The role of water and energy use in expanding the boundaries of irrigated agriculture in the Berrechid plain of Morocco

Romaissa Ouassissou, Guillaume Lacombe, Marcel Kuper, Ali Hammani, Mohamed El Amrani

RESEARCH ARTICLE

WILEY

The role of water and energy use in expanding the boundaries of irrigated agriculture in the Berrechid plain of Morocco

Romaissa Ouassissou[1] | Guillaume Lacombe[1,2] | Marcel Kuper[2] |
Ali Hammani[1] | Mohamed El Amrani[3]

[1]Département du Génie Rural, Institut Agronomique et Vétérinaire Hassan II, Rabat, Morocco

[2]UMR G-EAU, Montpellier University, AgroParisTech, BRGM, CIRAD, INRAE, Institut Agro, IRD, F-34398, Montpellier, France

[3]Département Ingénierie de Développement, Ecole Nationale d'Agriculture de Meknès, Meknès, Morocco

Correspondence
Guillaume Lacombe, Institut Agronomique et Vétérinaire Hassan II, Département du Génie Rural, Rabat, Morocco.
Email: guillaume.lacombe@cirad.fr

Abstract

Despite the attention given to the water–energy–food nexus, there is little field evidence of how this plays out for irrigators. This article analyses the diversity of irrigation system configurations and their related water and energy use in semi-arid Morocco, where groundwater-fed and pressurized drip irrigation, although supposedly thrifty, is energy intensive. The analysis relying on hydraulic calculations and multiple linear regressions was based on interviews, observations and measurements on irrigation systems in 25 farms. The results show that each farmer used between one and three pumps and up to two storage reservoirs to pump groundwater from up to 120 m deep borehole(s) and transfer it along a distance often exceeding 2 km to reach available fertile lands that are rented. Such distances had little effect on the system-wise energy consumption, varying between 4.62 and 4.88 kWh m^{-3}, although the recycled car engines powering these irrigation systems were largely inefficient, consuming on average 2.5 kWh m^{-3}. State subsidies encourage these water-intensive and energy-inefficient farming systems, increasing pressure on groundwater and land. These findings underline the importance of going beyond a strict nexus perspective, as expansion of the 'groundwater economy' is accompanied by conflicts over tenure and increasing inequalities in access to water that threaten the sustainability of irrigated agriculture.

KEYWORDS
energy efficiency, groundwater, land tenure, semi-arid climate, water–energy–food nexus

Résumé

Malgré une attention croissante accordée au nexus eau–énergie–alimentation, peu de travaux ont montré comment il se traduit pour les irrigants. Cet article analyse la diversité des systèmes d'irrigation et comment ils influencent l'utilisation de l'eau et de l'énergie dans le Maroc semi-aride où l'irrigation

Article title in French: Le rôle de l'utilisation de l'eau et de l'énergie dans l'expansion de l'agriculture irriguée dans la plaine de Berrechid au Maroc.

- -

goutte-à-goutte par l'eau souterraine, théoriquement économe en eau, est énergivore. Des données sur les systèmes d'irrigation et les consommations d'eau et d'énergie, collectées par des entretiens, des observations et des mesures dans 25 exploitations agricoles, ont été analysées au moyen de calculs hydrauliques et de régressions linéaires multiples. Les résultats montrent que chaque agriculteur utilise entre une et trois pompes, et jusqu'à deux bassins de stockage d'eau, pour pomper l'eau de forages pouvant atteindre 120 m de profondeur, et la transférer sur plusieurs kilomètres, afin d'atteindre des terres fertiles prises en location pour l'irrigation. Ces distances s'avèrent n'avoir que peu d'effet sur la consommation énergétique de chaque système, variant entre 4.62 et 4.88 kWh m^{-3}, mais les moteurs de voiture recyclés utilisés pour ces pompages sont largement inefficaces, consommant en moyenne 2.5 kWh m^{-3}. La résultante pression sur les ressources en eau souterraines et les terres disponibles, et l'inefficience énergétique de leur irrigation, sont accentuées par les subventions étatiques. L'expansion de l'agriculture irriguée intensive s'accompagne d'arrangements fonciers conflictuels et d'inégalités croissantes dans l'accès à l'eau conditionnant la durabilité de ces systèmes et démontrant l'intérêt d'analyses qui dépassent la stricte perspective de nexus.

MOTS CLÉS

eaux souterraines, lien eau–énergie/alimentation, régime foncier, climat semi-aride, efficacité énergétique

1 | INTRODUCTION

In recent decades, irrigated agriculture has increasingly relied on energy (Belaud et al., 2019). This trend results from two ongoing changes: the replacement of open irrigation channels by pressurized pipes for sprinkler or drip irrigation (Rocamora et al., 2013; Wang et al., 2012) and the increased dependence on groundwater as a reliable source of water for intensive agriculture (Llamas & Martínez-Santos, 2005). In many countries, the promotion of pressurized irrigation through public subsidies is intended to save water, but the associated increase in energy consumption is rarely accounted for, despite its high cost (Berbel et al., 2019; Tarjuelo et al., 2015). In Morocco, the public support for investment in drip irrigation was accompanied by the subsidy of butane gas for domestic consumption, which farmers massively diverted to pump groundwater and to power pressurized irrigation. Direct subsidies aimed at encouraging the use of 'water-saving' pressurized irrigation have thus indirectly increased the use of subsidized energy, while indirect energy subsidies have encouraged the expansion of irrigated agriculture, thereby also increasing energy use (Doukkali & Lejars, 2015). The interdependencies between the water and energy sectors in irrigated agriculture are highlighted through the water–energy–food

(WEF) nexus concept (Hoff, 2011). It explores how different sectors often considered disconnected are actually linked and how these connections evolve at a macroscale (Allan et al., 2015; Berbel et al., 2019). Although it is difficult to disagree with the integrated vision of the WEF nexus, it may lead to losing sight of other important inputs and resources (Wichelns, 2017). For instance, farmers may switch to pressurized irrigation to reduce labour or drudgery associated with gravity irrigation rather than to save water or energy (Benouniche et al., 2014). Little is known about the practical implications of the WEF nexus for irrigators (Allouche et al., 2015) and irrigated agriculture, particularly in the context of the subsidized expansion of intensive irrigated agriculture such as that currently observed in Morocco. Which irrigation systems are put in place, and what are the energetic implications of these configurations in terms of pumping and water transfer efficiencies?

This article aims to address these questions by exploring the diversity of irrigation systems configured at the farm level and assessing and comparing the energy that they use to extract and transfer groundwater to the irrigated plots of a semi-arid agricultural plain in Morocco. First, the diversity of irrigation systems is assessed in terms of infrastructures used to access, store and transfer water. Second, irrigation water volumes and consumed

energy are quantified and compared with the aim of understanding farmers' decisions related to irrigation practices. Finally, the energy efficiency of these irrigation systems is analysed and discussed in relation to agricultural policies and their implications for environmental and social sustainability.

2 | METHODOLOGY

2.1 | Study site

The study was carried out in the Berrechid plain (Figure 1), known as Morocco's granary for rainfed production of cereals. The climate is semi-arid. The mean annual rainfall is 350 mm, and the mean standard evapotranspiration is 1600 mm. Irrigated agriculture, relying on a 1500 km² aquifer, has become an important economic activity over the last 30 years and now accounts for 13 800 ha. Fieldwork was conducted in two villages covering 1046 ha in the municipality of Ouled Zidane (Ouassissou, Kuper, Dugué, et al., 2019). Their agricultural area covers 972 ha, of which 17% is irrigated. The main rainfed crops are cereals and pulses. Irrigated crops include those in market gardening (potatoes, carrots,

onions) and fodder crops (maize, alfalfa). Livestock includes sheep, cattle and equines. Groundwater depths, averaging 64 m, vary between 45 and 120 m among the 55 monitored wells (1 m < diameter < 1.2 m) and boreholes (0.27 m < diameter < 0.40 m) used for irrigation in the study area. Other wells and boreholes are used to supply drinking water and for livestock. Farmers are either local smallholders or large-scale resident and non-resident tenants. Among the 334 farmers in the study area, 65 practise irrigation. Among them, 50 smallholders own their plots averaging 1.6 ha per farm. Ten resident tenants own and/or rent 6.1 ha each. Five non-resident tenants only focus on market-oriented agriculture over 26 ha in total (Ouassissou, Kuper, Dugué, et al., 2019).

Resident and non-resident tenants generally have more financial resources, conduct intensive agriculture over larger areas, and withdraw, on average, 2.5–4.5 times more groundwater than smallholders (Ouassissou, Kuper, Hammani & El Amrani, 2019). According to the river basin agency in charge of monitoring water resources in the study area, irrigated agriculture is responsible for more than 96% of groundwater withdrawals. The overexploitation of the Berrechid aquifer is mainly explained by the extension of irrigation by entrepreneurial tenants, producing carrots, potatoes and maize
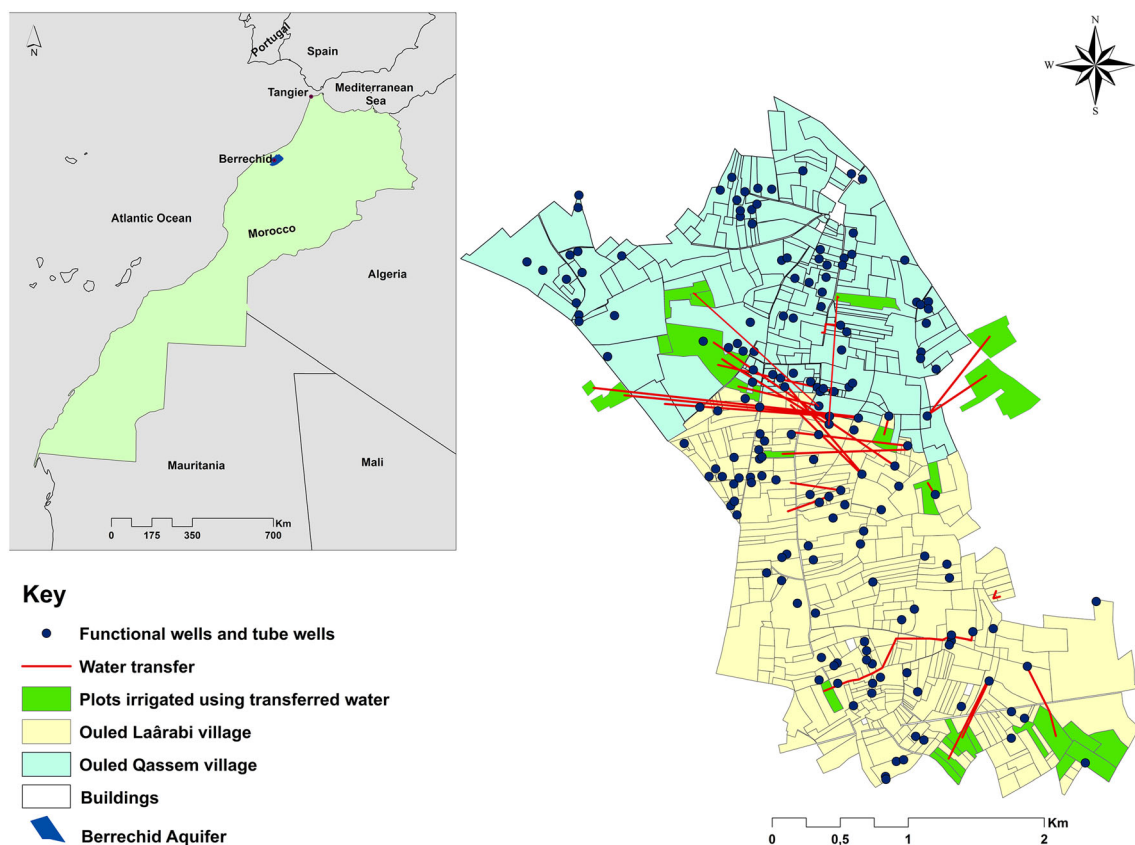

Key
- • Functional wells and tube wells
- — Water transfer
- ▮ Plots irrigated using transferred water
- ▮ Ouled Laârabi village
- ▮ Ouled Qassem village
- □ Buildings
- ◤ Berrechid Aquifer

FIGURE 1 Study area in the Berrechid plain

(Ouassissou, Kuper, Dugué, et al., 2019). The extension of irrigated land is driven by the high demand for vegetables in national markets, as the plain is located close to Casablanca, Morocco's largest city. The export of vegetables to sub-Saharan Africa is also a powerful driver of irrigated agriculture.

Smallholder farmers irrigate land located in the immediate vicinity of their wells, but farmers renting land transfer the water through pipes over up to 3 km (Figure 1). Several farmers own one or two concrete reservoirs with a storage capacity of a few hundred cubic metres to regulate water availability and transfer water over longer distances with additional pumps. Vertical pumps extract groundwater and lift it to a reservoir or to the drip irrigation system of the farmed plot. Centrifugal horizontal pumps transfer water from one reservoir either to another or to the pressurized drip irrigation system. Recycled car engines power all pumps with power ranging from 70 to 107 kW, modified to be run on subsidized butane gas packaged in 12 kg bottles. The most powerful engines are usually chosen to power vertical pumps requiring more energy to lift water than horizontal pumps transferring water horizontally.

2.2 | Field surveys and GIS mapping

Individual field interviews were conducted with 25 farmers to quantify irrigation volumes and the energy cost of pumping and the main factors explaining energy consumption and pumping rates. The following information was collected from each interviewee: (1) the number of pumps and reservoirs used and (2) the number of butane gas bottles used to pump 1 cubic meter of water. This variable was estimated by measuring the pumping rate (m^3 h^{-1}) with an Ultraflux flowmeter and by surveying the daily pumping duration, (3) the brand and the number of cylinders of the motors. A geographic information system was used to map the irrigation systems (well, borehole and irrigated plot) and assess the lengths of the horizontal water transfers. Obtaining this extensive set of data from busy farmers required prolonged and active presence in the field. The sampling of interviewed farmers was carried out to include all types of irrigation configurations likely to influence the WEF nexus in the study area, thus ensuring representativeness. The reliability of the collected data was verified by cross-checking information between interviewees and questioning any doubtful outlying values. While the current sample size is adequate to eliminate uncertainties related to data collection, future research should undoubtedly aim for a larger sample size.

2.3 | Statistical analysis

This analysis was carried out at the pumping station level. A pumping station is defined as a powered pump (either vertical or centrifugal horizontal) and the pipe that conveys pumped water to a plot or a reservoir. The objective was to identify the factors that most influence (1) the amount of energy required to pump water (Gb), expressed as the number of butane gas bottle(s) required to pump 1 cubic meter of water, and (2) the pumping rate (Pr) in m^3 s^{-1}. While the causal linkages between energy and water discharge in a pumping station are governed by known hydraulic laws, these theoretical relationships are difficult to demonstrate through field measurements for several reasons: (1) water leakages and singular pressure losses are unknown, and (2) several metrics were estimated through discussions with farmers, thus introducing some subjectivity and related uncertainties. A modelling approach was, therefore, adopted that does not assume specified mathematical relationships between predicted and explanatory variables. With that aim, multiple linear regressions were performed to predict Gb and Pr (independent variables) from dependent variables selected among a set of candidate explanatory variables likely to influence Gb and Pr. Coefficients of these regressions were calculated by applying the regressions to all categories of pumping stations in the study area (49 observations), made of a vertical pump or a centrifugal horizontal pump. The multiple regression can be represented by Equation (1) as follows:

$$Y = a_0 + a_1 x_1 + a_2 x_2 + ... + a_n x_n \qquad (1)$$

where Y is the independent variable, x_1, x_2, ...,x_n are the explanatory dependent variables and a_0, a_1, a_2, and a_n are the coefficients to be determined.

Several dependent variables were tested for inclusion in Equation (1) according to their explanatory power. Potential explanatory variables of Gb include the depth of the groundwater table (Wd) (m), the pumping rate (Pr) (m^3 h^{-1}), the length of the horizontal water transfer between the well/borehole and the outflow location (reservoir or drip-irrigated plot) (L) (m), the number of cylinders of the pump engine (Nc) and the motor code (Mc) varying between 1 (least powerful) and 4 (most powerful). Coding was based on the manufacturers' information on the power of the models and brands of car engines used by the farmers. The following correspondences were established. Renault 19: Mc = 1, Renault 21: Mc = 2, Renault 25: Mc = 3, Peugeot 504: Mc = 3 and Volvo 760: Mc = 4. The potential explanatory variables of Pr include Wd, Mc, L and Nc. The best set of explanatory variables was selected by applying

stepwise regressions to all potential explanatory variables. Each variable was considered to be significantly different from zero if its p-value, derived from Student's test, was lower than 0.05. The variable with the highest p-value was removed, and the regression was recomputed following the process of backwards elimination to maximize the R^2. The 'variance inflation factor' was calculated to control for the possible influence of multicollinearity between the explanatory variables on the R^2 value of the regression.

The multiple regression analyses aimed at predicting Gb and Pr were based on a limited number of potential explanatory variables, not including other controlling factors, such as the condition of the pump and the engine and the performance of the irrigation network (leakages, hydraulic singularities, tightness, wear and tear of the pipes). These limitations should be accounted for when assessing the reliability and performance of the resulting equations.

2.4 | Hydraulic analysis

Based on hydraulic laws, this assessment is complementary to the statistical approach (section 2.3). The objectives are twofold: (1) to verify whether the selection of the explanatory variables and their coefficients in the resulting multiple linear regression equations is consistent with the hydraulic properties of the pumping stations and (2) to assess the overall efficiency of the pumping stations. While the statistical approach presented in section 2.3 relied on measurements made at individual pumping stations, the hydraulic-based approach relies on values of hydraulic variables averaged among the studied pumping stations to reduce biases caused by measurement-related uncertainties.

To assess the contributions of the different components of a pumping station to its total energy consumption (lifting water, transferring water and discharging pressurized water), the total manometric head (TMH) (m) was calculated using Equation (2) as follows:

$$\text{TMH} = \Delta H + J_1 + J_2 + \frac{P}{\rho g} \tag{2}$$

where ΔH is the hydraulic head (m), equivalent to the difference in elevation between the irrigated plot and the level of water in the well, J_1 and J_2 are the friction losses (m) in the well pipe and in the transfer pipe, respectively, P is the discharge pressure (Pa) at the outlet of the pumping station, ρ is the density of water (1 kg m^{-3}) and g is the gravitational acceleration (9.81 m s^{-2}). It was assumed that P is close to 1 bar (= 10^5 Pa), i.e. $P/(\rho g)$

= 10 m, in accordance with actual field practices in Morocco. Losses due to friction were calculated using the Darcy–Weisbach formula (Brown, 2002) using Equation (3):

$$J = \lambda \times Q^2 \times L \times 8 / \left(\pi^2 \times D^5 \times \mathfrak{g} \right) \tag{3}$$

where λ is the Darcy friction factor estimated from the relative pipe roughness and the Reynolds number using the Moody chart (Moody & Princeton, 1944), Q is the pumping rate (m^3 s^{-1}), and L and D are the length and diameter (m) of the pipe, respectively. The influence of L on the total pumping energy consumption is evaluated by comparing J_2 and TMH.

While water leaks and singular pressure losses were assumed to be negligible in the computation of J_1 and J_2, as transfer pipes are mostly linear and field observations did not reveal major leakages, it is possible to integrate them by computing the energy efficiency (E_e) of the pumping stations. E_e is the ratio between the useful power (P_u), which is actually used to deliver the water pumping rate, and the power consumed (P_c) by the pump motor. In general, E_e is much lower than unity because of a number of energy losses: engine thermic losses, pump energy losses, leakage losses and pipe friction losses. E_e is calculated using Equation (4) (IADB, 2011):

$$E_e = \frac{P_u}{P_c} = \frac{g \times \text{TMH} \times \rho \times \text{Pr}}{B_w \times B_{nb} \times \text{CP}_b} \tag{4}$$

where the pumping rate (Pr) is expressed in m^3 s^{-1}, Bw is the net weight of one butane gas bottle (i.e., 12 kg), B_{nb} is the number of butane gas bottle(s) consumed per second and CP_b is the calorific capacity of butane gas (13.78 kWh kg^{-1}). Estimating E_e is a way to quantify the water–energy nexus in our context.

An irrigation system is made up of all the pump(s), reservoir(s) and pipes used by one farmer to irrigate one farming plot. The total energy consumption of an irrigation system is evaluated by adding its Gb values for pumps in series and averaging their Pr-weighted values for pumps in parallel (see Figure 3).

3 | RESULTS

The performance of irrigation is assessed at two levels: the pumping station (section 3.1) and the irrigation system (section 3.2) made up of one or more pumping station(s). The energy consumption per volume of pumped water (kWh m^{-3}) is equivalent to Gb $\times 12 \times \text{CP}_b$.

3.1 | Energy performance of the pumping stations and their correlated variables

Table 1 shows that the vertical pump rates are approximately half those of the horizontal pumps but consume more than three times their energy. The rates of the pumps discharging in a reservoir are higher than those connected to drip irrigation, but the significance of this difference is impeded by contrasting sample sizes. Daily pumping durations vary between 6 and 16 h (average = 11 h) for the vertical pumps and between 6 and 18 h (average = 10 h) for the horizontal pumps.

Equation (5) resulting from the multiple regression analysis applied to the four pump types indicates that Gb is positively correlated with Wd and negatively correlated with Pr.

$$Gb = 1.66 \times 10^{-4} \times Wd - 2.47 \times 10^{-8} \times Pr + 2.06 \times 10^{-2} \quad (5)$$
$$R^2 = 0.703$$

Pumps with greater discharge consume less energy per pumped volume, while pumping from a deeper water table consumes more energy. Equation (6) indicates that Pr is negatively correlated with Wd and positively correlated with Mc. This result is consistent with the fact that centrifugal horizontal pumps installed in the reservoirs have a higher discharge than vertical pumps lifting water from wells (Table 1). For both pump types, a more powerful engine (i.e. a greater value of Mc) consistently tends to enhance the pumping rate.

$$Pr = -0.48 \times Wd + 19.09 \times Mc \quad (6)$$
$$R^2 = 0.893$$

Energy efficiencies (E_e) and the energy consumption of the horizontal water transfers relative to the total pumping energy were assessed for the vertical pumping stations because of the greater reliability of their estimated total manometric head's components (e.g. ΔH and J). The results from Equation (4) indicate that E_e varied between 2.6 and 12.6% with a median of 5.2%. These variations are not correlated with the distance of the horizontal water transfer (F-test p-value = 0.6) but are significantly positively correlated with the pumping rate (F-test p-value = 6×10^{-6}) in accordance with Equation (5). A field survey revealed the propensity of farmers to transfer irrigation water over relatively long distances to reach fertile farming plots available for rent. According to Equation (2), the energy consumed by the vertical pumps to horizontally transfer water relative to their total consumed energy is equivalent to J_2/TMH. This ratio was estimated for the 19 vertical pumping stations that included a transferring pipe measuring between 50 and 2500 m, following the steps below.

3.2 | Estimation of ΔH and J_1

The groundwater depth in the wells (Wd = ΔH) varied between 40 and 96 m (median = 50.5 m). The vertical pipes extracting groundwater were made of galvanized steel with a diameter (D) of 10.5–13 cm. The average discharge of the vertical pumps (Pr) varied between 9.1 and 58.9 $m^3 \ h^{-1}$ (median = 25.7 $m^3 \ h^{-1}$). The Reynolds number (Re) was determined using the value of 1.007×10^{-6} for the kinematic viscosity coefficient of water (ν) as follows: $Re = VD/\nu$, where V is the velocity of water ($m^3 \ s^{-1}$). The resulting value and the relative pipe roughness value corresponding to galvanized steel ($\varepsilon/D = 2.1 \times 10^{-4}$) enabled identification of the Darcy friction factor (λ) on the Moody chart (Moody & Princeton, 1944). Using Equation (3), J_1 is estimated to vary between 1.23×10^{-2} and 6.34×10^{-1} m (median = 1.02×10^{-1} m).

TABLE 1 Performance of pumping stations

Pump type	Pump outlet	Number of pumps	Mean pumping rate ($m^3 \ h^{-1}$)	Mean energy consumption (kWh m^{-3})
Vertical pump in a well/ borehole	Reservoir	23	32.5	3.59
	Drip-irrigated plot	4	21.4	4.73
Horizontal pump in a reservoir	Reservoir	2	58.8	1.17
	Drip-irrigated plot	21	55.8	1.07

3.3 | Estimation of J_2 and J_2/TMH

The length of the water transfer pipes (L) varied between 50 and 2500 m. They had a diameter of 9–11 cm. Made of PVC, their relative pipe roughness is approximately 9.0×10^{-4}%. Using Equation (3), J_2 is estimated to vary between 2.93×10^{-2} and 17.63 m (median = 1.65 m). The ratio J_2/TMH, derived from Equation (2), varies between 0.04 and 25.9% (median = 2.43%). The lowest value was observed for a pump extracting groundwater at a depth of 90 m and transferring it at a rate of 13.8 m^3 h^{-1} over a horizontal distance of 80 m. In contrast, the highest value was observed for a pump extracting groundwater at a depth of 40 m and transferring it at a rate of 54.9 m^3 h^{-1} over a horizontal distance of 2 km. The longest horizontal water transfer (2.5 km) was associated with a ratio of 6.9%, a groundwater depth of 50 m and a pumping rate of 24.8 m^3 h^{-1}. These calculations confirm that friction losses J_2 caused by horizontal water transfer are low compared to TMH. This result is consistent with the fact that L is not an explanatory variable of Gb and Pr in Equations (5) and (6), respectively.

Figure 2 shows the relationships between L and Wd for specified values of J_2/THM, within the ranges of measured values. This shows that farmers equipped with underperforming pumping systems (i.e. low pumping rate and low energy efficiency) have more magnitude to increase the length of horizontal water transfer without excessive additional energy losses.

3.4 | Configurations and energy performance of irrigation systems

Depending on how many well(s) and reservoir(s) each farmer used to irrigate their plot, four configurations of irrigation systems were identified (Table 2) and illustrated in Figure 3.

System 1 is used by smallholders who irrigate plots averaging 1.5 ha and not exceeding 4 ha. The mean

pumped volumes (200 m^3 day^{-1}) are lower than those measured in the other systems (360 m^3 day^{-1}). To adapt the irrigation system to the limited discharge, one farmer installed valves on each mainline pipe to increase the water pressure. Agricultural practices were less intensive than those of other irrigation systems used by entrepreneurial tenants renting the land.

System 2 includes one reservoir with a capacity ranging from 150 to 600 m^3. Due to the greater discharge of the horizontal pump exceeding that of the vertical pump (Table 1), the mean emptying rate of the reservoirs (470 m^3 day^{-1}), derived from the daily operating hours of the pumps, exceeds the mean filling rate (341 m^3 day^{-1}). The reservoirs thus have two main functions: (i) to enable the use of two water pumps to compensate for friction losses caused by water transfers over distances exceeding 1 km, longer than those in system 1; (ii) to buffer the groundwater pumping rate so that the horizontal and vertical pumps can operate over different time periods, thus reconciling different discharge rates while offering flexibility in scheduling irrigation. The reservoirs are usually located close to the irrigated plots to ensure sufficient and constant pressure in the drip irrigation system.

System 3 includes two reservoirs in series. The second reservoir has the same functions as the single reservoir used in system 2. The first reservoir aims to reduce the length of the pipe connected to the groundwater pump, which could reach up to 2 km otherwise. This setting enables the maintenance of a sufficient pumping rate from the well/borehole to the irrigated plot, despite longer water transfer distances. One farmer used a Renault 25 engine to pump water from a 45 m deep well, then a Peugeot 504 engine to transfer the water from the first reservoir to the second one and irrigated his crops using a third Peugeot 504 engine to pump water from the second reservoir and to pressurize it for the drip irrigation system. The second farmer used three pumps powered by Renault 25 engines. This lessee rented the well but was not allowed to work the land

FIGURE 2 Length of horizontal water transfer (L) and groundwater depth (Wd) for specified values of J_2/TMH (1, 5 and 10%). (a) Pr = 30 m^3 h^{-1}; (b) Pr = 50 m^3 h^{-1}. J_2: Friction losses in the horizontal transfer pipe. TMH: Total manometric head of the pumping station. Pr: Pumping rate
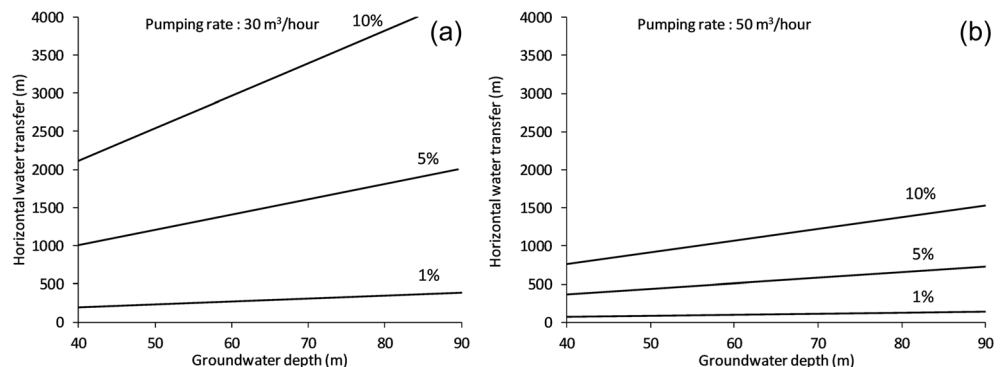
TABLE 2 Characteristics of each irrigation system

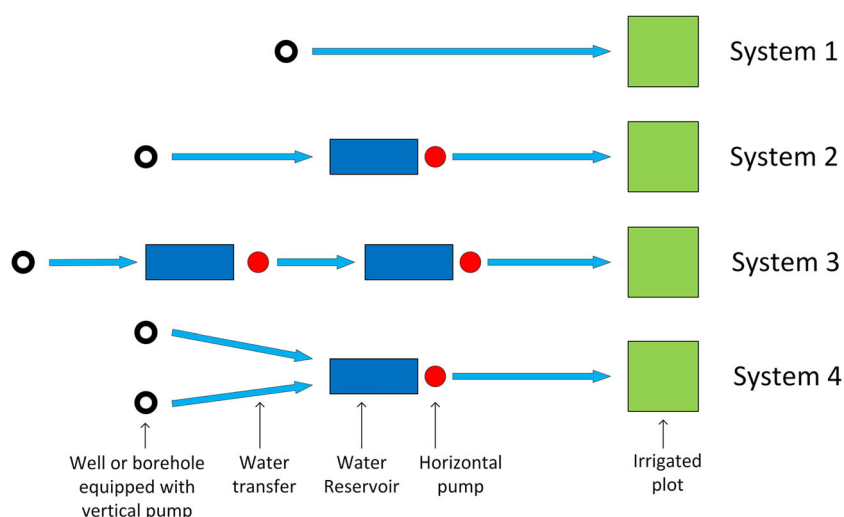| Configuration	Number of involved farmers	Number of well/borehole(s)	Number of reservoir(s)	Number of vertical pump(s)	Number of horizontal pump(s)	Mean distance from well/borehole(s) to drip-irrigated plot (m)	Mean energy consumption (kWh m^{-3})
System 1	4	1	0	1	0	125	4.73
System 2	17	1	1	1	1	602	4.62
System 3	2	1	2	1	2	3 100	4.88
System 4	2	2	1	2	1	398	4.85

FIGURE 3 Configurations of the irrigation systems in the study area

close by. He consequently built a first reservoir at an estimated distance of 1 km from the well, from which water was transferred to a second reservoir located 1.5 km from the first. This system involving significant investment to enable transferring irrigation water over long distances (>2.5 km) is typically designed by tenants maximizing their profits by renting irrigated plots larger than those that are available in the immediate vicinity of the well/boreholes.

System 4 involves tenant farmers engaged in profitable intensive farming, renting large and fertile lands to produce potatoes, carrots and forage maize. The limited amount of water available in each well/borehole is offset by pumping water from two different wells, both connected to the same reservoir.

Table 2 shows that the total energy consumption of the irrigation systems is relatively stable between different configurations, indicating that the combined energy consumption of the pumps in series (systems 2 and 3) or in parallel (system 4) is equivalent to the energy consumption (Gb) of the single pump of system 1.

4 | DISCUSSION

4.1 | Energy-inefficient irrigation systems

Our results show that the current patterns of irrigated agriculture in the study area are shaped by water-intensive and energy-inefficient farming systems rather than water- and energy-saving objectives. There has been an expansion of irrigation for high-value crops, requiring large volumes of water (Ouassissou, Kuper, Hammani & El Amrani, 2019). The energy consumption of pumping stations was approximately one order of magnitude greater than typical values measured in pressurized irrigation systems, rarely exceeding 0.5 kWh m^{-3} (Pérez-Sanchez, 2017; Urrestarazu & Burt, 2012). This overconsumption results from two main factors: (i) the great depth of wells requires a large amount of pumping energy. The energy consumption of vertical pumps is more than threefold that of horizontal pumps (Table 1); (ii) the pumping stations, relying on modified car motors, exhibit

energy efficiencies (E_e) averaging 5.2%, lower than that of regular engines used to power hydraulic pumps, about twice greater (IADB, 2011). The main energy losses explaining such low performance are usually related to the pump itself (approximately 50% of the consumed power P_c, cf. Equation (4) and the motor (approximately 20% of P_c). Other losses not exceeding 20% of P_c include leakages and network head losses (IADB, 2011).

Multiple regression analyses showed, first, that energy consumption per unit of pumped water volume (Gb) increases with a decrease in pumping rate (Pr) and an increase in water depth (Wd) (Equation (5)). Concomitantly, the pumping rate of pumps with more powerful engines is higher and decreases with an increase in Wd Equation (6). The negative correlation between Gb and Pr Equation (5) means that pumps discharging more water are more energy efficient. This behaviour stems from the fact that all pumping stations delivered useful power (Pu) ranging from 1.5 to 13.9 kW, far below the optimal values of 100–110 kW, usually yielding the best efficiencies in the case of a fuel-powered car engine operated at a regular speed (i.e. >2500 rpm) (Baron & Pescarou, 2013). Therefore, pumping stations with greater Pr values deliver useful power closer to the optimum level, hence the lower Gb value. This positive correlation between Pr and pumping efficiency was consistently observed among a large set of electrical pumps used for irrigation in California (Urrestarazu & Burt, 2012). The negative correlation between Pr and Wd (6) is consistent with the fact that farmers in the study area are keen to locate their wells and boreholes where the pumping depth is shallowest. It also demonstrates the benefit of reservoirs enabling horizontal pumps to operate at rates greater than that of their connected vertical pumps in systems 2, 3 and 4 (Figure 3).

Second, the multiple linear regression analysis indicates that the influence of the distance between the well/borehole and the irrigated plots (L) on Gb and Pr is statistically insignificant (i.e. L is not an explanatory variable in Equations (5) and Equation (6). This result is consistent with several energy assessments of irrigation water transport systems (Cabrera et al., 2019) and in agreement with hydraulic analyses showing that pumping consumption is moderately influenced by L, especially for lower values of Pr and E_e (Figure 2). This means that the lower energy efficiency of water pumping offers a greater flexibility to large-scale tenants practising intensive irrigated agriculture to significantly increase the length of their water transfer pipes to reach fertile cropping lands at minor additional cost (Figure 1). They change the location of their plots every year to compensate for the loss of soil fertility. Available plots are limited because of competition for farmland, especially near wells that deliver

high water yields. The spatial heterogeneity of the fractured karstic aquifers results in highly variable water yields over short distances. Consequently, tenants prefer to secure reliable wells/boreholes by using longer water transfer pipes to reach available land rather than counting on less reliable wells close to the newly cropped area. Fragmentation of land located close to traditional wells is a further incentive for tenants to rent lands further away. The flat topography of the Berrechid plain favours these extensive water transfers, often exceeding 2 km, while minimizing the additional manometric head. These extensions intensify groundwater use for entrepreneurial farming, in particular for horticulture (carrots, potatoes) and for the production of livestock feed. Smallholders often refer to the large-scale tenants using irrigation systems 2, 3 and 4 to irrigate more than 4 ha as having 'water bulimia'. Similar long-distance water transfers for irrigated agriculture have been observed elsewhere, for example, in Peru (Boelens et al., 2014).

Finally, the assessment of energy consumption at the irrigation system level (Table 2) has shown that Gb is not influenced by the number of pumping stations and by their connections (either in series where one well/borehole is used or in parallel where two are used). This result shows that, in the context of our study site, pumps connected in series or in parallel in the same system (Figure 3) share pumping work and the associated consumed energy, thus offering flexibility in adjusting irrigation systems to land and water access constraints without additional energy costs. However, this assessment accounts for operating costs only and does not consider investment in pumps, reservoirs and pipes.

4.2 | Energy and agricultural subsidies have resulted in energy- and water-intensive farming systems

Up to the 1970s, direct investment in the water sector in Morocco focused on developing gravity irrigation infrastructure to reduce dependence on (imported) energy (Kettani et al., 2020). The promotion of pressurized irrigation started in the 1970s with sprinkler irrigation and has accelerated over the past two decades with the promotion and subsidy of drip irrigation (Boularbah et al., 2019), often outstripping direct agricultural investment by the state (Doukkali & Lejars, 2015). Both indirect energy subsidies and direct agricultural subsidies, considered the major pillars of the overarching 'Green Moroccan plan' aiming at developing intensive irrigated agriculture (Kuper et al., 2017), have converged to encourage energy- and water-intensive farming systems. This came at the expense of energy efficiency, as observed in our study area

and globally, among other communities of smallholder irrigators (Mateos et al., 2018). These policies aimed to increase the production of high-value crops, mostly fruit and vegetables, and the development of the food processing sector (El Youssfi et al., 2020), thereby further increasing energy requirements: in 2012, the global food supply chains represented approximately 30% of the total energy demand, with inherent environmental costs and questions concerning the sustainability of this agricultural model (Ameur et al., 2017; Mukuve & Fenner, 2015).

4.3 | Subsidizing unsustainable forms of irrigated agriculture

The interactions and interdependencies across and between various sectors are a standard focus of the WEF nexus approaches (Hoff, 2011). However, the nexus perspective is often 'largely silent on issues pertaining to other critical inputs, such as land, labour, capital, seeds, plant nutrients, and farm chemicals' (Wichelns, 2017). Another fundamental criticism is that 'nexus framing obliterates inequalities of access as the root of resource crises', as it ignores power relations (Allouche et al., 2015).

In North Africa, two interlinked phenomena are important in relation to these criticisms. First, Ameur et al. (2017) showed how the development of the groundwater economy was accompanied by increasing inequalities, as groundwater was overexploited by a minority of farmers whose intensive agriculture required powerful and expensive pumps in the context of a drop in water tables, thereby excluding small-scale farmers whose wells were running dry. This is also the case in the Berrechid plain. Due to market-oriented and profitable agricultural products, some large-scale farmers located near the study area have progressively increased their own irrigated area up to 200 ha (Ouassissou, Kuper, Hammani & El Amrani, 2019). Second, there is increasing evidence of the mobility of capital-owning farmers in North Africa, renting the land from local farmers to practise highly intensive agriculture through a variety of informal arrangements and contracts with local well owners (Ameur et al., 2017; El Youssfi et al., 2020; Ouassissou, Kuper, Dugué, et al., 2019). These capital-intensive farmers have gained the upper hand in these arrangements, and while they constitute a small minority of farmers, they exploit a large part of the groundwater. The water volume extracted for irrigation in 2016–2017 in the study area was approximately 1.3 million m^3, of which more than 50% was used by such tenants (Ouassissou, Kuper, Hammani & El Amrani, 2019). This is in agreement with studies elsewhere that have documented evidence of a power switch in favour of capital-owning

'tenants', which can even be commercial and agricultural societies, who 'grab' groundwater at the expense of local landowners (Amblard & Colin, 2009). These tenure arrangements thus lead to the deterioration of natural resources: depletion of groundwater and loss of soil fertility through highly intensive cropping systems requiring shifting plots every 1–2 years, while at the same time compounding inequalities in rural areas (Ouassissou, Kuper, Dugué, et al., 2019). Land tenure is therefore an important issue to consider in nexus approaches (Wichelns, 2017).

5 | CONCLUSION

The analysis showed how subsidized energy and the promotion of drip irrigation facilitated the expansion of intensive, energy-inefficient groundwater-based irrigated agriculture. Farmers seek fertile and available land, often located several kilometres away from existing wells and boreholes, as water transfer is affordable for an expanding 'groundwater economy'. This trend is likely enhanced by the moderate additional energy consumption of extending horizontal water transfer using additional PVC pipes. Currently, irrigation facilities almost exclusively use fossil fuels, either directly or indirectly, through the electricity grid. However, recently, there has been a shift towards the use of solar energy. Although renewable energy may be attractive as green energy, it will likely have considerable 'economic and ecological impacts on the way the regional groundwater irrigation regime functions' (Shah et al., 2018). The negligible operational cost of solar energy, once the investment is made, may encourage farmers to intensify groundwater use. The interdependencies between water, energy and irrigated agriculture therefore require continuing attention to preserve land and limit overexploitation of groundwater resources.

Our analysis showed that the expansion of the groundwater economy involves a range of irrigation configurations and land-tenure modalities favouring a minority of large-scale mobile farmers, possibly exacerbating social inequalities. This suggests that the debate in Morocco regarding the shift of gravity irrigation to drip irrigation should not be confined to water productivity and water saving but should account for all other social, economic and environmental consequences.

The WEF nexus perspective is an interesting lens through which to study current patterns of irrigated agriculture. However, when addressing the necessary transitions to sustainable irrigated agriculture, other significant inputs and resources that influence the use of water and energy and fundamental issues affecting the groundwater economy, such as social and environmental justice, should not be ignored.

ORCID
Guillaume Lacombe https://orcid.org/0000-0002-3882-2697
Marcel Kuper https://orcid.org/0000-0002-1240-0592

REFERENCES

Allan, T., Keulertz, M. & Woertz, E. (2015) The water-food-energy nexus: an introduction to nexus concepts and some conceptual and operational problems. *International Journal of Water Resources Development*, 31(3), 301–311. Available from: https://doi.org/10.1080/07900627.2015.1029118

Allouche, J., Middleton, C. & Gyawali, D. (2015) Technical veil, hidden politics: Interrogating the power linkages behind the nexus. *Water Alternatives*, 8(1), 610–626.

Amblard, L. & Colin, J.P. (2009) Reverse tenancy in Romania: Actors rationales and equity outcomes. *Land Use Policy*, 26(3), 828–836. Available from: https://doi.org/10.1016/j.landusepol.2008.10.008

Ameur, F., Amichi, H., Kuper, M. & Hammani, A. (2017) Specifying the differentiated contribution of farmers to groundwater depletion in two irrigated areas in North Africa. *Hydrogeology Journal*, 25(6), 1579–1591. Available from: https://doi.org/10.1007/s10040-017-1569-1

Baron, E. & Pescarou, P. (2013) Transmissions dans l'automobile: influence sur la consommation du véhicule. *Technique de l'ingénieur*, TIP151WEB. BM 2584. Available from: https://doi.org/10.51257/a-v1-bm2584

Belaud, G., Mateos, L., Aliod, R., Buisson, M.C., Faci, E., Gendre, S., Ghinassi, G., Gonzales Perea, R., Lejars, C., Maruejols, F. & Zapata, N. (2019) Irrigation and Energy: Issues and Challenges. *Irrigation and Drainage*, 69(S1), 177–185. Available from: https://doi.org/10.1002/ird.2343

Benouniche, M., Kuper, M., Hammani, A. & Boesveld, H. (2014) Making the user visible: analysing irrigation practices and farmers logic to explain actual drip irrigation performance. *Irrigation Science*, 32(6), 405–420. Available from: https://doi.org/10.1007/s00271-014-0438-0

Berbel, J., Borrego-Marin, M.M., Exposito, A., Giannoccaro, G., Montilla-Lopez, N.M. & Roseta-Palma, C. (2019) Analysis of irrigation water tariffs and taxes in Europe. *Water Policy*, 21(4), 806–825. Available from: https://doi.org/10.2166/wp.2019.197

Boelens, R., Gaybor, A. & Hendriks, J. (2014) Water grabbing in the Andean region: illustrative cases from Peru and Ecuador. In: Kaag, M. & Zoomers, A. (Eds.) *Beyond the hype: a critical analysis of the 'Global Land Grab'*. Nova Scotia: Fernwood Publishing. pp. 100–116 https://doi.org/10.5040/9781350223172.ch-006

Boularbah, S., Kuper, M., Hammani, A., Mailhol, J.C. & Taky, A. (2019) The blind angle: Performance assessment of drip irrigation in use in a large-scale irrigation scheme in Morocco. *Irrigation and Drainage*, 68(5), 925–936. Available from: https://doi.org/10.1002/ird.2369

Brown, G.O. (2002) The history of the Darcy-Weisbach equation for pipe flow resistance. *Environmental and Water Resources History*, 40650, 34–43. Available from: https://doi.org/10.1061/40650(2003)4

Cabrera, E., del Teso, R., Gomez, E., Estruch-Juan, E. & Soriano, J. (2019) Quick energy assessment of irrigation water transport systems. *Biosystems Engineering*, 188, 96–105. Available from: https://doi.org/10.1016/j.biosystemseng.2019.10.013

Doukkali, M.R. & Lejars, C. (2015) Energy cost of irrigation policy in Morocco: a social accounting matrix assessment. *International Journal of Water Resources Development*, 31(3), 37–41. Available from: https://doi.org/10.1080/07900627.2015.1036966

El Youssfi, L., Doorsamy, W., Aghzar, A., Cherkaoui, S.I., Elouadi, I., Faundez, A.G. & Salazar, D.R. (2020) Review of water energy food nexus in Africa: Morocco and South Africa as case studies. *E3S Web of Conferences*, 183, 1–17 Available from: https://doi.org/10.1051/e3sconf/202018302002

Hoff, H. (2011) *Understanding the Nexus. Background paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus*. Stockholm: Stockholm Environment Institute.

IADB. (2011) Evaluation of water pumping systems. In: *Efficiency Assessment Manual*, First edition. Washington D.C: Inter-American Development Bank (IADB), Water and Sanitation Initiative, Sustainable Energy and Climate Change Initiative.

Kettani, A., Hammani, A., Taky, A. & Kuper, M. (2020) L'expérience de l'irrigation par aspersion dans les secteurs collectifs de la Grande Hydraulique du Maroc. *Revue Marocaine des Sciences Agronomiques et Vétérinaires*, 8(4), 399–410.

Kuper, M., Ameur, F. & Hammani, A. (2017) Unraveling the enduring paradox of increased pressure on groundwater through efficient drip irrigation. In: Venot, J.P., Kuper, M. & Zwarteveen, M. (Eds.) *Drip irrigation for agriculture: untold stories of efficiency, innovation and development*. Abingdon: Routledge, pp. 85–104. https://doi.org/10.4324/9781315537146-6

Llamas, M.R. & Martínez-Santos, P. (2005) Intensive groundwater use: silent revolution and potential source of social conflicts. *Journal of Water Resources Planning and Management*, 131(5), 337–341. Available from: https://doi.org/10.1061/(ASCE)0733-9496(2005)131:5(337)

Mateos, L., dos Santos Almeida, A.C., Frizzone, J.A. & Lima, S.C.R. V. (2018) Performance assessment of smallholder irrigation based on an energy-water-yield nexus approach. *Agriculture Water Management*, 206, 176–186. Available from: https://doi.org/10.1016/j.agwat.2018.05.012

Moody, L.F. & Princeton, N.J. (1944) Friction factors for pipe flow. *Transactions of the American Society of Mechanical Engineers*, 66, 670–684.

Mukuve, F.M. & Fenner, R. (2015) Scale variability of water, land, and energy resource interactions and their influence on the food system in Uganda. *Journal of Sustainable Production and Consumption*, 2, 79–95. Available from: https://doi.org/10.1016/j.spc.2015.07.009

Ouassissou, R., Kuper, M., Dugué, P., El Amrani, M., Hammani, A. & Ameur, F. (2019) Rivalités et arrangements coopératifs pour l'accès à l'eau souterraine dans la plaine de Berrechid au Maroc. *Cahiers Agricultures*, 28(4), 1–10. Available from: https://doi.org/10.1051/cagri/2019006

Ouassissou, R., Kuper, M., Hammani, A. & El Amrani, M. (2019) Le contrat de gestion participative pourrait-il résoudre la crise de gouvernance des eaux souterraines ? Cas de la nappe de Berrechid au Maroc. *Alternatives Rurales*, 7, 1–15.

Pérez-Sanchez, M. (2017) Methodology for energy efficiency improvement analysis in pressurized irrigation networks. Practical application. PhD thesis. University of València. p. 268.

Rocamora, C., Vera, J. & Abadía, R. (2013) Strategy for efficient energy management to solve energy problems in modernized irrigation: analysis of the Spanish case. *Irrigation Science*, 31(5), 1139–1158. Available from: https://doi.org/10.1007/s00271-012-0394-5

Shah, T., Rajan, A., Rai, G.P., Verma, S. & Durga, N. (2018) Solar pumps and South Asias energy-groundwater nexus: exploring implications and reimagining its future. *Environmental Research Letters*, 13(11), 115003. Available from: https://doi.org/10.1088/1748-9326/aae53f

Tarjuelo, J.M., Rodriguez-Diaz, J.A., Abadía, R., Camacho, E., Rocamora, C. & Moreno, M.A. (2015) Efficient water and energy use in irrigation modernization: Lessons from Spanish case studies. *Agricultural Water Management*, 162, 67–77. Available from: https://doi.org/10.1016/j.agwat.2015.08.009

Urrestarazu, P.L. & Burt, C.M. (2012) Characterization of pumps for irrigation in central California: potential energy savings. *Journal of Irrigation and Drainage Engineering*, 138(9), 815–822.

Wang, J., Rothausen, S.G.S.A., Conway, D., Zhang, L., Xiong, W., Holman, I.P. & Li, Y. (2012) Chinas water-energy nexus: greenhouse-gas emissions from groundwater use for agriculture. *Environmental Research Letters*, 7(1), 014035. Available from: https://doi.org/10.1088/1748-9326/7/1/014035

Wichelns, D. (2017) The water-energy-food nexus: Is the increasing attention warranted, from either a research or policy perspective? *Environmental Science and Policy*, 69, 113–123. Available from: https://doi.org/10.1016/j.envsci.2016.12.018