China's water–energy nexus: greenhouse-gas emissions from groundwater use for agriculture

2012 Environ. Res. Lett. 7 014035

(http://iopscience.iop.org/1748-9326/7/1/014035)

IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS

Environ. Res. Lett. **7** (2012) 014035 (10pp) doi:10.1088/1748-9326/7/1/014035

China's water–energy nexus: greenhouse-gas emissions from groundwater use for agriculture

Jinxia Wang[1], **Sabrina G S A Rothausen**[2,3], **Declan Conway**[2,4], **Lijuan Zhang**[1], **Wei Xiong**[5], **Ian P Holman**[6] **and Yumin Li**[1]

[1] Centre for Chinese Agricultural Policy, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, No Jia 11, Datun Road, Anwai, 100101 Beijing, People's Republic of China
[2] School of International Development, University of East Anglia, Norwich NR4 7TJ, UK
[3] Water Security Research Centre, University of East Anglia, Norwich NR4 7TJ, UK
[4] Tyndall Centre for Climate Change Research, University of East Anglia, Norwich NR4 7TJ, UK
[5] Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, 12 Zhongguancun Nandajie, 100081 Beijing, People's Republic of China
[6] Cranfield Water Science Institute, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK

E-mail: jxwang.ccap@igsnrr.ac.cn and d.conway@uea.ac.uk

Received 2 December 2011
Accepted for publication 23 February 2012
Published 14 March 2012
Online at stacks.iop.org/ERL/7/014035

Abstract
China is the world's largest emitter of greenhouse gases (GHGs) and the agricultural sector in China is responsible for 17–20% of annual emissions and 62% of total freshwater use. Groundwater abstraction in China has increased rapidly from 10 $km^3\ yr^{-1}$ in the 1950s to more than 100 $km^3\ yr^{-1}$ in the 2000s, such that roughly 70% of the irrigated area in northern China is now groundwater-fed. Pumping of water for irrigation is one of the most energy consuming on-farm processes; however, to date this source of GHG emissions in China and elsewhere has been relatively neglected. We derive the first detailed estimate of GHG emissions from groundwater pumping for irrigation in China, using extensive village survey data from 11 provinces, broadly representative of the situation during the mid-2000s. The 11 provinces cover roughly half of China's irrigated cropland and we upscale to the national level using government statistics for the remaining 20 provinces. Our results show emissions of 33.1 $MtCO_2e$, just over half a per cent of the national total. Groundwater abstraction represents an important source of GHG emissions that has been rapidly increasing and which at present is largely unregulated. Water scarcity in China is already driving policies to improve water conservation. These results suggest that significant potential exists to promote the co-benefits of water and energy saving in order to meet national planning targets.

Keywords: climate change, water, energy, irrigation, emissions, China

S Online supplementary data available from stacks.iop.org/ERL/7/014035/mmedia

1. Introduction

China faces its own 'perfect storm' as rapid economic transition drives increasing per capita demand for water, food and energy with far-reaching environmental consequences. Food production in China depends fundamentally on water because of the extensive use of irrigation. China is the world's second largest irrigator with agricultural water use accounting for 62% of total freshwater use (Ministry of Water Resources 2009). Irrigated agriculture has been essential in sustaining growth in national crop production, but multiple drivers are generating immense pressure on water resources and water supply for irrigation, especially in northern China. This has greatly promoted groundwater abstraction which has increased from roughly 10 $\mathrm{km}^3\ \mathrm{yr}^{-1}$ during the 1950s to more than 100 $\mathrm{km}^3\ \mathrm{yr}^{-1}$ in the 2000s (Wang *et al* 2007, Shah 2009). Today, roughly 70% of the irrigated area in northern China is groundwater-fed (Wang *et al* 2009) and irrigation produces approximately 70% of total grain production (Amarasinghe *et al* 2005). Studies on direct energy use in farm operations show that pumping water for irrigation is one of the highest on-farm energy consuming processes (e.g. Lal 2004, Mushtaq *et al* 2009).

Whilst China is the world's highest emitter of greenhouse gases (GHGs), per capital emissions are low relative to OECD country averages. The agricultural sector in China is responsible for roughly 17–20% of annual GHG emissions (Wang *et al* 2010) of which an unknown proportion originates from groundwater pumping for irrigation. In spite of the rapid growth in groundwater use there has been no detailed attempt to quantify the related energy use and GHG emissions of groundwater abstraction. Indeed, the broader 'energy for water' dimensions of the water–energy nexus are under-recognised and poorly quantified (Rothausen and Conway 2011). China's 12th Five Year Plan (2011–5) aims to increase irrigation water use efficiency by 3% by 2015 and emphasizes the importance of improving groundwater resource management to control over-exploitation. However, these targets are to be achieved whilst increasing total grain production by roughly 13% to 450 million tonnes and decreasing national energy consumption per unit of GDP by 16%. Response measures will need to be both water and energy efficient to ensure consistent policy outcomes.

Research on climate change in China suggests that the interactive effects of climate change and other socio-economic drivers could lead to substantial changes in total production by the 2040s (Xiong *et al* 2009). Water availability plays a particularly significant role in limiting potential crop production, due to the combined effects of higher crop water requirements and increasing demand for non-agricultural use of water. Increasing frequency of extremes in heat and water stress have also been shown to induce higher crop failure rates (Challinor *et al* 2010). Successful adaptation policies will be essential in order for China to produce enough to keep pace with per capita growth in demand and the effects of other drivers such as land use change. However, production oriented policy goals may often fail to consider wider issues of sustainability, such as the intensity of fossil fuel and water use required to meet specific targets.

In this study we use extensive survey data to develop a detailed method to estimate the GHG emissions from groundwater pumping for irrigation in China. Section 2 describes the data and methods and section 3 presents the results and a sensitivity analysis of provincial and national emissions. Section 4 compares our results with those from other countries and considers other energy uses for agricultural water in China. We end by discussing the wider context of agricultural water management and the challenges and opportunities for reducing both energy and water use.

2. Methodology

Our method comprises several steps (figure 1). First, we estimate energy use and associated GHG emissions from groundwater abstraction for irrigation in 11 surveyed provinces. Then, we upscale the survey results and calculate the emissions from the remaining 20 provinces of China to obtain a national estimate of GHG emissions. The methods and data sources for each step are described in detail as follows.

2.1. The 11 surveyed provinces

We use extensive survey data collected in rural China by the Centre for Chinese Agricultural Policy (CCAP), of the Chinese Academy of Sciences. CCAP conducted several large field surveys during the period between 2004 and 2006, covering more than 500 randomly selected villages in 11 provinces, representing the main groundwater using provinces. Sample screening for villages with no tubewells and quality control checking for survey errors of groundwater levels and pump lifts reduced the number of villages to 366 for our analysis. Figure 2 shows the location of the 366 villages and the 11 provinces. The surveys covered population, cultivated area, groundwater and surface water irrigated area, the number of deep and shallow tubewells and their corresponding pump lift, groundwater level, power sources of pumps (electricity or diesel) and socio-economic characteristics of the villages. Full details of the surveys and sampling techniques can be found in Wang *et al* (2006, 2007, 2009).

2.1.1. Energy use rate. The main components of energy use associated with irrigated agriculture are primarily related to processes required to apply water to crops in the field by lifting, conveying, and in some cases, pressurizing it (Rothausen and Conway 2011). Lift relates to the vertical distance over which water is raised prior to application and is the most crucial factor but energy use varies both with the source of water (groundwater or surface water) and the application method (i.e. whether it is gravity fed or pressurized irrigation system). The efficiencies of the power generation and supply, the pump and pipeline system also influence energy use. Here we focus on energy for abstraction of water and for this purpose we apply a basic theoretical physical relationship, which prescribes the energy required to lift 1 m^3 of water (with a density 1000 kg m^{-3}) up 1 m at 100% efficiency is 0.0027 kWh (see equation (1), Rothausen and Conway 2011)

$$\text{Energy (kWh)} = \frac{9.8\ \mathrm{m\ s^{-2}} \times \text{Lift (m)} \times \text{Mass (kg)}}{3.6 \times 10^6 \times \text{Efficiency (\%)}}. \quad (1)$$

Given a lack of detailed knowledge of the efficiency of the individual pumps, we select efficiencies according to available

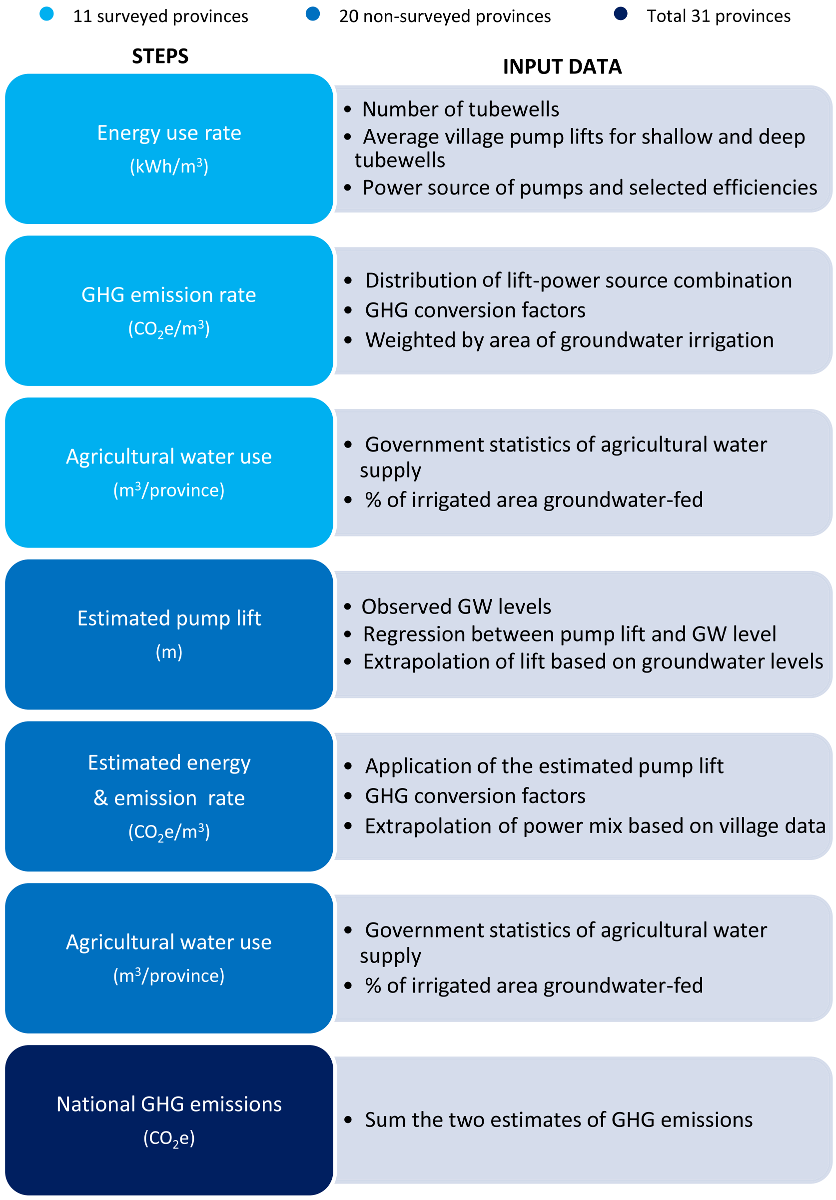

Figure 1. Methodological steps and data input for the estimate of GHG emissions.

information on pumping efficiency, Chinese conditions and studies of energy use for irrigation pumping in India where the pumping efficiencies are around 30% (Nelson *et al* 2009, Shah 2009). Overall efficiencies in diesel powered pumping systems result from the compounded efficiencies of the diesel engine (typically 15–40%), transmission (60–100%), pump (40–80%) and pipes (30–95%), giving an overall efficiency of 0.5–27% (Fraenkel 1986), for which we have selected the approximate mid-point of 15%. With higher efficiencies of electrical motors of 75–85% (Fraenkel 1986, Kay 2008) and the direct coupling of motor and pump within down-hole submersible pumps, higher overall efficiencies of 30–60% are achieved within electrical pumping systems, for which we have used 40%. The overall efficiency of using electricity to power pumps is reduced further by inefficiencies in the transmission and distribution (T&D) of electricity. There is some disagreement about the T&D losses in China but according to three studies of the rural electricity network it is between 10 and 19% (Li *et al* 2007, Sun 2006, Xia 2003). We adopt a mid-range value of 15% T&D loss. Applying equation (1) and the selected efficiencies, we can estimate by village the average energy use required to pump/lift a cubic metre of groundwater (kWh m^{-3}). The field survey showed that all tubewells categorized as deep relied on electric pumps. Other studies also indicate that most pump sets run on electricity in China (e.g. Zhu *et al* 2007) and our study confirms this with more than three-quarters of the surveyed pumps being electric (also see table 1).

2.1.2. GHG emission rate. The UK Department of Environment, Food and Rural Affairs/Department of Energy and Climate Change GHG conversion factors for diesel

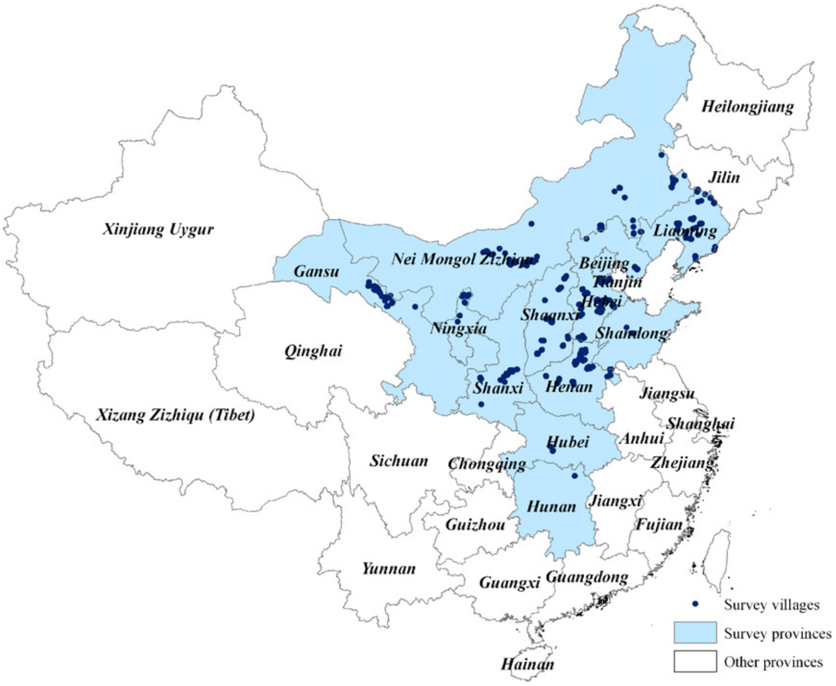

Figure 2. Location of the 11 survey provinces and 366 survey villages. Many villages are located near each other and may appear as one point on the map.

Table 1. Basic characteristics of the 366 surveyed villages in 11 provinces in China.

Province	No. of surveyed villages	Average village irrigated area (ha)	Proportion of groundwater-fed irrigated areas (%)	Average no. of tubewells in villages	Proportion of deep tubewells (%)	Proportion of diesel pumps (%)	Average deep pump lift (m)	Average shallow pump lift (m)
Hebei	93	96	90	18	43	10	83	34
Henan	56	114	81	67	10	67	42	24
Shaanxi	25	125	67	28	29	0	98	50
Shanxi	46	96	77	8	59	1	82	59
Inner Mongolia	56	232	67	56	38	8	44	29
Liaoning	45	139	60	113	11	17	35	17
Ningxia	10	264	9	50	11	0	40	24
Gansu	27	294	64	19	49	0	80	29
Hubei	4	238	16	46	9	2	59	23
Hunan	1	26	15	2	100	0	50	NA
Shandong	3	18	93	7	0	0	NA	58
Total	366	149	69	38	23	24	61	35

(0.320 21 $\mathrm{kgCO_2e\ kWh^{-1}}$) and electricity produced in China (0.947 73 $\mathrm{kgCO_2e\ kWh^{-1}}$) are used to derive the average GHG emission rate ($\mathrm{kgCO_2e\ m^{-3}}$) based on the combination of power sources for pumps in each village. Equation (2) illustrates this calculation, with each energy use rate expressed as a proportion of the total number of pumps under the assumption that all pumps in the village are used equally. To obtain a provincial average GHG emission rate we weight the village emissions by its area under groundwater irrigation. This proportional weighting captures the greater importance of the villages with large areas of groundwater irrigation and discounts villages where groundwater pumps were not used for irrigation purposes.

$$
\begin{aligned}
&\text{GHG emission rate}\left(\frac{\mathrm{kgCO_2e}}{\mathrm{m^3}}\right)\\
&\quad=\text{Energy use rate}_{\mathrm{Deep_{Electric}}}\left(\frac{\mathrm{kWh}}{\mathrm{m^3}}\right)\\
&\qquad\times 0.94773\,\frac{\mathrm{kgCO_2e}}{\mathrm{kWh}}\\
&\qquad+\text{Energy use rate}_{\mathrm{Shallow_{Electric}}}\left(\frac{\mathrm{kWh}}{\mathrm{m^3}}\right)
\end{aligned}
$$

$$\times 0.94773 \frac{\text{kgCO}_2\text{e}}{\text{kWh}} + \text{Energy use rate}_{\text{Shallow}_{\text{Diesel}}} \left(\frac{\text{kWh}}{\text{m}^3}\right) \times 0.32021 \frac{\text{kgCO}_2\text{e}}{\text{kWh}}. \quad (2)$$

2.1.3. Agricultural water use. Detailed and/or comprehensive information on actual water use for irrigation (including how much is from groundwater) for all provinces in China are unavailable. The most appropriate data are the provincial level statistics of total agricultural water use reported in the China National Statistical Yearbook (National Statistical Bureau of China 2006). Although these data include all agricultural uses of water, the field survey data showed there is very limited use of water for non-irrigated agricultural production such as livestock (less than 5%). These data for the year 2005 are the best available and accurate enough for the purpose of our study. To determine the proportion of total agricultural water derived from groundwater we multiply it by the percentage of groundwater irrigated land relative to the total irrigated land across all of the surveyed villages, in each province. This allows a calculation of GHG emissions from groundwater pumping for irrigation in each of the 11 surveyed provinces.

2.2. The 20 non-surveyed provinces

2.2.1. Estimated pump lift. To determine GHG emissions in the 20 non-surveyed provinces we extrapolate pump lift (the most essential factor for energy use, see equation (1)) from observations of groundwater levels for different aquifer types for year 2005, from unpublished data and published data in the China Groundwater Level Yearbook from GEO-Environmental Monitoring Institute (China GEO-Environmental Monitoring Institute 2006). Pump lift is greater than groundwater level because pumping causes a localized lowering of the aquifer groundwater level. To define a relationship between groundwater levels and pump lifts, a linear regression of these variables is used based on the data from the 366 surveyed villages. The correlation between groundwater level (x) and average pump lift (y) is shown in equation (3)

$$y = 0.906x + 21.75 \qquad R^2 = 0.62 \quad (3)$$

with the pump lift being an average of 20 m deeper than groundwater level (supplementary figure S1 available at stacks.iop.org/ERL/7/014035/mmedia). This relationship was used with the groundwater level observed in the 20 non-surveyed provinces to generate an estimate of pump lift.

2.2.2. Estimated energy use rate and emission rate. Using the estimated pump lifts we can calculate the energy use rate equation (1) and the GHG emission rate. The distribution of electric and diesel pumps are set to 76% and 24%, respectively, under the assumption that the mix of power supply for pumps in the 366 surveyed villages can be used to represent the remaining provinces of China. This may not be representative for some southern provinces of China since they have shallower groundwater levels. However, as data on power source distribution for pumps is very hard to find on a provincial level, we apply these figures with caution.

2.2.3. Agricultural water use. Total agricultural water use reported in the China National Statistical Yearbook (for year 2005) is used (as in 2.1.3). The proportion of groundwater is calculated using provincial level statistics of the percentage groundwater-fed irrigated area obtained from a national monitoring station administrated by the Chinese Ministry of Agriculture and further field surveys and key informant interviews with officials in the Provincial Water Resources Bureaus. The resulting estimate of agricultural groundwater use multiplied by the GHG emission rate provides total GHG emissions from groundwater irrigation pumping in each of the 20 non-surveyed provinces.

2.3. National GHG emissions

This step involves simply adding together the emissions from the surveyed and non-surveyed provinces to obtain a national estimate of total GHG emissions from groundwater use for irrigation.

3. Results

The characteristics of the 366 surveyed villages are listed by province in table 1. In the 11 provinces the average village area of irrigated land is 149 ha of which 69% is fed by groundwater. The majority of tubewells are categorized as shallow with an average pump lift of 35 m and the deep wells have an average pump lift of 61 m. Only 24% of pumps are diesel driven, due to the widespread electrification of rural China. Shaanxi (see figure 2 for location) has the deepest overall average pump lift of 78 m.

Energy use rates and GHG emission rates are shown in figures 3(d) and (e), respectively, with details of the 11 surveyed provinces presented in table 2. The GHG emission rates reflect the mix of pump lift and power source so that the provinces show considerable differences in their rates, with a range of 0.15–0.60 $\text{kgCO}_2\text{e m}^{-3}$. Shaanxi has the highest energy use rate of 0.64 kWh m^{-3} which is directly related to the greater pump lift. In Henan, however, roughly two-thirds of pumps are diesel powered causing its GHG emission rate to drop from fourth equal lowest energy use rate (0.30 kWh m^{-3}) by province to second lowest GHG emission rate (0.18 $\text{kgCO}_2\text{e m}^{-3}$) highlighting the importance of the power source (see sensitivity analysis below). Overall, the 11 surveyed provinces emit a total of 24.13 MtCO_2e with Hebei the largest contributor by far, accounting for 27.4% of the total, due to its mix of high proportion of deep tubewells (83 m pump lift) and high agricultural groundwater use (see figures 3(a)–(c) and 2 for location). In contrast, Shandong, with higher agricultural groundwater use but no deep tubewells, produces almost half the emissions of Hebei (table 2).

Table 3 presents the results for the 20 non-surveyed provinces. Despite a 100 km^3 larger total agricultural water

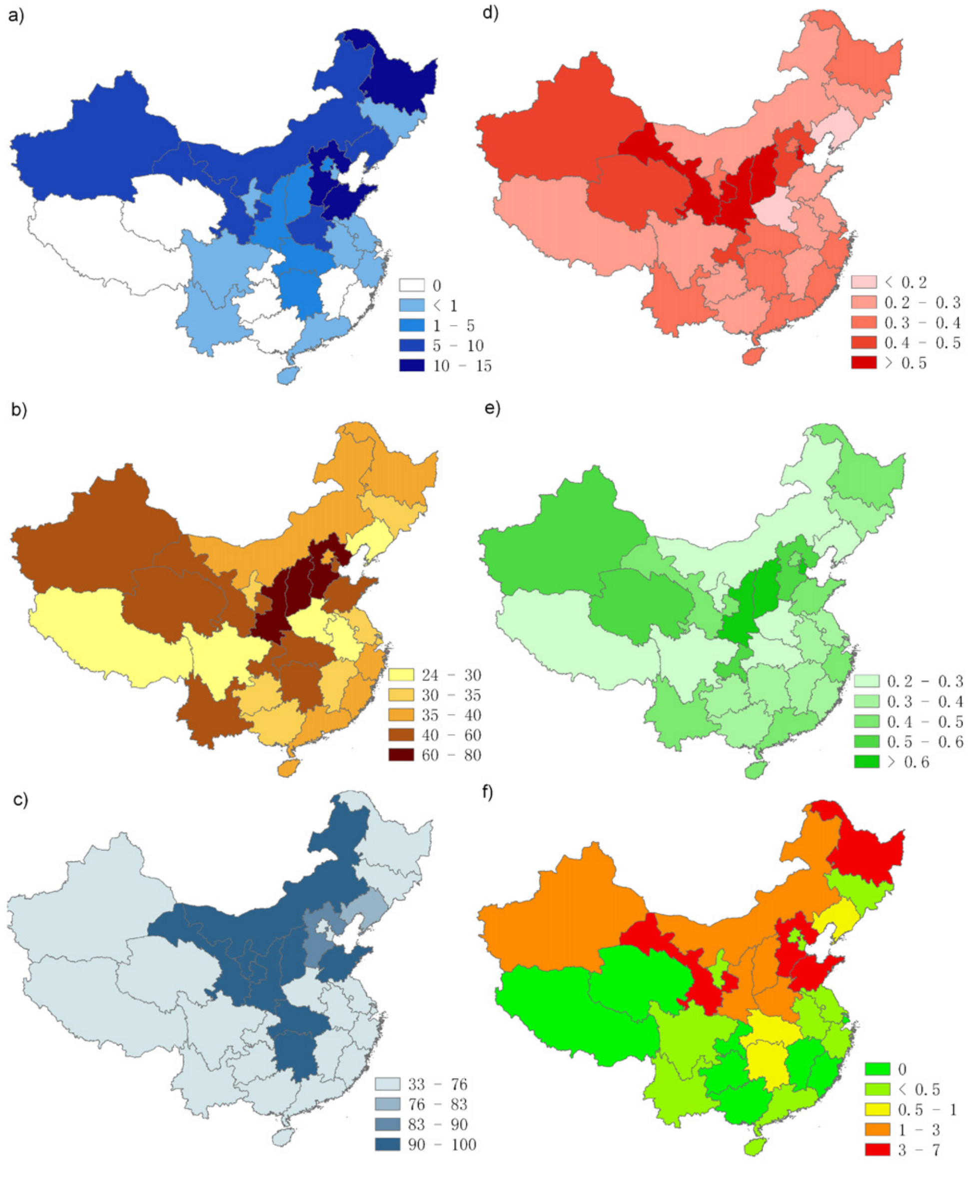

Figure 3. Provincial data and results. (a) Agricultural groundwater use ($km^3\ yr^{-1}$), (b) average pump lift (m), (c) share of electric pumps (%), (d) average energy use rate ($kWh\ m^{-3}$), (e) average GHG emission rate ($kgCO_2e\ m^{-3}$), (f) actual GHG emission ($MtCO_2e$).

use, the total GHG emissions are 8.97 $MtCO_2e$, much less than the 11 surveyed provinces. This is because the groundwater use in the 20 non-surveyed provinces is nearly three times lower than in the 11 surveyed provinces. The average emission rate is almost 30% lower than the surveyed provinces due to the shallower groundwater levels in the non-surveyed provinces (primarily located in southern China, see figure 3(b)). The total national GHG emissions from groundwater use for agriculture in China are 33.1 $MtCO_2e$, around 3% of agricultural emissions and 0.58% of national total emissions (5670 $MtCO_2e$, National Statistical Bureau of China 2006). Figure 3(f) shows the concentration of highest GHG emissions in provinces located in north and north-east China.

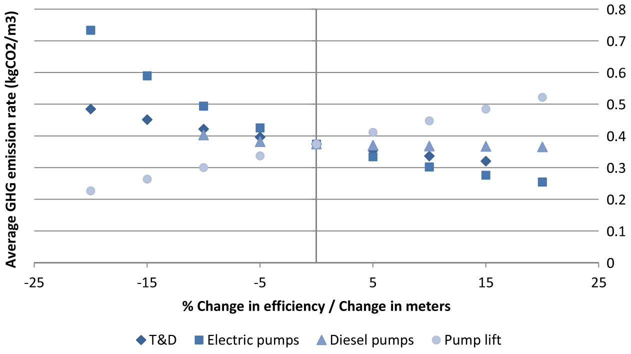

Figure 4. Sensitivity of average GHG emission rate of the surveyed villages to changes in efficiencies (%) and pump lift (m).

3.1. Sensitivity analysis

We explore the sensitivity of our results to varying assumptions about efficiency and pump lift. Figure 4 shows the average GHG emission rate for the 366 surveyed villages with a range of values. Our estimate uses 85% T&D efficiency, 40% electric pump efficiency and 15% diesel pump efficiency,

Table 2. Total GHG emissions from groundwater pumping for irrigation in the 11 surveyed provinces.

	Energy use rate[a] (kWh m^{-3})	GHG emission rate[b] ($kgCO_2e$ m^{-3})	Agricultural water use (km^3 yr^{-1})	Proportion of groundwater-fed irrigated areas (%)	Agricultural groundwater use (km^3 yr^{-1})	Emissions from groundwater ($MtCO_2e$)
Province	1	2	3	4	5 (3 × 4/100)	6 (2 × 5)
Hebei	0.53	0.49	15.02	90	13.53	6.61
Henan	0.30	0.18	11.45	81	9.31	1.71
Shaanxi	0.64	0.60	5.22	67	3.47	2.10
Shanxi	0.62	0.59	3.27	77	2.51	1.47
Inner Mongolia	0.30	0.25	14.39	67	9.62	2.36
Liaoning	0.21	0.15	8.72	60	5.24	0.79
Ningxia	0.27	0.37	7.23	9	0.67	0.24
Gansu	0.50	0.57	9.50	64	6.05	3.47
Hubei	0.22	0.31	14.28	16	2.28	0.70
Hunan	0.40	0.38	14.21	15	2.19	0.83
Shandong	0.47	0.26	15.63	93	14.50	3.84
Total			118.91		69.38	24.13

[a] Efficiency for diesel is 15% and for electric 40% while T&D losses are 15%.

[b] GHG conversion factors: electricity = 0.947 73 $kgCO_2e$ kWh^{-1}, diesel= 0.320 21 $kgCO_2e$ kWh^{-1}. Average provincial GHG emission rate is weighted by village groundwater irrigated area.

Table 3. Total GHG emissions from groundwater pumping for irrigation in the 20 non-surveyed provinces.

	Ground water level (m)	Est. pump lift[a] (m)	Energy use rate (kWh m^{-3})	GHG emission rate ($kgCO_2e$ m^{-3})	Agricultural water use (km^3 yr^{-1})	Proportion of groundwater-fed irrigated areas (%)	Agricultural groundwater use (km^3 yr^{-1})	Emissions from groundwater ($MtCO_2e$)
Province	1	2	3	4	5	6	7 (5 × 6/100)	8 (4 × 7)
Beijing	19.14	39.09	0.44	0.35	1.27	100.00	1.27	0.45
Tianjin	40.36	58.31	0.66	0.52	1.36	32.30	0.44	0.23
Jilin	9.92	30.73	0.35	0.28	6.64	4.70	0.31	0.09
HeilongJiang	17.86	37.93	0.43	0.34	19.21	73.00	14.02	4.77
Shanghai	13.96	34.39	0.39	0.31	1.85	0.00	0.00	0.00
Jiangsu	11.68	32.33	0.36	0.29	26.38	1.73	0.46	0.13
Zhejiang	17.73	37.81	0.43	0.34	10.67	1.06	0.11	0.04
Anhui	7.11	28.19	0.32	0.25	11.36	5.56	0.63	0.16
Fujian	15.59	35.87	0.40	0.32	10.15	0.00	0.00	0.00
Jiangxi	12.63	33.19	0.37	0.30	13.46	0.00	0.00	0.00
Guangdong	16.36	36.57	0.41	0.33	23.07	1.24	0.29	0.10
Guangxi	9.80	30.62	0.34	0.27	22.54	0.00	0.00	0.00
Hainan	15.96	36.20	0.41	0.32	3.51	6.85	0.24	0.08
Chongqing	31.78	50.54	0.57	0.45	2.14	0.00	0.00	0.00
Sichuan	5.17	26.43	0.30	0.24	12.18	2.24	0.27	0.06
Guizhou	11.46	32.13	0.36	0.29	5.05	0.00	0.00	0.00
Yunan	20.24	40.08	0.45	0.36	10.84	1.49	0.16	0.06
Xizhang	4.37	25.70	0.29	0.23	3.03	0.00	0.00	0.00
Qinghai	27.08	46.28	0.52	0.42	2.11	0.23	0.00	0.00
Xinjiang	34.90	53.36	0.60	0.48	46.44	12.67	5.88	2.81
Total					233.24		24.09	8.97

[a] column2 = 0.906 × column1 + 21.75, Est.: estimated

and average deep and shallow pump lift for each village. By changing these factors in intervals of 5% or 5 m (absolute changes), we can evaluate their individual effects on the GHG emission rate. Whilst there is some debate about the rate and extent of declining groundwater levels in China (Wang *et al* 2007, 2009), it is likely that in many areas pump lifts will increase. An average 5 m deeper pump lift would increase total GHG emissions by almost 10%. Yet figure 4 shows that changes in the efficiency of electric pumps have the largest effect on GHG emission rates. The GHG emissions would more than double with a 20% decrease in electric pump efficiency, whereas a 20% increase in electric pump efficiency will reduce the emission rate by a third. Changes in diesel pump efficiency have the least effect. Accurate data on pump efficiency and its influencing factors will be important for estimating GHG emissions and appropriate pump selection and regular maintenance crucial for limiting emissions.

4. Discussion

4.1. Comparison with other studies

National estimates of energy use and GHG emissions from water delivery for irrigation are, to our knowledge, only available for India and the US. India is the world's largest irrigator and has experienced even greater development of groundwater abstraction than China, with the area of groundwater irrigation quadrupling since 1950 (Shah *et al* 2004). Emissions from groundwater pumping for irrigated rice were estimated to be 58.7 $MtCO_2e$ in 2000 (Nelson *et al* 2009). Another estimate, including all water pumped or lifted for irrigation, was 95.0 $MtCO_2e\ yr^{-1}$ (Shah 2009), roughly 6% of India's total GHG emissions. Both studies show much higher GHG emissions than our results for China, mainly because of India's greater use of groundwater for agriculture but partly due to differences in methodology (see supplementary table S1 for more detail available at stacks.iop.org/ERL/7/014035/mmedia). Nelson *et al* (2009) applies a similar methodology to ours, with minor differences in pump lifts and assumptions about pump efficiencies and power source distribution. Their overall emission rate ($MtCO_2e\ km^{-3}$) is also similar to ours, however, the modelled agricultural groundwater use in India is 195 km^3 (Nelson *et al* 2009) compared with approximately 93 km^3 in China. Shah (2009) bases calculations purely on information about the number of well structures, standardized pump energy requirements and operating hours, without considering actual agricultural water use. This approach includes energy used for pumping surface water and the results for groundwater pumping are much higher (~93 $MtCO_2e\ yr^{-1}$). The village survey data used for this study show a very weak relationship between the area under groundwater irrigation and the number of tubewells (see supplementary figure S2 available at stacks.iop.org/ERL/7/014035/mmedia) which suggests that individual wells/pumps support widely varying areas of irrigation and supply water for purposes other than irrigation. Hence, calculating energy use based on the number of well structures may not be as accurate. In the US, the world's third largest irrigator, where irrigation accounts for 34% of the water use, an estimate of energy use and GHG emissions from pumping water for irrigation was 15.8 $MtCO_2e$ in 2005 (Griffiths-Sattenspiel and Wilson 2009).

4.2. Other energy requirements for agricultural water use in China

Irrigation in China relies heavily on surface water from rivers and reservoirs which sometimes also require energy use for pumping and conveyance. However, information on this is sparse and to our knowledge no quantification of aggregate energy use exists. Currently, power equipment for pumping surface water resources in China has a capacity of 22 million kW (Irrigation and Drainage Center 2007), and the related energy use is likely to be considerable. Imbalances in local and inter-province water resources distribution and demand have exacerbated problems of water scarcity and enhanced the energy intensity of water supply. For example, China has many large-scale inter-basin water transfers. Out of the seven established, two of them include a total of 24 pumping stations to irrigate 2.89×10^6 ha (Shao *et al* 2003). A further seven projects are planned, including the south to north water transfer scheme. Four of the proposed projects are to include a total of 37 pumping stations to irrigate 5.80×10^6 ha (Shao *et al* 2003). The construction and operation of this water supply infrastructure will require energy as will water quality treatment where this is necessary.

While the abstraction/supply of water is proportional to the lift and distance over which it is pumped/transported, the energy required to apply water to fields is dependent on the irrigation method/technology. Across the largest proportion of irrigated land in China water is applied as flood/gravity irrigation, yet water conservation policies are promoting the introduction of pressurized irrigation systems (e.g. sprinkler, drip) which require energy to operate. These technologies generally provide a larger degree of control and depending upon other factors can improve water use efficiency considerably, so that any additional energy use may be offset by water savings. However, only 3.5% of the irrigated areas in our surveyed villages were equipped with pressurized irrigation systems and there is little evidence for widespread or effective adoption of water-saving technologies in China (Lohmar *et al* 2003). Many argue that a lack of economic incentives to save water is a barrier to the uptake of water-saving practices (e.g. Blanke *et al* 2007), while others emphasize that problems with water rights (e.g. institutional and policy dimensions of ensuring stability of supply and sufficient access) are also critical (Webber *et al* 2008). Nevertheless, potential exists to realize co-benefits in water and energy savings through improved irrigation technology and this opportunity may be under-recognised in the design and cost benefit analysis of water-saving practices and policy in China and elsewhere (Rothausen and Conway 2011).

4.3. A future outlook

Agriculture in China is by far the largest water user with irrigated agriculture generating around 70% of total grain production, yet the national crop deficit was 11% in 2000 (Amarasinghe *et al* 2005). With a growing population and rising living standards, the demand for food, particularly animal products, is increasing. Shifts in food consumption patterns and population growth may lead to additional unconstrained requirements of 407–515 km^3 water for food production by 2030, compared with 2003 (Liu and Savenije 2008). Such large increases would likely induce further water resource deterioration and higher energy intensive supply. Intensification and expansion of irrigated agriculture is often seen as necessary to meet future demand and to achieve growth in the agricultural sector and such measures will require more water and more energy for abstraction, transportation and application to crops.

Given China's continued rapid economic transition, the demand for water in the urban and industrial sectors is also likely to increase (Kahrl and Roland-Holst 2008, Xiong *et al* 2009). Re-allocation of already scarce water resources from agriculture to other sectors with higher output/water use ratios may become increasingly necessary (Kahrl and Roland-Holst 2008). During the past 60 years, with expansion of industrialization and urbanization, the share of water allocated to agriculture has declined from 97% in 1949 to 62% in 2009 (Ministry of Water Resources 2009). During this process, increasing (and sometimes unsustainable) exploitation of groundwater resources has played an important role in sustaining irrigated agriculture. Between 1978 and 2003, the number of groundwater tubewells across China more than doubled (Wang *et al* 2007) and with increasing privatization of tubewells it is likely that development will continue to exacerbate declining trends in groundwater levels. Groundwater utilization in northern China is over 70% of known resources in the region. In contrast, 70% of all China's groundwater resources are located in southern China, where less than 30% of the resources are currently in use (Wang *et al* 2007). Drought in parts of southern China (e.g. Qui 2010) may promote groundwater use to secure yields, and multi-climate model averages project drier conditions in southern China out to the 2050s (Li *et al* 2011). These pressures point towards further groundwater development across China with implications for energy use.

Strategic reform of water resources allocation has been initiated by the Chinese Government with attempts to regulate agricultural water use through a water use rights system (Huang *et al* 2009). The system is designed to gradually reduce surface water quotas for farmers to transfer agricultural water to other sectors. However, studies show that farmers compensate the 'loss' of surface water by using more groundwater to maintain production practices and yields (Zhang 2007, Pittock 2011). Regulation of groundwater use is well known to be difficult (e.g. Shah *et al* 2003). These conditions have promoted a shift in policy from supply-side measures towards more water 'efficient' agriculture and irrigation technology innovations. China is to an increasing degree investing in water-saving technologies for farming. Programmes under China's Agenda 21: White Paper on Population, Environment and Development and 'Dryland Farming' are major initiatives that provide support for selected research facilities which target increasing water utilization efficiency by 20–30% (PRC 1994). Various approaches to improve regulation and compliance are also being tested as part of water-saving programmes (World Bank 2009). Since 1991, the water use intensity of Chinese agriculture has decreased, as agricultural investments in channel lining, field levelling, pressurized irrigation systems etc have reduced inefficiencies and water losses (Wu *et al* 2010).

Yet, many of these technologies require energy and, pressurized irrigation systems especially, are often coupled with groundwater use. It will be a challenge to harmonize water conservation with the 12th Five Year Plan targets of reducing energy and carbon intensity by 16% and 17%, respectively (Hannon *et al* 2011). Water-saving technologies need to be assessed in relation to energy trade-offs and potential co-benefits. Our sensitivity analysis highlights the importance of optimization of the efficiency of electric pumps as a promising way of decreasing energy use (section 3.1). Research from India also shows widespread low efficiencies of agricultural pumps, with significant potential for economic (and hence energy) savings through improved standards (Sant and Dixit 1996). The use of renewable energy sources for pumping and application of water should also be explored, although projections of renewable energy dissemination in India show that water pumping technologies may not reach their maximum potential even after 25 years (Purohit and Kandpal 2005).

5. Conclusion

This first detailed estimate of GHG emissions from groundwater pumping for irrigation in China is 33.1 $MtCO_2e$ for the mid-2000s, 0.58% of total national emissions (in 2006). Groundwater pumping for irrigation alone accounts for roughly 3% of the total emissions from agriculture in China. To date this source of GHG emissions has been relatively ignored; our results highlight their significance in relation to national GHG emissions and underline the importance of energy use for groundwater irrigation. The method used extensive primary survey data originally designed for understanding agricultural water use to upscale from village to province to national level. In exploring this aspect of China's water–energy nexus it is clear that government monitoring systems and data sets do not capture energy use very well. This is also the case for surface water use such as inter-basin transfers. Groundwater abstraction in China has grown rapidly since the 1950s, and without intervention, continued growth could lead to substantial increases in energy use and GHG emissions. Sensitivity analysis of factors affecting energy use in abstraction highlights the importance of pump efficiency, suggesting potential for interventions to target pump set standards. Water scarcity in China is already driving policies to improve water conservation and the results obtained here suggest that quantification and promotion of the co-benefits of water and energy savings could be considerable.

Acknowledgments

This study was conducted as part of a project funded by the UK Department for Environment, Food and Rural Affairs: ADMIT—harmonising adaptation and mitigation for agriculture and water in China (Grant No. D00383, www.sain-online.org). We also acknowledge financial support from the Swiss Agency for Development and Cooperation SDC (81014421) and the National Natural Sciences Foundation (70733004, 70925001) in China. We thank Huang Chen and Kaixing Huang for their help with data collection and preparation.

References

Amarasinghe U A, Giordano M, Liao Y and Shu Z 2005 *Water Supply, Water Demand and Agricultural Water Scarcity in China: A Basin Approach. CPSP Report 11* (New Delhi:

International Water Management Institute and International Commission on Irrigation and Drainage)

Blanke A, Rozelle S, Lohmar B, Wang J and Huang J 2007 Water saving technology and saving water in China *Agric. Water Manag.* **87** 139–50

Challinor A J, Simelton E S, Fraser E D G, Hemming D and Colins M 2010 Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China *Environ. Res. Lett.* **5** 034012

China GEO-Environmental Monitoring Institute 2006 *China Groundwater Level Yearbook of GEO-Environmental Monitoring* (Beijing: China Land Press)

Fraenkel P L 1986 Water lifting devices *FAO Irrigation and Drainage Paper 43* (Rome: Food and Agriculture Organisation)

Griffiths-Sattenspiel B and Wilson W 2009 *The Carbon Footprint of Water* (Portland, OR: River Network)

Hannon A, Liu Y, Walker J and Wu C 2011 *Delivering Low Carbon Growth. A Guide to China's 12th Five Year Plan* (The Climate Group)

Huang Q, Rozelle S, Wang J and Huang J 2009 Water management institutional reform: a representative look at northern China *Agric. Water Manag.* **96** 215–25

Irrigation and Drainage Center 2007 *Introduction of Irrigation Development* (Ministry of Water Resources) (www.jsgg.com.cn/Index/Display.asp?NewsID=9242)

Kahrl F and Roland-Holst D 2008 China's water–energy nexus *Water Policy* **10** 51–65

Kay M 2008 *Practical Hydraulics* (Oxfordshire: Taylor and Francis)

Lal R 2004 Carbon emission from farm operations *Environ. Int.* **30** 981–90

Li M, Zhang X and Feng G 2007 Several methods to reduce T&D losses in the rural electricity network *Rural Electrif.* **7** 44 (in Chinese)

Li Y, Conway D, Xiong W, Gao Q, Wu Y, Wan Y, Li Y and Zhang S 2011 Effects of climate variability and change on Chinese agriculture: a review *Clim. Res.* **50** 83–102

Liu J and Savenije H H G 2008 Food consumption patterns and their effect on water requirement in China *Hydrol. Earth Syst. Sci.* **12** 887–98

Lohmar B, Wang J, Rozelle S, Huang J and Dawe D 2003 China's agricultural water policy reforms: increasing investment, resolving conflicts, and revising incentives *Agriculture Information Bulletin No. 782* (Washington, DC: Market and Trade Economics Division, Economic Research Service, US Department of Agriculture)

Ministry of Water Resources 2009 *Water Resources Bulletin* (Beijing: Ministry of Water Resources)

Mushtaq S, Maraseni T N, Maroulis J and Hafeez M 2009 Energy and water tradeoffs in enhancing food security: a selective international assessment *Energy Policy* **37** 3635–44

National Statistical Bureau of China 2006 *National Statistical Yearbook* (Beijing: National Statistical Bureau of China)

Nelson G C, Robertson R, Msangi S, Zhu T, Liao X and Jawajar P 2009 Greenhouse gas mitigation. Issues for Indian agriculture *IFPRI Discussion Paper 00900* (Washington, DC: International Food Policy Research Institute, Environment and Production Technology Division)

Pittock J 2011 National climate change policies and sustainable water management: conflicts and synergies *Ecol. Soc.* **16** (2) 25

PRC (People's Republic of China) 1994 *China's Agenda 21: White Paper on Population, Environment and Development*

Purohit P and Kandpal T C 2005 Renewable energy technologies for irrigation water pumping in India: projected levels of dissemination, energy delivery and investment requirements using available diffusion models *Renew. Sustain. Energy Rev.* **9** 592–607

Qui J 2010 China drought highlights future climate threats *Nature* **465** 142–3

Rothausen S G S A and Conway D 2011 Greenhouse gas emissions from energy use in the water sector *Nature Clim. Change* **1** 210–9

Sant G and Dixit S 1996 Agricultural pumping efficiency in India: the role of standards *Energy Sustain. Dev.* **3** 29–37

Shah T 2009 Climate change and groundwater: India's opportunities for mitigation and adaptation *Environ. Res. Lett.* **4** 035005

Shah T, Roy A D, Qureshi A S and Wang J 2003 Sustaining Asia's groundwater boom: an overview of issues and evidence *Natural Resour. Forum* **27** 130–41

Shah T, Scott C, Kishore A and Sharma A 2004 Energy-irrigation nexus in South Asia: improving groundwater conservation and power sector viability *Research Report 70* 2nd edn (Colombo: International Water Management Institute)

Shao X, Wang H and Wang Z 2003 Interbasin transfer projects and their implications: a China case study *Int. J. River Basin Manag.* **1** 5–14

Sun H 2006 Theoretical calculation for T&D losses in the rural electricity network *Rural Electrif.* **4** 12–3 (in Chinese)

Wang J, Huang J, Huang Q and Rozelle S 2006 Privatization of tubewells in North China: determinants and impacts on irrigated areas, productivity and the water table *Hydrogeol. J.* **14** 275–85

Wang J, Huang J and Rozelle S 2010 Climate change and China's agricultural sector: an overview of impacts, adaptations and mitigation *Issue Brief No. 5, May 2010* (Geneva: ICTSD)

Wang J, Huang J, Rozelle S, Huang Q and Blanke A 2007 Agriculture and groundwater development in Northern China: trends, institutional responses and policy options *Water Policy* **9** 61–74

Wang J, Huang J, Rozelle S, Huang Q and Zhang L 2009 Understanding the water crisis in Northern China: what the government and farmers are doing *Int. J. Water Res. Dev.* **25** 141–58

Webber M, Barnett J, Finlayson B and Wang M 2008 Pricing China's irrigation water *Glob. Environ. Change* **18** 617–25

World Bank 2009 *Addressing China's Water Scarcity* Washington DC

Wu P, Jin J and Zhao X 2010 Impact of climate change and irrigation technology advancement on agricultural water use in China *Clim. Change* **100** 797–805

Xia X 2003 Analysis of present T&D losses in the rural electricity network *Rural Electrif.* **10** 20 (in Chinese)

Xiong W, Conway D, Lin E, Xu Y, Ju H, Jiang J, Holman I and Li Y 2009 Future cereal production in China: the interaction of climate change, water availability and socio-economic scenarios *Glob. Environ. Change* **19** 34–44

Zhang J 2007 Barriers to water markets in the Heihe River basin in northwest China *Agric. Water Manag.* **87** 32–40

Zhu T, Ringler C and Cai X 2007 Energy price and groundwater extraction for agriculture: exploring the energy-water-food nexus at the global and basin levels *Proc. Int. Conf. on Linkages between Energy and Water Management for Agriculture in Developing Countries (Hyderabad, India, 29–30 January 2007)*