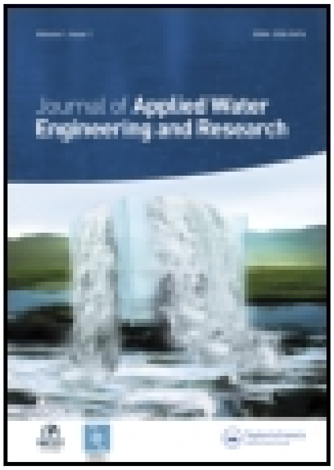

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Evaluation of groundwater-based irrigation systems using a water-energy-food nexus approach: a case study from Southeast Nepal

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Evaluation of groundwater-based irrigation systems using a water–energy–food nexus approach: a case study from Southeast Nepal

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This study aims to evaluate the performance of groundwater-based tube well irrigation systems of Sarlahi District in Nepal considering a water–energy–food nexus approach. The deep tube well (DTW) irrigation systems showed better performance over shallow tube well (STW) irrigation systems in terms of water supply and agricultural output per unit of irrigated area. On the other hand, the STW-based irrigation systems showed better performance in terms of energy use, management operation and maintenance (MOM) cost and benefit–cost ratio compared to DTW-irrigated systems. The productivity of irrigation water and energy input to major crops showed the best performance for maize followed by rice and wheat. The simulated yields of cereal crops through the AquaCrop model showed significant scope for enhancing crop yields and associated benefits through judicious use of water and fertilizer.

Keywords: water–energy–food nexus; groundwater; irrigation; Nepal

1. Introduction

Of all the natural resources, water, energy, and food are most needed to sustain life on earth. These three strategic resources are facing constraints on a global scale due to rapid growth of demand (FAO 2011). Moreover, the global water cycle, carbon energy cycle, and food production are inseparably linked. Since they are essential to the function of any society, they represent a deep issue for resources conservation (UNESCAP 2013).

Groundwater which is considered as a hidden resource has been recognized as a major element of the water resources system in many parts of the world. Irrigated agriculture is the prime abstractor and user of groundwater resources accounting for 70% of total withdrawal and 43% of total consumptive use (Siebert et al. 2010; GWP 2012). Currently, groundwater accounts for about 38% of all global irrigation supply and about 50% in South Asia (Shah 2009). The 20-year Agriculture Perspective Plan of Nepal recognizes that year-round irrigation is the prerequisite for achieving higher cropping intensities and rapid growth output. Currently, more than 0.363 million ha of agricultural land in Nepal is receiving irrigation from 103,874 Shallow tube wells (STWs) and 904 Deep tube wells (DTWs) and there is still huge potential to expand the irrigation over 1 million ha in Southern plain region (Terai) by increasing the number of tube wells (GRDB 2012; NADS 2012).

Energy consumption is the essential component for any agricultural production process, in the form of either direct mechanical operation or indirect energy input. The increasing use of energy resources (machinery and fertilizer) has boosted agriculture productivity, at the same time resulting in higher Greenhouse gas emissions from the sectors (Eurostat 2012). Withdrawal of groundwater for irrigation is an energy-intensive farm operation (Lal 2004; Rothausen and Conway 2011; Wang et al. 2012). Singh et al. (2002) found that in the arid zone of India, irrigation alone consumes 33–48% of the total energy used in farming operations, which forms the largest part of the total energy used in the farming system.

Global crop production has expanded threefold over the past 50 years, largely through higher yields per unit of land and crop intensification (FAO 2011). Cereal crops occupy more than half of the world's harvested area and are the most important food source for human consumption. Irrigated agriculture plays a crucial role in the global food production system, accounting for more than 40% of the world's production on less than 20% of the cultivated land (Rothausen and Conway 2011; Soto-García et al. 2013). Evidence has shown that irrigated crop yields are about 2.7 times higher than those of the rain-fed farming on a worldwide scale (WWAP 2012). The agricultural sector of Nepal provides the prime livelihood for people and is also the basis of the national economy. It is providing employment

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to two-thirds of the population, contributing to one-third of gross domestic product (NPC 2010). The agricultural productivity of Nepal is still very poor in comparison with neighboring countries due to insufficient resource inputs (Piya et al. 2011).

In developing countries, the energy and water use in agriculture largely remains inefficient (Chen et al. 2008; Jackson et al. 2011). The tendency towards inefficient input systems and current levels of energy inefficiency in agricultural systems may be due to lack of awareness and low energy costs. However, this scenario has been changing under current circumstances, where energy and water costs are becoming prime factors for producers and one of the fastest growing costs (Chen et al. 2008). The energy–yield relationship is becoming increasingly important with enhanced mechanization and agricultural intensification, considered to be the only means of boosting agricultural production in land-limited situations (Mushtaq et al. 2009).

Water and energy are the primary components of any production process, and the appropriate management of these resources significantly impacts the total yield and benefits. In many instances, the management of resources is considered separately and can improve one sector in particular, but, at the same time, create problems in other sectors. To avoid unwanted consequences, the nexus approach can be a guiding tool for the policy- and decision-makers. The nexus approach basically focuses on the interdependence of resources (Water–Energy–Food) by understanding the challenges and finding opportunities. The general principle behind this approach is to produce more with less water and energy, eliminating the wasteful practices. The trend of energy use in the water sector has increased significantly in the last few decades; yet, its importance is poorly understood (Chen et al. 2008). There has been a lack of comprehensive study considering the issues of water and energy-use performance for crop production and their trade-off on total benefits. Therefore, this study aims to evaluate performances of groundwater-based tube well irrigation systems considering the water–energy and crop production as a nexus approach and attempt to explore the potential areas of improvement to maximize gains by reducing losses and trimming costs.

2. Study area

2.1. Study site

The study site is located at the Ranigunj Village Development Committee (VDC), of the Sarlahi District, Southeast Nepal (Figure 1). The total area coverage is 18.1 km^2 in between the two intermittent rivers; Phuljor and Kalinjor. It has a monsoon-based tropical climate with average annual rainfall and potential evapotranspiration of 1780 mm and 1466 mm, respectively. In the northern part, approximately 20% of the area is covered with forest and agricultural coverage and is around 1150 ha in the central and southern parts. Almost all kinds of crops and vegetables are suitable for its climate. Soil texture in the study area is of a mixed type; fine to coarse textured from south to north. Due to geographical constraints, the development of a surface irrigation system has not been possible, and groundwater is the only source of irrigation water in Raniganj. So far, 4 DTWs and 46 STWs have been developed and used solely for irrigation in Raniganj. The total tube well system covers 25% of the agricultural land and farmers are bound to practice rain-fed farming in the remaining area.

2.2. Agricultural system

Agriculture is the main business in Ranigunj with approximately 80% of the population involved in agriculture. The study area is suitable for all kinds of cereal crops and vegetables; the only limiting factor is the irrigation water. Primarily, rice, maize, wheat, legumes, oil seeds, and sugarcane are the major commodities of the study area (DADO 2012). There are basically two main seasons for agriculture, that is, Kharif (wet season) and Rabi (cool dry season). Rice and summer maize are primarily grown in the wet season, whereas wheat, winter maize, oil seeds, legumes, and vegetables are grown in the dry season. In the irrigated farms, maize is cultivated in both seasons. The cropping calendar of the major crops grown in the study area is shown in Figure 2.

Seed bed preparation, planting, weeding, fertilizer application, irrigation, and harvesting are the major farm operations of the agricultural system in Raniganj. The resource inputs in the agricultural farm operations consist of diesel fuel, electricity, animal power, human labor, fertilizer, and manure. Diesel fuel is used in tractor and machinery operation for land preparation and threshing of crops and electricity for groundwater pumping. The use of animal power in the farm is limited, but human labor is vital in every activity. Manure use is irregular and is a decreasing trend along with a decreasing number of animals.

2.3. Groundwater irrigation systems

Before 2000, there was a trend towards the development of privately owned small-scale STWs in Raniganj. The STWs are smaller in size (4 inch) and capacity. But after 2000, farmers have tended to shift from privately owned shallow wells to community-based DTWs because of their capacity and reliability. Currently, there are altogether 4 DTWs and 62 STWs installed in Raniganj. The DTWs tap groundwater from more than one aquifer, and usually have a depth of 90–150 m. The DTWs in the study area are characterized by their larger depths (100–150 m), tube well size (12–14 inch), and larger command area (30–40 ha). The STWs are the tube well schemes of smaller size and capacity, usually inserted to a depth of 15–50 m to tap groundwater from the shallow aquifers. In the Raniganj area, the STWs are

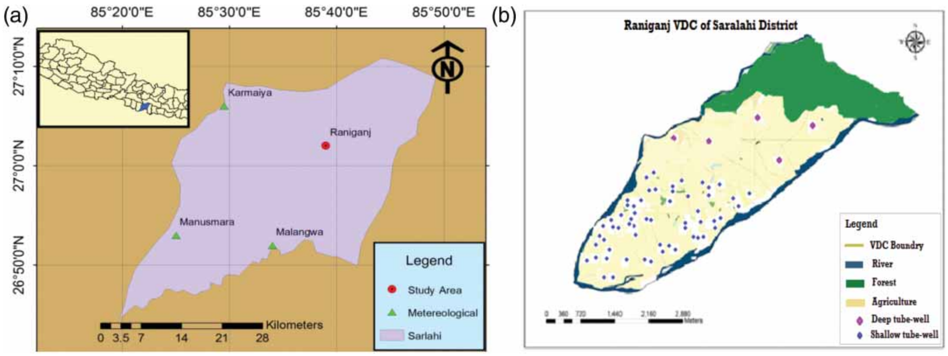
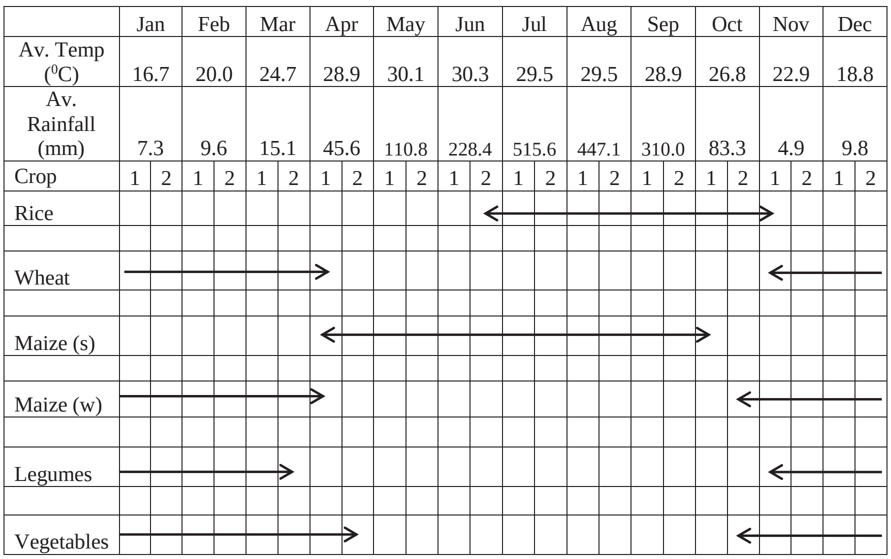


Figure 1. Location map of Raniganj VDC in the Sarlahi district of Southeast Nepal.



*Maize (s): Summer maize grown during April-September, Maize (w): Winter maize grown during October-March

Figure 2. Cropping calendar of major crops in Raniganj VDC, Sarlahi.

inserted to a depth of 20–30 m having a tube size of 4 inch and covering a command area of 2–4 ha. The DTWs are concentrated in the northern part across the highway, and STWs are distributed throughout the southern part where the water table is relatively shallow. Brief characteristics of the DTW and STW of the study area are presented in Table 1. Farmers are practicing traditional flooding methods of irrigation to irrigate cereal crops and furrow methods for some vegetables. They supply 3–4 irrigation for maize, 2–3 irrigation for wheat, and 1–2 irrigation for rice. The minimum number of irrigation for rice is due to available excess rainfall during the season.

3. Methods and data

3.1. Performance evaluation

The methodology for developing this study was structured into several steps. First, a set of indicators that characterize the performance of irrigation systems was selected. This study evaluates the tube well irrigation system using 11

Table 1. Characteristics of tube wells in the study area.

Tube well schemes	Depth (m)	Filter length (m)	Pumping water level (m)	Discharge rate (lps)	Pumping unit (HP)	Command area (ha)
DTWs	90–154	90–154	35–52	25–48	30–55	25–40
STWs	20–30	3.5–8	7–10	3–12	2–8	2.0–4.0

Table 2. Selected performance indicators to evaluate irrigation systems.

Performance group	Selected indicators	Physical parameters
Water supply	Water supplied per unit of irrigated area	$\frac{\text{Total annual volume supplied}}{\text{Total irrigated area}}$
	WDC	$\frac{\text{Pump capacity to supply water}}{\text{Irrigation demand}}$
	Relative water supply (RWS)	$\frac{\text{Irrigation } water \pm \text{ Effective rainfall}}{\text{Total crop demand}}$
	Relative Irrigation supply (RIS)	$\frac{\text{Annual volume of } irrigation \text{ water}}{\text{Evapotranspiration} - \text{Effective rainfall}}$
Agricultural outputs	Output per unit of irrigated area	$\frac{\text{Gross outputs of irrigated area (\$)}}{\text{Total irrigated area (ha)}}$
	Output per unit of irrigation supply	$\frac{\text{Gross outputs of irrigated area (\$)}}{\text{Total volume of irrigation supply (m}^3\text{)}}$
Energy use	Energy used per unit of irrigation supply	$\frac{\text{Annual total energy used (kWh)}}{\text{Annual volume of water supply (m}^3\text{)}}$
	Energy used per unit of irrigated area	$\frac{\text{Annual total energy used (kWh)}}{\text{Total irrigated area (ha)}}$
Economic	MOM cost per unit of irrigated area	$\frac{\text{Annual MOM cost (\$/yr)}}{\text{Total irrigated area (ha)}}$
	MOM cost per unit of irrigation water	$\frac{\text{Total annual MOM cost (\$/yr)}}{\text{Annual volume of water supply (m}^3\text{)}}$
	Benefit–cost ratio	$\frac{\text{Incremental benefits of Irr. (NPV)}}{\text{Incremental production cost (NPV)}}$

sets of performance indicators, categorized broadly into four groups. The indicators used for evaluation are listed in Table 2. The field-level data were collected through a designed survey approach. The survey design includes a selection of sample tube wells, farming households, design of questionnaire, and analysis of survey data. A CropWat model adopted by Food and Agriculture Organization (CROPWAT, Version 8) was used to estimate the reference evapotranspiration (ET_o) and crop water requirements of major crops. The energy and carbon auditing approach was used to examine the energy-use efficiency and environmental footprints of major crop production. The AquaCrop model (version 4) was further used to simulate the crop yields for different scenarios of water and energy inputs. The detailed methodology adopted for the study is presented in Figure 3.

The field-level data were collected through a comprehensive survey at the selected pump stations and farming households. It includes the full data set relating to farm enterprises, pump characteristics, water, and energy management. Two DTWs and one STW were selected as sampled irrigation systems based on their capacity. The most commonly grown crops (rice, wheat, and maize) and farming practices were included.

The benefit and cost of an irrigation project can be expressed as a ratio of annual incremental benefits due to irrigation schemes and the annual incremental cost of production. The difference in gross output before and after the introduction of irrigation systems is considered as benefits of irrigation:

$$\text{B} - \text{C ratio} = \frac{\text{Incremental benefit from irrigation system (NPV)}}{\text{Incremental cost of production (NPV)}}. \quad (1)$$

Here

$$\text{Benefit from irrigation (\$ /ha)} = [\text{SGVP of irrigated farm (\$ /ha)} - \text{SGVP of rainfed farm (\$ /ha)}], \quad (2)$$

$$\text{Irrigation structure cost (\$ /ha)} = \frac{\text{Annual cost of of the project (NPV)}}{\text{Annual irrigated area (NPV)}}, \quad (3)$$

where NPV is the Net Present Value and SGVP the Standardized Gross Value of Production. The NPV is the difference between the present value of cash inflows and the present value of cash outflows. The SGVP in all equations is the output of the irrigated area in terms of the gross or

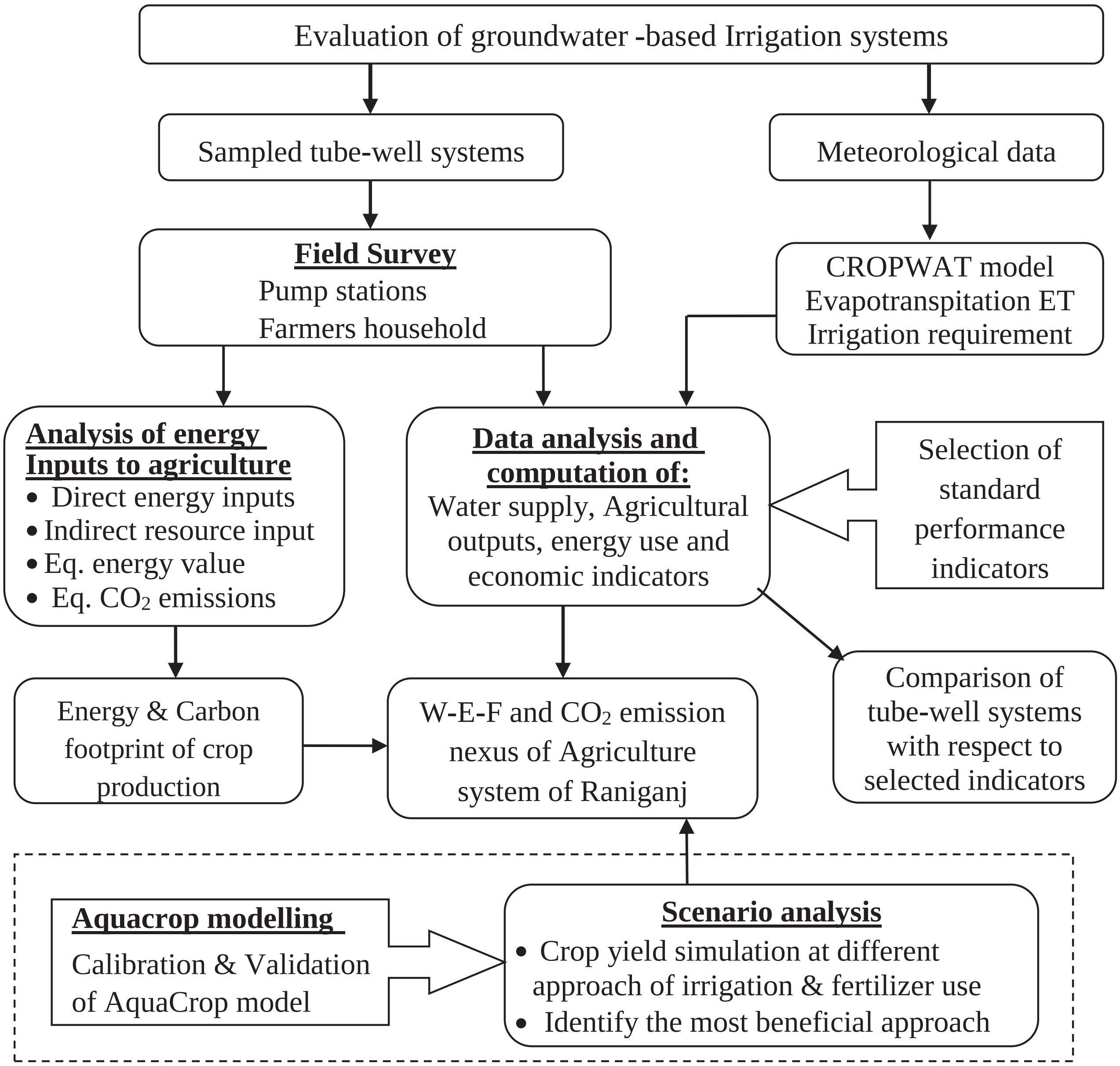


Figure 3. Methodological framework used to evaluate the performance of a tube well irrigation system, considering water supply, energy use, and food production.

net value of production measured at local or world prices. It is expressed as:

$$\mathrm{SGVP} = \left(\sum_{\mathrm{crop}} A_i Y_i \frac{P_i}{P_b}\right) P_{\mathrm{world}}, \quad (4)$$

where A_i is the area cropped with crop i (ha), Y_i the yield of crop i (ton/ha), P_b the local price of the base crop (\$/ton), and P_{world} the value of base crop traded at world price. SGVP is used for the cross-system comparison, and there exist some differences in local prices at different locations throughout the world.

The NPV of any involved cost is computed considering the discount rate and time horizon of the project. The discount rate of 10% was considered in this study. The period of discounting was considered to be 5 years for DTWs and 12 years for STWs as per the dates of their construction. The average working life of the tube well systems is considered to be 25 years:

$$\mathrm{Cost(NPV)} = C_0 * (1 + i)^n, \quad (5)$$

where C_0 is the initial cost involved, i the discount rate, and n the number of years considered.

Table 3. Energy contents of agricultural inputs relevant to this study.

Materials	Unit	Equivalent energy contents (MJ)	Reference
Machinery	h	62.7	Mushtaq et al. (2009)
Diesel	L	38.6	Jackson et al. (2010)
Human	h	1.96	Ozkan et al. (2004)
Animal (Ox)	day	10.0	FAO (2000)
Nitrogen	kg	65.0	FAO (2000)
Phosphate	kg	9.0	FAO (2000)
Seed	kg	14.0	FAO (2000)
Insecticide	kg	200	FAO (2000)

Table 4. Equivalent CO_2 emission factors for different farm inputs relevant to this study.

Materials	Unit	Eq. Carbon emissions (kg CO_{2-e})	References
Diesel	Liter	2.679	Carbon Trust (2008)
Electricity	kWh	0.004	Defra (2010)
Urea	kg	0.93	CSE, India (2009)
DAP	kg	1.79	Woods and Cowie (2004)
Phosphate	kg	1.94	Woods and Cowie (2004)
Nitrogen	kg	3.25	Barber (2004)
Pesticide	kg	4.92	Elsayad (2003)

3.2. *Water, energy, and emission budget*

The monthly and seasonal irrigation supply rates reported by the farmers were used for baseline data. The irrigation volume was determined based on the pump discharge and total irrigation hours. The average irrigation efficiency for the tube well system was assumed to be 50% as suggested by the Janakpur Agriculture Development Project (JADP). The energy data used for pumping units were collected as per the monthly records of their energy bills as reported by the pump operators.

In addition to this, the total energy inputs for crop production at the farm level were quantified based on the energy audit method used by Hatirli et al. (2006) and Khan et al. (2008). Resource inputs used at the farm level from land preparation to harvest were quantified based on the information provided by the farmers. Crop cultivation, irrigation supply, fertilizer application, and harvesting are the major agricultural activities requiring energy input. The equivalent energy contents of the farm inputs were reviewed from the previous studies and used for the accounting method (Table 3).

Each level of farm input is associated with equivalent carbon emissions. It is estimated from the total amount of energy associated with an input (MJ) and multiplying it with equivalent emissions factors (CO_{2-e}). This method has been used in several previous studies (Barber 2004; Khan et al. 2008; Jackson et al. 2011). Animal and human labor was not included in the emission budget. The functional unit used for the emission budget was kgCO_{2-e}/ha. The equivalent emission resources used for this study are given in Table 4.

3.3. *Crop yields simulation using the AquaCrop model*

The FAO AquaCrop model (Raes et al. 2009) was used to simulate the crop yields for different levels of irrigation and soil fertility management. Before applying the model for simulations, it was calibrated with data for local conditions and validated by comparing the results with the experimental yield data. The data for field conditions such as soil data, soil management practice, irrigation management, and actual yields were collected from a field survey. The crop phonological parameters were obtained from the relevant literature. The crop-specific data such as crop growing stage, maximum rooting depth, plant density, and maximum crop canopy were adjusted for local conditions.

After validation of the model, a scenario analysis was performed for different rates of Nitrogen (N) fertilizer and irrigation application to determine the best strategy to achieve optimum benefit for rice, wheat, and maize production in the study area. Three scenarios of N fertilizer dose and four scenarios of irrigation rates were considered for the assessment (Table 5).

4. Results and discussion

4.1. *Water supply performances*

The general features and operational practice of the selected tube well system are presented in Table 6. The DTWs are larger in size and capacity covering 30–40 ha of the command area. The STWs are smaller in size and their service capacity is almost 10% of the DTWs. The average discharge of DTWs was found to be 130 and 172 m^3/h with a total annual operation of 2248 and 2214 hours, respectively. The irrigation supply volumes per ha of the command area were larger from the DTWs (9666 and 9594 m^3) and relatively less from the STW (93130 m^3). In terms of irrigation depth, the STWs and DTWs supplied almost 62% and 65% of the total annual potential evapotranspiration of the study area (1466 mm), respectively.

The water delivery capacity (WDC) was good for DTWs (1.78), but poor for STW (0.91), indicating the failure of STW to meet the peak irrigation demands in STW-irrigated areas. The DTWs with higher discharge rates and WDC seem to be in a better position to supply irrigation water compared with STWs.

4.2. *Agricultural performance*

In terms of agricultural performance, the highest yields of rice (4.3 t/ha) and wheat (2.4 t/ha) were observed in

Table 5. Irrigation and fertilizer application scenarios used for simulations.

Crop	Irrigation treatments	N fertilizer treatments
Wheat	Existing farmers' application rate ($I_b = 110$ mm) 125% of I_b 150% of I_b 200% of I_b	Existing farmers' application rate ($F_b = 80$ kg/ha) 125% of F_b 150% of F_b
Maize	Existing farmers' application rate ($I_b = 170$ mm) 125% of I_b 150% of I_b 175% of I_b	Existing farmers' application rate ($F_b = 100$ kg/ha) 130% of F_b 160% of F_b
Rice	Existing farmers' application rate ($I_b = 100$ mm) 50% of I_b 150% of I_b 200% of I_b	Existing farmers' application rate ($F_b = 80$ kg/ha) 125% of F_b 150% of F_b

Note: I_b, base-level application of irrigation and F_b, base-level application of N fertilizer.

Table 6. Features of selected tube well systems during 2011–2012.

Performance	DTW1	DTW2	STW1
Pumping unit size (HP)	55	40	3.0
Average discharge (m^3/h)	172	130	22
Command area (ha)	40.0	30.0	3.0
No. of farmers (No)	72.0	48.0	4.0
Annual operation hours (h)	2248	2214	1245
Water supplied per cropped area (m^3/ha)	4986	4964	4677
Annual irrigation supplied (mm)	965	959	912
Annual potential evapotranspiration (mm)	1466	1466	1466

areas irrigated by DTW1 and DTW2, respectively. There is no large variation in crop productivity between the two DTWs, since both have identical conditions of irrigation supply and other inputs. However, in areas irrigated by STW1, the average productivity was slightly less for maize. The highest gross output per ha of cropped area was observed (2621.7 $/ha) for DTW1 because of the higher productivity of maize and vegetables in the command area compared with other schemes. The output per cubic meter of irrigation supply showed the highest value for STW1 (0.275 $/m^3), indicating better use of irrigation. Kumar et al. (2011) reported that the output of groundwater irrigation supply in Uttar Pradesh and Bihar in India varied from 0.185 to 0.258 US$/m^3, which is slightly less than that for the Raniganj cases.

4.3. *Energy-use performance*

The energy-use performance indicators help identify the energy-efficient and economical tube well systems. The STW1 showed the lowest energy requirements of 0.145 kWh to pump 1 m^3 of water (Table 8) due to the lower pumping head required. Both DTWs showed identical figures of 0.227 and 0.223 kWh/m^3 of water supply. The relatively higher energy requirement for DTW1 was due to the higher pumping lift of 37.5 m compared to 33 m of DTW2.

The seasonal energy required to irrigate 1 ha of the cropped area was found to be 677 kWh for the STW system, whereas it was around 1120 kWh for DTWs. In the DTW schemes, the pumping lift and water supply volume per unit area were both larger than for STWs, and as a result, the total energy requirement was also higher. Shah (2008) estimated the average quantity of electricity used by pumping sets in the major states of India as being 1935 kWh/ha. This relatively larger amount of energy used in Indian pumping stations was due to the required higher pumping lifts in the western and southern parts of India.

4.4. *Economic performance*

The MOM costs and benefit–cost ratio of selected irrigation systems were evaluated in order to understand the economic worth and social acceptability of the irrigation projects. The results showed that there is no significant variation in the MOM cost of irrigation water across the tube wells. On average, the cost of irrigation water was found to be 0.0133 $/m^3 across all tube wells (Table 7). The estimated benefit–cost ratio of the tube well systems indicated a value of more than 2 for all projects. STW1 was found to be the most beneficial, having the largest B–C ratio of 2.4. The initial investment and operational costs were both significantly viable for the STW systems. The DTWs also have B–C ratio values greater than 2 and justify the costs of public investment. Mushtaq et al. (2009) reported the benefit–cost ratio of tube well-irrigated rice cultivation in Pakistan, China, and the Philippines as 1.31, 1.67, and 1.83, respectively. In general, the higher

Table 7. Agricultural and socioeconomic performances of DTW and STW.

	Indicators	Unit	DTW1	DTW2	STW1
Water supply	Water supplied per unit of irrigated area	m^3/ha	4986.60	4964.30	4677.00
	WDC	%	1.77	1.78	0.91
	RWS	ratio	0.99	0.98	0.97
	RIS	ratio	0.95	0.94	0.94
Agricultural output	Output per unit of irrigated area	US$/ha	2695.80	2611.00	2552.40
	Output per unit of irrigation supply	US$/$m^3$	0.270	0.263	0.275
Energy use	Energy used per unit of irrigation supply	kwh/m^3	0.227	0.223	0.145
	Energy used per unit of irrigated area	Kwh/ha	1134.09	1105.09	676.70
Economic	MOM cost per unit of irrigated area	US$/ha	67.29	66.05	62.07
	MOM cost per unit of irrigation water	US$/$m^3$	0.0135	0.0133	0.0133
	Benefit–cost ratio	Ratio	2.33	2.11	2.48

benefit–cost ratios of tube wells in Raniganj are due to the cultivation of high-value maize and vegetables in addition to rice.

To sum up the comparative performance of the selected tube well irrigation schemes, the figures of the water supply performance group indicated a better performance for DTWs in comparison with STW. In addition, output per unit area (US$/ha) also demonstrated a superior performance for DTWs. The STW1 showed better results for energy use and economic performance. The lowest MOM cost ($62.07/ha) and highest benefit–cost ratio (2.48) of this tube well scheme make it superior to others.

4.5. Resources inputs and crop production

The energy resources used for different farm operations were quantified based on the information provided by the farmers. The energy inputs to various agricultural operations were almost similar at the farm level, but irrigation was observed as a major energy-varying operation across the tube well systems. Based on the size of tube well systems, the farm-level study was divided into two categories (Table 8). Cultivation, irrigation, fertilizer application, and harvesting were identified as the major four farm operations requiring energy inputs. For a given crop, cultivation and harvesting operations were almost identical across the tube wells system consuming the same level of energy inputs. The rate of fertilizer and irrigation applications was found to be the most varied at the farm level. The total energy used under the DTW system (per ha) was found to be larger by 7–13% in relation to the STW system because of the varying amount of irrigation water and fertilizer use.

Maize shows the highest level of energy (11087–12662 MJ) inputs per ha in both irrigation systems, followed by

Table 8. Analysis of water, energy and carbon footprints for rice, wheat, and maize production.

	Rice		Wheat		Maize	
Variables	DTW	STW	DTW	STW	DTW	STW
Total energy inputs (MJ/ha)	10410	9710	9438	8686	12562	11087
Cultivation	2304	2304	1081	1081	1777	1777
Irrigation	1698	1116	1981	1228	3254	1920
Fertilizer	5401	5267	5401	5401	6510	6375
Harvesting	1006	1006	975	975	1021	1021
Water used (m^3/ha)	2035	2200	2408	2420	3956	3784
Crop yields (t/ha)	4.3	4.2	2.4	2.4	7.6	7.15
Energy used per ton of yield (MJ/ton)	2421	2312	3932	3619	1653	1551
Water used per ton of yield (m^3/t)	473	524	1003	1008	520	529
Eq. CO_2 emission per ha (kg/ha)	400.8	382.2	385.2	384.1	501.0	481.2
CO_2 emission per ton of yield	92.7	95.23	159.3	160.0	65.9	67.3
Economic benefit[a]	879.6	859.1	654.5	654.5	1856.8	1746.9

[a]Economic benefit = Gross benefit–(irrigation cost + fertilizer cost).

Table 9. Observed and simulated yields of rice, wheat, and maize and relative error.

Crop	Year	Observed (t/ha)	Simulated (t/ha)	Relative error (%)	RMSE
Rice (Mansuli- Sabitri)	2008	4.45	4.36	2.02	0.1063
	2009	4.52	4.41	2.43	
	2010	4.15	4.30	– 3.61	
	2011	4.26	4.21	1.17	
Wheat (Gautam)	2008	2.95	2.86	3.05	0.1099
	2009	3.15	3.28	– 4.13	
	2010	3.10	2.97	4.19	
	2011	3.27	3.19	2.45	
Maize (Gaurav)	2009	8.40	8.13	3.33	0.2186
	2010	7.85	8.06	– 2.42	
	2011	8.55	8.36	1.99	

rice (9710–10410 MJ) and wheat (8686–9438 MJ). The indirect energy input through the application of fertilizer represents the largest share of total energy for wheat (57%) followed by rice (52%) and maize (52%). Irrigation water constitutes the second largest energy input. Wheat indicates the largest requirement for water (1008 m^3) and energy (3956 MJ) resources per ton of yield. Maize seems to be the most water- and energy-efficient crop and requires almost half of the resources used in wheat production for each ton of yield (Table 8). However, rice is the most water-intensive crop, but showing the least irrigation water and associated energy input due to excess water from monsoon rainfall during the season.

The Indian Council of Agriculture Research (ICAR) has reported the energy use for rice, wheat, and maize crops in Indian farms as: 13076, 14657, and 9956 MJ/ha, respectively. The higher productivity of rice and wheat in Indian farms is associated with these high levels of energy inputs. For the maize crop, Raniganj farmers are using a relatively higher amount of energy resources compared with Indian farmers. Khan et al. (2009) evaluated the quantity of energy required to produce one ton of rice (2436 MJ) and wheat (2240 MJ) in South Australia. Here, the energy intensity of rice produced in South Australia seems to be very similar to that of Raniganj farms (2312–2421 MJ/t). However, the wheat crop showed significantly higher

Table 10. Water–energy and yield nexus of rice and maize production at various resource levels.

			Energy used for rice production			
Irrigation (mm)	N fertilizer (kg/ha)	Yield (t/ha)	Energy (MJ/ha)	Energy (MJ/ton)	Benefit ($/ha)	Benefit increment (%)
Rice						
100	80	4.28	10,067	2352.1	747.74	0
150	80	4.29	10,916	2544.5	729.34	– 2.5
200	80	4.28	11,765	2748.8	706.83	– 5.5
100	100	4.52	11,367	2514.8	778.66	4.1
150	100	4.54	12,216	2690.7	762.3	1.9
200	100	4.53	13,065	2884.1	739.79	– 1.1
100	120	4.71	12,667	2689.4	796.38	6.5
150	120	4.74	13,516	2851.5	782.07	4.6
200	120	4.73	14,365	3037.0	759.57	1.6
Maize						
170	100	7.30	12,264.3	1680.0	1603.54	
215	100	7.46	13,000.0	1742.6	1624.90	1.3
260	100	7.58	13,742.8	1813.0	1636.33	2.0
300	100	7.64	14,400.7	1884.9	1635.12	2.0
170	130	7.77	14,214.3	1829.4	1681.44	4.9
215	130	8.03	14,950.0	1861.8	1727.23	7.7
260	130	8.11	15,692.8	1935.0	1728.88	7.8
300	130	8.15	16,350.7	2006.2	1722.80	7.4
170	160	8.26	16,164.3	1956.9	1770.13	10.4
215	160	8.58	16,900.0	1969.7	1830.59	14.2
260	160	8.64	17,642.8	2042.0	1827.34	14.0
300	160	8.68	18,300.7	2108.4	1821.27	13.6

energy intensity compared with Raniganj farms (3932 MJ/t), indicating a high scope for improvement in energy productivity and total benefit from wheat production.

The carbon equivalent emissions associated with crop production are directly related to the energy inputs for crop production, mainly diesel fuel for farm machinery operations, pumping irrigation water, and application of chemical fertilizer. The electricity used for pumping irrigation water was obtained completely from hydropower and no direct emission was considered from it. Similarly, as with energy consumption, Maize showed the largest equivalent CO_2 emissions (per ha) of 501 kg followed by rice (400.8) and wheat (385.2). The methane emissions from the flooded paddy field were not considered here. The environmental footprint per ton of grain produced (kg CO_{2-e}/ton) shows the most for wheat (159.3), which is almost 1.7 times that of rice (92.7) and 2.5 (65.9) times that of maize.

Pathak et al. (2012) estimated the CO_2 emissions per ton of rice (26.7–54.7 kg) and wheat (51–67 kg) produced in the Indogangetic plain of India. These figures are much less (one-third) in comparison with Raniganj's emission rates because the researcher did not consider the separate groundwater-irrigated farms of the Indogangetic plain.

Along with the higher rates for resource inputs, the crop yields and economic benefits are also relatively higher in DTW farms in comparison with STW farms. For rice and wheat crops, no significant difference in benefits was observed across the tube well systems (Table 8). The largest difference in gross benefit (110 \$/ha) was observed for maize production across the tube wells because of yield gap. To sum up, Table 4 illustrates that wheat production under current practice is very high energy- and carbon-intensive, giving the least benefit in comparison with rice and maize. In these circumstances, it would be wise to shift from wheat to maize crops; this not only increases the benefits per ha but also improves the productivity of the resources used.

4.6. *Crop yield responses to water and energy*

The existing cultivars of rice, wheat, and maize were simulated through the AquaCrop model and compared with the respective experimental yield data from 2008 to 2011.

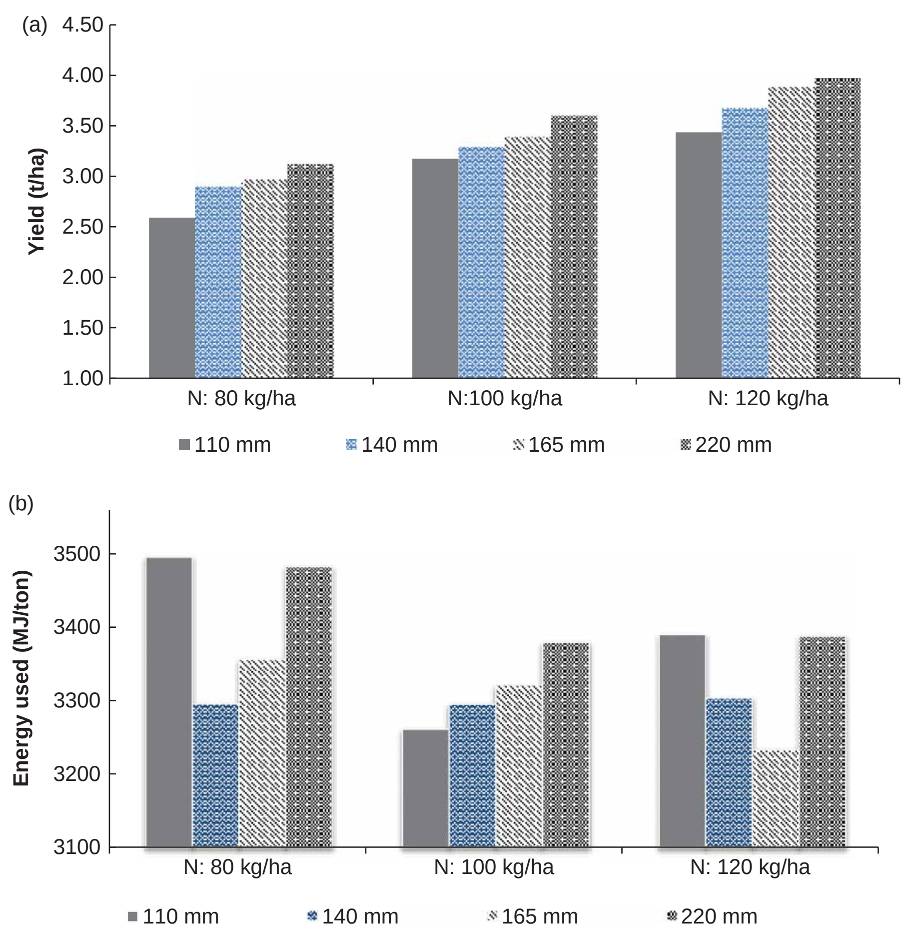


Figure 4. (a) Yield response of wheat at different application rates of irrigation and fertilizer. (b) Energy used per ton of wheat produced (MJ/t) at different application rates irrigation and fertilizer in DTW farms.

However, the grain yield was the only parameter available to calibrate the model, and it showed good agreement with the observed data. The relative error (%) of observed and simulated yields for the duration of 2008–2011 was examined to check the representation of the AquaCrop model with the existing crops (Table 9).

4.6.1. *Rice*

Rice is the most commonly grown crop during the monsoon season in the Raniganj area. Farmers usually follow the rainfall pattern for rice cultivation, so the total irrigation requirement is minimal. In general, farmers apply 100 mm of irrigation and 80 kg/ha of N fertilizer as a base-level input to the rice field. The rice yield was simulated for different application rates of irrigation and fertilizer to examine the nexus of resources used (Table 10).

The yield response of rice showed significance with the added fertilizer dose. In the current farming practice, the average yield of rice is 4.28 t/ha and a maximum achievable yield is 4.74 t/ha (10% increment) when fertilizer application is increased by 50%. But for a given doze of fertilizer, there is no significant increment of rice yield with the addition of irrigation. A diminishing yield was observed when the irrigation supply was doubled. The leaching of nutrients with excess irrigation water can be a reason for yield reduction. This signifies that the nutrient supply is more important than irrigation for the rice crop in Raniganj.

At current levels of resource inputs (100 mm of irrigation and 80 kg of N fertilizer), the total energy used for rice production comes to around 10067 MJ/ha. It increases proportionally with each additional unit of resources used. When the irrigation rate was doubled and fertilizer application increased by 50%, the total production energy per ha increased by 42% from the current level. ICAR reported the total energy used for rice production as 13076 MJ/ha in Indian farms, which is almost 30% higher than in Raniganj's rice farms. The energy intensity of rice produced was observed as 2352 MJ/ton for the existing farming practice. It showed proportionally enlarged values for each level of increased inputs (Table 10).

4.6.2. *Wheat*

Wheat is a winter season crop for Raniganj. In current practice, farmers are applying on average 110 mm of irrigation water and 80 kg of N fertilizer per ha for wheat production. Yield response of wheat (Gautam) for various applications of irrigation and fertilizer was simulated. The average simulated yield of wheat and nexus of resources used for four different levels of irrigation and three levels of fertilizer are illustrated in Figure 4(a).

An increment of wheat yields was observed for every additional unit of resources used. The yield response was equally reactive with both added fertilizer and irrigation water (Figure 4(b)). The best perceived strategy to maximize the yield (3.98 t/ha) is to increase the irrigation by 100% and fertilizer by 50%. This signifies that both the increased rate of irrigation and fertilizer are very important factors in maximizing the wheat production in Raniganj.

Figure 4(b) illustrates the nexus of water and energy resources to produce one ton of wheat under the DTW system. Unfortunately, it indicates the largest quantity of energy (3495 MJ) per ton of wheat produced for the existing practice of wheat production. There exist fluctuations of energy requirements with each set of resource strategies used. The lowest energy intensity can be 3232 MJ/ton when both the irrigation and fertilizer applications are increased by 50%. This will increase the total benefit (per ha) by 51%, consuming an extra 38.7% of energy at the base level.

Here, the increased magnitude of energy is associated with the electricity used for pumping water and the indirect energy of fertilizer.

4.6.3. *Maize*

The most commonly grown maize cultivar (Gaurav) was simulated considering different rates of irrigation and fertilizer use for the base years 2008–2011. The average simulated yields and resource use nexus are illustrated in Table 10. The positive yield responses are observed with every additional unit of irrigation and fertilizer application. The higher rates of fertilizer application appear to

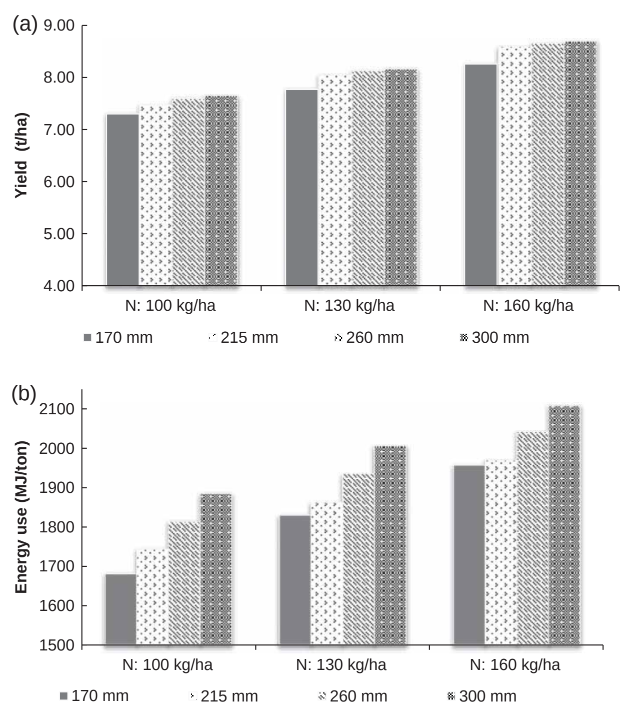


Figure 5. (a) Yield response of maize at different application rates of irrigation and fertilizer. (b) Energy used per ton of maize produced (MJ/t) at different application rates in DTW farms.

Table 11. Resources used to produce 1 ton of cereal grain under the DTW system in Raniganj.

Crop	Irrigation water (m^3/ton)	Energy inputs (MJ/ton)	Economic benefit[a]($/ha)	Remarks
Rice				
EP	520	2352	747.74	$I_b + F_b$
MBP	471 (−9.4%)	2689 (+14.3%)	796.38(+6.5%)	$I_b + 1.5F_b$
Wheat				
EP	944	3495	572.46	$I_b + F_b$
MBP	942 (−0.2%)	3232 (−7.5%)	864.48(+51%)	$1.5I_b + 1.5F_b$
Maize				
EP	518	1680	1603.54	$I_b + F_b$
MBP	555 (+7.1%)	1979 (+17.3%)	1830.59(+14.2%)	$1.25I_b + 1.6F_b$

Note: EP, existing farmers' practice and MBP, maximum beneficial practice.
[a]The gross benefit minus irrigation and fertilizer cost.

be very important in order to achieve the maximum possible yield. In the present conditions, farmers apply 170 mm of irrigation and 100 kg/ha of N fertilizer to maize fields and achieve a yield of 7.30 t/ha. The maximum possible yield that can be harvested is around 8.64 t/ha when the irrigation application is increased by 50% (215 mm) and fertilizer by 60% (Figure 5(a)).

Although it shows a positive maize yield with increased use of resources, the marginal benefit is not always attractive. In present conditions, farmers can achieve an economic benefit of 1603 $/ha. The maximum possible benefit that can be achieved is 1830 $/ha when the irrigation application is increased by 25% and fertilizer by 60%. An increased irrigation supply beyond 215 mm does not show a positive economic return for all rates of fertilizer.

The current level of energy inputs to maize production showed 12264 MJ/ha and can be increased by almost 50% when water and fertilizer applications are increased to achieve the maximum yield. Figure 5(b) illustrates the energy consumed per ton of maize produced with different combinations of resource inputs. Fortunately, it indicates the lowest energy value of 1680 MJ/ton for the existing farmers' approach to resources. All the other approaches showed larger energy intensity than the base case. When the irrigation and fertilizer applications were increased by 25 and 60%, respectively, the maximum benefit is obtained (1830 $/ha) and at that time, the energy intensity was increased by 17% of the base case (1970 MJ/ton) (Table 11).

5. Conclusions

Groundwater has been identified as an important source of water across the globe and the irrigation sector is the largest abstractor. Groundwater-based irrigation through the installation of DTW and STW has been identified as a potential means for the expansion and intensification of irrigated agriculture in Nepal. In this context, this study aims to evaluate the performance of the groundwater-based irrigation systems of Raniganj considering water–energy–food nexus.

The DTWs system of Raniganj showed a better performance in terms of water supply and agricultural outputs per unit of irrigated area. The WDC was good for DTWs (1.78), but poor for STWs (0.91), indicating the failure to meet the peak irrigation demands in STW-irrigated area. In terms of agricultural performance, the highest yields of rice (4.3 t/ha) and wheat (2.4 t/ha) were observed in field irrigated with DTWs. Shifting from traditional crops to hybrid maize with the introduction of DTWs has been the prime factor for better outputs. Although the STWs are smaller in size and capacity, their performance in terms of energy use and economic benefit was superior to the DTWs. The higher benefit–cost ratios of tube wells in Raniganj are due to the cultivation of high-value maize and vegetables in addition to rice. Due to the more reliable irrigation water and higher outputs per unit of irrigated area and investment support from the government, farmers of Raniganj have tended to have DTWs rather than STWs in recent years. The STW1 showed the lowest energy requirements of 0.145 kWh to pump 1 m^3 of water due to the lower pumping head required. Both DTWs showed identical figures of 0.227 and 0.223 kWh/m^3 of water supply.

Although the productivity of major cereal crops in Raniganj was found to be better than the national average, their yields are still below potential due to insufficient resource inputs. The rice and maize showed a relatively better performance yield in relation to water and energy inputs, whereas wheat showed a very poor performance. Wheat requires almost double the amount of water and energy resources than that required by maize to produce 1 ton of grain.

The productivity of resources can be increased either by introducing a high-yielding variety of wheat or by shifting to maize crops. The average fertilizer application rates for major crops in Raniganj are still less than the national recommended dose, resulting in yields below potential. The approach of an additional irrigation supply along with the full dose of fertilizer can maximize the yields. Similarly, it is important to encourage farmers to shift from wheat to maize cultivation in the winter season in order to optimize the benefits of per-unit resource use and per-unit cultivated area. More importantly, water–energy and crop yield should be analyzed in an integrated approach to optimize the overall resource-use efficiency, rather than considering each individually. In this study, the environmental aspect of resources use was not considered. However, it is recommended to further carry out the study related to the impacts of increasing use of fertilizers and pesticides to increase the crop yield since it might contaminate (for e.g. nitrate pollution) the groundwater resources of the area.

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