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REDUCING CARBON EMISSIONS THROUGH IMPROVED IRRIGATION MANAGEMENT: A CASE STUDY FROM PAKISTAN†

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ABSTRACT

Increasing use of groundwater for irrigation is linked to high energy demand, depleting resources and resulting in a high carbon footprint. This paper explores how improved on-farm irrigation management can help in reducing groundwater extraction, limiting energy consumption and CO_2 emissions. In Pakistan, every year about 50 billion cubic metres (BCM) of groundwater is pumped for irrigation, which consumes more than 6 billion kWh of electricity and 3.5 billion litres of diesel. Carbon emissions attributed to this energy use amount to 3.8 million metric tons (MMT) of CO_2 per year. Considerable research carried out in Pakistan has suggested that improved irrigation management can significantly reduce the irrigation water applied to different crops. This study revealed that by adopting improved irrigation schedules, water productivity will increase and groundwater withdrawals for irrigation can be reduced by 24 BCM. Reduced groundwater extraction will result in a 62% decline in energy demand (1.5 billion litres of diesel as most of the private tubewells run on diesel) and a 40% reduction in carbon emissions. In addition, a reduction in irrigation applications will also be beneficial for stabilizing groundwater tables and groundwater quality.

KEY WORDS: climate change mitigation; CO_2 emissions; groundwater–energy nexus; groundwater table; Pakistan; agricultural practices; water management

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RÉSUMÉ

L'augmentation de l'utilisation des eaux souterraines pour l'irrigation induit une forte demande d'énergie, épuise la ressource et élève l'empreinte carbone. Cet article explore comment l'amélioration de la gestion de l'irrigation à la ferme peut aider à réduire l'extraction d'eau souterraine, la consommation d'énergie et les émissions de CO_2. Au Pakistan, chaque année environ 50 milliards de mètres cubes (BCM) d'eau souterraine sont pompés pour l'irrigation, qui consomme plus de 6 milliards de kWh d'électricité et 3,5 milliards de litres de diesel. Les émissions de carbone attribuables à cette consommation d'énergie sont 3,8 millions de tonnes métriques (MMT) de CO_2 par an. Le travail de recherche considérable accompli au Pakistan a suggéré que l'amélioration de la gestion de l'irrigation peut réduire considérablement l'eau d'irrigation appliquée aux cultures. Cette étude a révélé qu'en améliorant la programmation des horaires d'irrigation, la productivité de l'eau va augmenter et les prélèvements d'eau souterraine pourront être réduits de 24 BCM. L'extraction de l'eau souterraine se traduira par une réduction de 62 % baisse de la demande d'énergie (1,5 milliard de litres de diesel, la plupart des forages privés fonctionnant au diesel) et réduction de 40 % des émissions de carbone. En outre, la réduction des applications d'irrigation sera également bénéfique à la stabilisation de la nappe phréatique et la qualité des eaux souterraines.

MOTS CLÉS: atténuation du changement climatique; émissions de CO_2 ; nexus eau souterraine–énergie; Pakistan; pratiques agricoles; gestion de l'eau

INTRODUCTION

Groundwater has emerged as an exceptionally important water resource, and growing demand for its use in agriculture, domestic and industrial contexts grades it as a resource of strategic importance. In view of the high evapotranspiration and salinity environment under which irrigated agriculture in the Indus basin is practised, the availability of surface water resources is only marginally sufficient for basin-wide, year-round high-intensity cropping (Bhutta and Smedema, 2007; Qureshi *et al*., 2009). This difference between crop water requirements and surface water supplies, combined with generally unreliable and relatively inefficient water distribution

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†Réduire les émissions de carbone grâce à une meilleure gestion de l'irrigation: une étude de cas du Pakistan.

systems, has led to the exploitation of groundwater where conditions allow (World Bank, 2007; Qureshi *et al*., 2009).

The increasing role of groundwater in agriculture has made it very energy-intensive. Groundwater exploitation has enabled farmers to supplement their irrigation requirements and to cope with the vagaries of the surface supplies. This allows them not only to increase their production level and incomes but also enhance their opportunities to diversify their income base and to reduce their vulnerability to the seasonality of agricultural production, and to external shocks such as droughts (Bhutta, 2002; Qureshi *et al*., 2009). Groundwater use has also increased resilience to climate change because surface storages have fared poorly on these counts. These benefits will become even more important as climate change heightens hydrological variability. From society's point of view, aquifer storage is also advantageous because it minimizes water loss through non-beneficial evaporation for semi-arid countries like Pakistan, where surface storages can lose 3 m or more of their storage every year through pan evaporation (Shah, 2009).

The introduction of cheap technologies has played a key role in the groundwater boom in Pakistan. As a result, farmers tend to over-irrigate and a considerable amount of pumped water evaporates, or goes back to the aquifer through deep percolation. In both ways, a significant amount of consumed energy does not contribute to biomass production (Karimi *et al*., 2012). Other disadvantages of excessive groundwater use are declining groundwater tables and increasing salt content in the pumped groundwater. Groundwater irrigation is also expensive as compared to gravity-run canal irrigation. Furthermore, groundwater irrigation is also considered an environmental hazard because the energy used in pumping groundwater directly contributes to CO_2 discharge (Shah, 2009).

Pakistan is one of the lowest carbon emitters in the world but the increasing use of groundwater for irrigation is putting extra pressure on energy resources and directly contributes to an increase in CO_2 discharge. Therefore, productive and efficient use of groundwater at farms and decreasing pumping is beneficial for stabilizing aquifers and reducing carbon emissions, which could be a key climate change adaptation strategy. This paper estimates the CO_2 emissions as a result of groundwater extraction and quantifies reductions in energy consumption and CO_2 emissions through the adoption of improved irrigation management strategies.

OVERVIEW OF GROUNDWATER IRRIGATION IN PAKISTAN

Groundwater evolution in Pakistan

The use of groundwater for irrigated agriculture in Pakistan has a long history. Before 1960s, groundwater extraction was carried out by means of open wells with rope and bucket, Persian wheels, *karezes*, reciprocating pumps and hand pumps. Large-scale extraction and use of groundwater for irrigated agriculture in the Indus basin started during the 1960s with the launching of Salinity Control and Reclamation Projects (SCARPs). Under this public sector programme, 16 700 wells (supplying an area of 2.6 million ha) with an average capacity of $80 \mathrm{l\,s^{-1}}$ were installed to control groundwater and salinity problems (Bhutta and Smedema, 2007).

The demonstration of SCARP tubewells was followed by an explosive development of private tubewells with an average discharge capacity of about $28 \mathrm{l\,s^{-1}}$. The provision of subsidized electricity by the government and the introduction of locally made diesel engines provided an impetus for a dramatic increase in the number of private tubewells. Currently, about 1.2 million small-capacity private tubewells are in operation in Pakistan (Qureshi *et al*., 2008). Out of these, 800 000 are located in Punjab (Figure 1). Investments in the installation of private tubewells are of the order of US $400 million whereas the annual benefits in the form of agricultural production are to the tune of US$2.5 billion (Shah *et al*., 2003). The estimated number of users is over 2.5 million farmers, who exploit groundwater directly or hire the services of tubewells from their neighbours. Groundwater currently provides more than 50% of the total crop water requirements, with flexibility of availability on an as and when needed basis (Shah, 2007).

Patterns and benefits of groundwater use

In Pakistan, about 70% of the private tubewells are located in the canal command areas where groundwater is used in combination with the canal water, whereas the rest provide irrigation based on groundwater alone. The combined use of surface water and groundwater (usually referred as conjunctive use) is now practised on more than 70% of the irrigated lands in Pakistan. The area irrigated by groundwater alone has increased from 2.7 to 3.4 million ha, whereas the

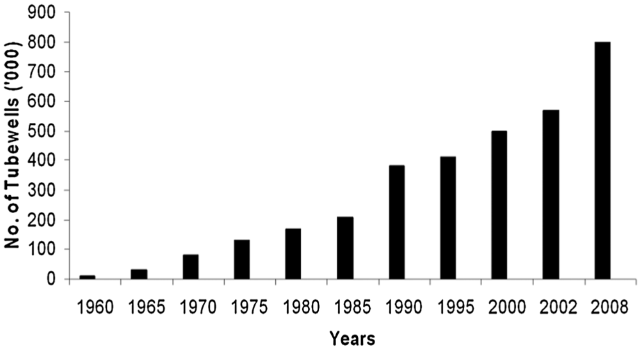

Figure 1. Development of private tubewells in the Punjab Province (Data source: Punjab Irrigation Department)

area irrigated by canal water alone has decreased from 7.9 to 6.9 million ha (Qureshi *et al*., 2004). In Pakistan large-scale production of major crops such as wheat, cotton, rice and sugar cane is only possible because of the supplemental use of groundwater for irrigation. The average cost of irrigating with groundwater is 30 times higher than that of surface irrigation (World Bank, 2007). The cost of canal water per year per hectare is US\$5.5, whereas groundwater is marketed as US\$67 ha^{-1} yr^{-1}.

The benefits of groundwater in Pakistan are multidimensional and range from drinking water supplies for the urban and rural population, to economic development as a result of higher agricultural production. The role groundwater irrigation has attained in maintaining the agricultural boom is unique and vital and will expand further in future due to mounting pressure to grow more food and increasing incidences of drought in the region. Qureshi *et al*. (2003) have shown that more than 70% of the farmers in the Punjab depend directly or indirectly on groundwater to meet their crop demands. Therefore management of this resource requires high level of attention and commitment both from government agencies and from agricultural and domestic users.

Sustainability of groundwater resources

The unregulated and uncontrolled use of groundwater has diminished its relative accessibility. The trend of continuous decline of the groundwater table has been observed in many areas of the Indus basin, which illustrates the serious imbalance between abstraction and recharge. Figure 2 shows the changes in groundwater table depths over a period of 10 years (1993–2003) in the Punjab province. As a result, many wells have gone out of production, yet the water tables continue to decline and the quality deteriorates. Excessive exploitation of aquifers in fresh groundwater areas has resulted in falling water tables and groundwater has become inaccessible in 5 and 15% of the irrigated areas of Punjab and Balochistan provinces, respectively. Although no recent estimates exist, it was estimated that under the ‘business as usual scenario’, this area is expected to increase to 15% in Punjab and 20% in Balochistan by 2020 (Punjab Private Sector Groundwater Development Project (PPSGDP), 2000). The variation between different canal commands is mainly linked to groundwater quality. In relatively fresh groundwater areas, extraction is greater because farmers there tend to grow water-intensive crops such as rice and sugar cane. In poor-quality groundwater areas, extraction is low in order to avoid secondary soil salinization.

Energy use for groundwater extraction in Pakistan

In Pakistan, the use of electricity for groundwater pumping started in the 1970s, when the rural electricity grid was expanded and the government provided much-needed incentives for farmers to install tubewells to boost agricultural production. In 1980s, the tubewell population surged from 37 000 to 84 000, making it difficult for the government to collect revenue through the metering system (Qureshi and Akhtar, 2003). Increased electricity prices and unannounced power cuts resulted in the stagnation of electric tubewells and an increase in diesel tubewells. Although the cost of water from diesel tubewells (2.20 US¢ m^{-3}) was still

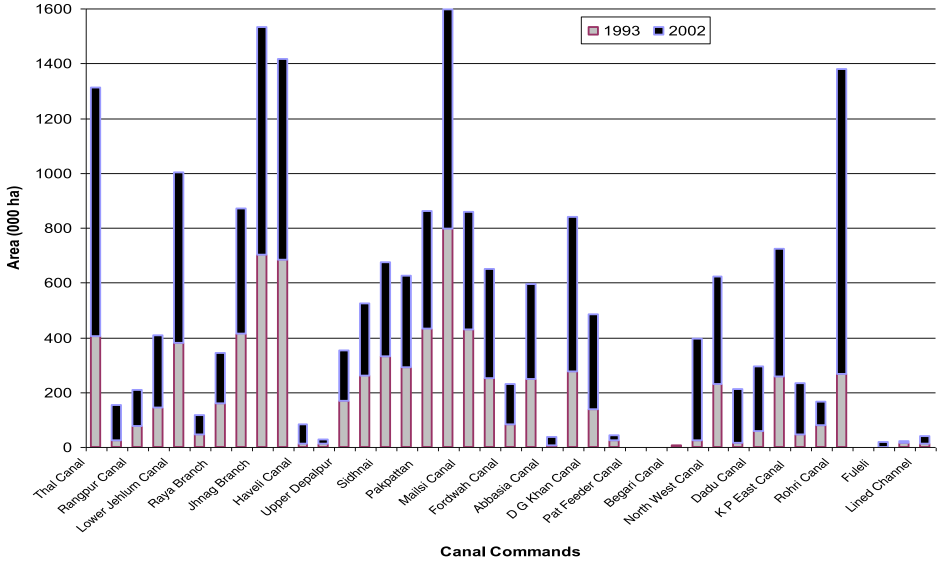

Figure 2. Increase in area with a groundwater table depth of 300 cm over a period of 10 years (1993–2003) in different canal commands of the Punjab and Sindh provinces (Source: Qureshi *et al*., 2009). This figure is available in colour online at wileyonlinelibrary.com/journal/ird

higher than electric tubewells (0.70 US¢ m^{-3}), diesel tubewells were preferred due to low initial installation and operational costs.

The latest estimates suggest that in 2010, farmers extracted 50 billion cubic metres (BCM) of groundwater through 1.2 million diesel and electric tubewells (Qureshi *et al.*, 2010). Of this, about 0.8 million are located in Punjab. About 200 000 tubewells are operated by electric motors whereas the remaining 1 million are run by diesel engines of various capacities.[1] Out of a total 50 BCM of groundwater extraction, about 12 BCM is extracted using electric pumps and the remaining 38 BCM using diesel pumps.

The depth to groundwater is directly linked to energy requirements for water extraction. In a countrywide survey of 1200 private tubewells, Qureshi *et al.* (2003) found that in Pakistan, electric tubewells are used to extract water from greater depths (40–80 m) and diesel tubewells are used for shallow water table areas (6.0–15 m). The farmers use pumps which are not energy-efficient due to low capital investment. Due to high friction losses in wells and inefficient water conveyance systems, energy losses are very high. Energy requirements for extracting groundwater are highly sensitive to the dynamic head over which the groundwater is lifted. Therefore for energy calculations for this paper, a conservative estimate of dynamic head for electric and diesel pumps has been taken. For electric tubewells, a dynamic head of 60 m is assumed. For diesel pumps, a dynamic head of 10–15 m is considered because beyond this depth diesel pumps become extremely inefficient, forcing irrigators to switch to electricity. Therefore for diesel pumps, operational hours are more important for energy requirement calculations than dynamic head.

Electricity consumption in groundwater irrigation can be calculated based on the energy requirement to lift the water. To lift 1000 m^3 water from 1-m depth at 100% efficiency (without considering friction losses), 2.73 kWh of energy are required (Karimi *et al.*, 2012). Thus energy consumption can be calculated as follows:

$$\mathrm{Ec} = 2.73 \times D \times V/\mathrm{OPE} \times (1\text{–}\mathrm{Tl}) \times 1000 \qquad (1)$$

where

Ec = electricity consumption (kWh)
D = lifting height (m)
V = volume (m^3)
OPE = overall pumping efficiency, and
Tl = transmission and distribution losses (only in the case of electric pumps; otherwise zero).

The average overall pumping plant efficiency[2] (OPE) of electric pumps in Pakistan is about 40% (Buksh *et al.*, 2000). Electricity transmission and distribution losses are usually taken as 25% (Water and Power Development Authority (WAPDA), 2009). Therefore, electricity that is actually used to lift 1000 m^3 of water from 1 m depth is 9.1 kWh. If we consider an average dynamic head of 60 m, then lifting 12 BCM of groundwater would require 6.0 billion kWh of electricity. This estimate is highly sensitive to the assumption about the dynamic head over which a representative electric pump lifts water.

Diesel-powered tubewells are even less efficient but they lift water to a smaller head; moreover, diesel does not face the transmission and distribution losses that electricity suffers and a litre of diesel provides the equivalent of 10 kWh of energy. Diesel tubewells are usually installed in shallow groundwater table areas (6.0–15 m). The fuel consumption of diesel engines (Chinese and slow speed diesel engines) is 1.5–2.5 l h^{-1} whereas tractor-operated tubewells burn 3.5–5.0 l h^{-1} (Qureshi *et al.*, 2003). The utilization factor of private diesel tubewells is between 10 and 15% (1350 h yr^{-1}). Therefore total annual fuel consumption of 1 million diesel tubewells (assuming 2.5 l h^{-1} and 1350 h yr^{-1}) would be 3.5 billion litres. Therefore total energy consumption for groundwater extraction amounts to 41 billion kWh. Taking into account the consumption of 6 billion kWh electricity and 3.5 billion litres of diesel, it can be calculated that on average extracting 1 m^3 groundwater requires 0.820 kWh of energy in Pakistan. This amount of energy is equivalent to lighting up a 100 W bulb for more than 8 h.

Carbon footprints of Pakistan's groundwater irrigation

Pakistan's contribution to total global greenhouse gas (GHG) emissions is miniscule (about 0.8%) and its per capita GHG emissions stand at a level which corresponds to one-third of the global average (Planning Commission, 2010). The total GHG emissions of Pakistan in 1994 were 182 MMT of CO_2 equivalence, which increased to 309 MMT of CO_2 equivalence in 2008, registering an increase of 3.9% yr^{-1} (Pakistan Atomic Energy Commission, 2009). The biggest contributor to GHG is the energy sector with 51% share, followed by the agriculture sector (39%), industrial processes (6%) and other activities (5%). Future estimates suggest that due to increasing energy demand, CO_2 emissions from the energy sector will increase to 2685 MMT of CO_2 equivalence from the current level of only 157 MMT of CO_2 equivalence. This shows the importance for Pakistan that it take serious steps to control GHG emissions in the energy sector. Controlling groundwater extraction could be one of the most effective strategies in this direction.

Carbon intensity of electricity and diesel is 0.4062 kg C kWh^{-1} and 0.732 kg C l^{-1}, respectively (Shah, 2009). This implies that annually a total sum of 3.8 MMT of CO_2 is emitted as a result of groundwater irrigation in Pakistan. Of this figure, which is roughly 1.2% of Pakistan's total carbon emissions, 1.4 MMT of CO_2 is emitted through electricity consumption and 2.4 MMT of CO_2 through diesel combustion. In other words, on average, the extraction of every cubic metre of groundwater in Pakistan comes with a hidden environmental cost of 80 g of carbon emissions. Therefore controlling energy demand in the agriculture sector would be a big step forward in limiting overall carbon emissions.

POTENTIAL FOR REDUCING CO_2 THROUGH IMPROVED IRRIGATION MANAGEMENT

There are different potential ways of reducing energy use in agriculture. The first option is to improve energy efficiency by increasing overall pumping plant efficiency through the use of high-quality pumps and electric motors. However, such interventions are expensive and, more importantly, have limited scope. The second option is to introduce on-site renewable energy sources such as wind and solar energy. These sources will neither lead to transmission and distribution losses, like electric energy, nor will they produce CO_2 emissions, like diesel tubewells. The initial investments in these resources might be high; however, considering their long-term economic and environmental benefits they should be given serious consideration. The third option is to reduce irrigation water demand through improved on-farm water management practices. This option is particularly relevant to Pakistan where on-farm water use efficiencies are extremely low. Average crop yields of major crops are low in Pakistan, for example: 2770 and 3190 kg ha^{-1} for wheat and rice, respectively. There is great variability in crop yields with some farmers achieving 5500 kg ha^{-1} of wheat and 3545 kg ha^{-1} of rice (Qureshi *et al*., 2004). The productivity of water in Pakistan is among the lowest in the world. For wheat, for example, it is 0.6 kg m^{-3} as compared to 1.0 kg m^{-3} in India. Maize yields in Pakistan (0.4 kg m^{-3}) are nine times lower than those in Argentina (2.7 kg m^{-3}) (Bastiaanssen, 2000). This reveals substantial potential for increasing water productivity.

Irrigation practices in Pakistan and options for improvement

Despite the shortage of water, over-irrigation is a major problem in Pakistan. The impact of this is not only wastage of water, which could be used by other sectors or used in expansion of agriculture, but also waterlogging and soil salinity problems. This means that a significant amount of the applied irrigation water is lost by seepage from the irrigation canals and deep percolation in the fields (Bhutta and Smedema, 2007). Even though much of this lost water is now captured by extensive groundwater pumping and used downstream, this does not apply to the saline groundwater zone. From a basin perspective, improvements in farm irrigation efficiency may result in little gain in saving water except for those areas where groundwater is saline (Clemmens and Allen, 2005). Nevertheless, reducing water delivery to farms and improving farm water use efficiency are important from the perspective of other considerations like reducing energy consumption, costs and improving production (Karimi *et al*., 2012).

Farmers' current irrigation practices in Pakistan are aimed at applying the maximum amount of water in an attempt to maximize their crop yields. Farmers having access to groundwater in addition to canal water tend to apply more water compared to those who are fully dependent on canal water. Due to uncertainties in canal water supplies, farmers usually do not plan their irrigations in advance. Their decision to irrigate mainly depends upon the crop water need and availability of water in the canal system and/or access to groundwater. The water requirements of different crops depend upon environmental conditions, soil types and other factors that are equal across all the farms. However, different studies have shown that the number of irrigations applied to a wheat crop varies from 4 to 7, to cotton from 4 to 8, and to rice from 16 to 25 (Vlotman *et al*., 1994; Raza and Choudhry, 1998). The depth of individual irrigation applications has been the subject of many research studies. Vehmeyer (1992) found that it ranged from 60 to 90 mm. Vlotman and Latif (1993) determined the average depth applied per irrigation at between 70 and 80 mm. On the basis of field measurements, Raza and Choudhry (1998) reached a value of 60–90 mm with an average of about 85 mm per irrigation. If, on average, 6 irrigations to wheat and cotton and 20 irrigations to rice crop are considered with an amount of 80 mm per irrigation, irrigation water applied to wheat and cotton will be equal to 480 mm whereas for rice it will be 1600 mm. The average irrigation application in the Indus basin is 36% (Ahmad, 2009).

Considering the water scarcity in the Indus basin, many researchers have tried to find optimal irrigation schedules for different crops. The modelling work of Qureshi and Bastiaanssen (2001) has suggested that applying 300 mm of water to wheat and cotton (instead of the current practice of 420 mm) is enough to produce optimal crop yields without increasing salinity levels in the soil. This saving can be achieved by reducing amounts of individual irrigations. Based on their field experiments, Choudhary and Qureshi (1991) have also shown that improved irrigation management techniques such as furrow-bed and furrow-ridge can reduce irrigation requirements by 40%. They have recommended an irrigation application of 260–300 mm for wheat and cotton crops to achieve optimal yields.

Prathapar and Qureshi (1999) used the Soil–Water–Atmosphere–Plant (SWAP) model (Van Dam *et al*., 1997) to simulate optimal irrigation schedules for wheat and cotton crops. They found that irrigation applications can be reduced to 80% of the total crop evapotranspiration (ET) without compromising on yields and soil salinization, and recommended 300–320 mm as the optimal irrigation amount for

Table I. Comparison of total water use and water savings under current and improved irrigation practices (Data source: Punjab Agriculture Department)

		Current irrigation practices		Improved irrigation practices		Total water saving (BCM)
Crop	Area (ha)	Irrigation (mm)	Total water use (BCM)	Irrigation (mm)	Total water use (BCM)	
Wheat	8 578 000	480	41.2	300	25.7	15.5
Cotton	3 100 000	480	14.9	300	9.4	5.5
Rice	1 016 000	1 600	16.3	1 300	13.3	3.0
Total			72.4		48.4	24.0

wheat and cotton crops. Similarly improved irrigation methods for rice such as direct seeding also reduce irrigation amounts by 15–20% (Qureshi *et al*., 2006). The amount of water applied to rice was 1200 mm as compared to the 1870 mm usually applied under traditional planting. High efficiency irrigation methods such as drip and sprinkler systems have also proved successful in increasing water use efficiency. However, in a country like Pakistan where continuous availability of water and energy are big issues, adoption of these technologies will remain a challenge, especially for small farmers (Qureshi *et al*., 2010). For this reason, on-farm water conservation techniques which are less costly and energy intensive should be encouraged more.

To summarize the results of the above studies, these results suggest that 300 mm of irrigation water for wheat and cotton and 1300 mm for the rice crop is sufficient to produce optimal yields under the existing soil and climatic conditions of the Indus basin. Table I compares the irrigation amounts, total water use and water savings for current and optimized irrigation practices.

Table I clearly shows that adoption of the above-mentioned irrigation practices for wheat, cotton and rice can save up to 24 BCM of water, which is about 14% of the total renewable water available in the Indus basin. Applying these improved irrigation techniques to other crops can further reduce the water demand for irrigation and stress on groundwater. Under the current surface-water-scarce conditions of the Indus basin, this water is contributed through groundwater extraction, as is evident from the declining groundwater table conditions in most of the canal commands (Figure 2). Farmers with access to groundwater tend to apply more irrigation water than those farmers fully relying on surface water (Shah *et al*., 2003). Reducing groundwater extraction by 24 BCM will reduce diesel consumption by 2.2 billion litres (62%) and CO_2 emissions by about 40% (1.5 MMT of CO_2). With these reductions, total consumption of diesel will be reduced to 1.3 billion litres and CO_2 emissions to 2.3 MMT of CO_2. These calculations have been made assuming an irrigation application efficiency of 65%. Under the furrow irrigation method (the most widely practised in the Indus basin) irrigation efficiency ranged between 65 and 95% with an attainable level of 85% (United States Department of Agriculture (USDA)). Therefore greater water savings can be achieved by implementing optimized irrigation schedules together with advanced farm levelling, application rate control, and other management options.

The above analysis demonstrates that the adoption of improved irrigation practices will not only help in reducing energy consumption and CO_2 emissions but will be a big step forward in stabilizing aquifers. Adoption of these improved practices requires a shift in the thinking of farmers from ’maximizing crop production’ with increased irrigation supplies to ’optimize crop production’ with minimum irrigation supplies. Such a change in farmers’ mentality could be facilitated by measures such as revising the existing energy pricing system. For instance, removing or limiting the subsidies on electricity could help to reduce groundwater over-pumping and encourage more efficient use of water.

CONCLUSIONS

Groundwater use in agriculture has increased significantly in the past few decades and it has become a lifeline to Pakistan’s agricultural production. Currently, it provides more than 50% of the total water available at the farm gate and in many areas is the sole water resource for summer crops. However, rapidly dropping groundwater water tables in aquifers all over the country indicate that the extraction rate is far greater than the real capacity of these resources. Under these circumstances, groundwater availability might decrease considerably in future, which will have serious consequences for the food security of this country. On the other hand, groundwater use is also linked with a high energy demand and carbon footprint in Pakistan. In Pakistan, the extraction of 50 BCM of groundwater consumes 30 billion kWh of energy. Carbon emissions attributed to this energy use are 3.8 MMT of CO_2 yr^{-1}. Therefore reducing irrigation water demand through improved irrigation practices is vital for preserving the environment and sustaining groundwater resources.

Despite the fact that pumping is an energy-intensive activity, so far very little attention has been given to the carbon footprint of groundwater irrigation in Pakistan. This study shows that adoption of improved irrigation practices will save up to 24 BCM of irrigation water, which in turn, will reduce the energy demand and carbon emissions by 40%. This shows that enhancing water productivity through improved irrigation management can help in coping with water, energy, and climate change issues in Pakistan's agricultural sector.

ENDNOTES

[1] Mostly privately owned diesel tubewells are powered by 10–24 hp engines. These engines are of two types, i.e. the 12–16 hp Chinese engines known locally as 'Petter engines' and 20–24 hp slow speed engines known locally as the 'Black (Kala) engine'.

[2] OPE is the product of power plant efficiency (engine, alternator, etc.), shaft efficiency and pump efficiency.

REFERENCES

Ahmad S. 2009. Water availability and future water requirements. Paper presented at the National Seminar on 'Water Conservation, Present Situation and Future Strategy. Ministry of Water and Power, Islamabad, Pakistan. May.

Bhutta MN. 2002. Sustainable management of groundwater in the Indus basin. Paper presented at the Second South Asia Water Forum, 14–16 December. Pakistan Water Partnership: Islamabad, Pakistan.

Bhutta MN, Smedema LK. 2007. One hundred years of waterlogging and salinity control in the Indus valley, Pakistan: a historical review. *Irrigation and Drainage* **56**: 581–590.

Bastiaanssen WGM. 2000. Water issues for 2025: a research perspective. Research contribution to the *World Water Vision* report. Colombo, Sri Lanka: International Water Management Institute.

Buksh D, Ijaz H, Ahmad S, Yasin M. 2000. EMz ceramics for improving fuel efficiency of diesel pump sets in Pakistan. *Journal of Nature Farming and Environment* **1**(2): 9–15.

Choudhary MR, Qureshi AS. 1991. Irrigation techniques to improve the application efficiency and crop yield. *Journal of Drainage and Reclamation* **3**(1): 14–18.

Clemmens AJ, Allen RG. 2005. Impact of agricultural water conservation on water availability. In *Proceedings of the EWRI World Water and Environmental Resources Congress, 2005: Impacts of Global Climate Change*, 15–19 May, Anchorage, Alaska, USA; 14 pp.

Karimi P, Qureshi AS, Bahramlo R, Model D. 2012. Reducing carbon emissions through improved irrigation and groundwater management: a case study from Iran. *Agricultural Water Management* **108**(2012): 52–60.

Pakistan Atomic Energy Commission. 2009. Greenhouse gas emission inventory of Pakistan for 2007–08. (Internal report – to be published.)

Punjab Private Sector Groundwater Development Project (PPSGDP). 2000. Legal and Regulatory Framework for Punjab Province. Technical Report No. 45. Lahore, Pakistan.

Prathapar SA, Qureshi AS. 1999. Modeling the effects of deficit irrigation on soil salinity, depth to watertable and transpiration in semi-arid zones with monsoon rains. *International Journal of Water Resources Development* **15**(1/2): 141–159.

Qureshi AS, Bastiaanssen WG. 2001. Long-term effects of irrigation water conservation on crop production and environment in semi-arid zones. *ASCE Irrigation and Drainage Engineering* **127**(6): 331–338.

Qureshi AS, Shah T, Akhtar M. 2003. The groundwater economy of Pakistan. IWMI Working Paper No. 64. International Water Management Institute, Colombo, Sri Lanka; 23 pp.

Qureshi AS, Akhtar M. 2003. Effect of electricity pricing policies on groundwater management in Pakistan. *Pakistan Journal of Water Resources* **7**(2): 1–9.

Qureshi AS, Asghar MN, Ahmad S, Masih I. 2004. Sustaining crop production under saline groundwater conditions: a case study from Pakistan. *Australian Journal of Agricultural Sciences* **54**(2): 421–431.

Qureshi AS, Masih I, Turral H. 2006. Comparing water productivities of transplanted and direct seeded rice for Pakistani Punjab. *Journal of Applied Irrigation Science* **41**(1): 47–60.

Qureshi AS, McCornick PG, Qadir M, Aslam Z. 2008. Managing salinity and waterlogging in the Indus Basin of Pakistan. *Agricultural Water Management* **95**: 1–10.

Qureshi AS, McCornick PG, Sarwar S, Sharma BR. 2009. Challenges and prospects for sustainable groundwater management in the Indus Basin, Pakistan. *Water Resources Management* **24**(8): 1551–1569.

Planning Commission. 2010. Final Report of the Task Force on Climate Change. Government of Pakistan, Islamabad, Pakistan. 98 pp.

Raza ZI, Choudhry MR. 1998. *Soil Salinity Trends under Farmer's Management in a Pipe Drainage Project*. International Waterlogging and Salinity Research Institute (IWASRI) Publication No. 189. Lahore, Pakistan; 88 pp.

Shah T, Debroy A, Qureshi AS, Wang J. 2003. Sustaining Asia's groundwater boom: an overview of issues and evidence. *Natural Resource Forum* **27**: 130–141.

Shah T. 2007. The groundwater economy of South-Asia: an assessment of size, significance and socio-ecological impacts. In Giordano M, Villholth KG (eds). *The Agricultural Groundwater Revolution: Opportunities and Threat to Development*. CABI Publications: United Kingdom; 7–36.

Shah T. 2009. Climate change and groundwater: opportunities for mitigation and adaptation. *Environmental Research Letters* **4**(2009): 13.

United States Department of Agriculture (USDA). Irrigation efficiency. http://ddr.nal.usda.gov/bitstream/10113/4018/IND43939089.pdf.

Van Dam JC, Huygen J, Wesseling JG, Feddes RA, Kabat P, Van Walsum PEV. 1997. *Simulation of Transport Processes in the Soil–Water–Air–Plant Environment. SWAP User's Manual*. DLO-Winand Staring Centre: Wageningen, the Netherlands.

Vehmeyer P. 1992. *Irrigation Management Strategies at the Farm Level in a Warabandi Schedule*. IWASRI Publication No. 122. International Waterlogging and Salinity Research Institute: Lahore, Pakistan; 127 pp.

Vlotman WF, Latif M. 1993. *Present and Suggested Water Management Strategies in Fixed Rotational Irrigation System at S1B9 of Fourth Drainage Project, Faisalabad*. IWASRI Publication No. 148. International Waterlogging and Salinity Research Institute: Lahore, Pakistan; 90 pp.

Vlotman WF, Beg A, Raza ZI. 1994. Warabandi, theory and farmers practices at S1B9, Fourth Drainage Project, Faisalabad. Working paper, IWASRI Publication No. 141. Lahore, Pakistan; 281 pp.

Water and Power Development Authority (WAPDA). 2009. Hydropower Potential in Pakistan. Lahore, Pakistan. www.wapda.gov.pk

World Bank. 2007. Punjab Groundwater Policy—Mission Report. WB-SA-PK-Punjab GW mission report, June 2007. www.worldbank.org/gwmate.