
Groundwater only	39	30	100	0	0	268	259	79
Groundwater+conjunctive use[1]	15	23	49	7	44	269	260	76
Conjunctive use[2] only	47	47	0	13	87	268	260	66
Fodder crops	100	100	100	0	0	328	268	110

Source: Based on sample survey.

Notes: [1] a part of the NIA is irrigated from groundwater only and the other part is irrigated from both canal water and groundwater;
[2] NIA is irrigated from both canal water and groundwater.

The contribution of canal water to rice and wheat irrigation is comparatively very small, and ranges from 4-8% and 7-13% of the total irrigation, respectively.

In general, rice irrigation has moderate to high water application rates. The ratio of net evapotranspiration (NET) requirement to total irrigation withdrawal of the rice crop is about 42%. When deep percolation (of about 200 mm) is also taken into account, the ratio of water requirement to water withdrawals of paddy is about 60%. The average water use ratio of wheat irrigation is even higher with an estimated average of 70%. Extensive use of groundwater through own tube wells contributes to this high water use ratio, suggesting that substantial savings in water and energy is possible without compromising on the irrigation water requirements. In Moga, 95% of the farmers own tube wells, and the tube well density is 14 per 100 ha.

Unlike paddy and wheat, average irrigation withdrawal for the fodder crop is less than the total irrigation requirement. Two reasons explain this high application ratio. First, the fodder area is much smaller than the rice and wheat area, and farmers judiciously use groundwater irrigation to meet just the crop water requirement of fodder as best as they can. Second, is a limitation in capturing the exact irrigated area, where some fodder crops have 3 to 4 multi-cut harvests, and thus part of the fodder area may receive less or no irrigation.

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