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Farm-level Hydroeconomic Analysis of Alternative Water Tariff Charges Using a Hybrid Solution Method

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Abstract

This paper's main objective is to develop a farm-level water programming model to realistically model extensive margin and intensive margin responses resulting from deficit irrigation to the implementation of volumetric water charges. The highly complex programming model that uses the FAO56 water budget calculations to simulate crop water use while using relative evapotranspiration to estimate crop yield is solved using a hybrid procedure. The hybrid solution procedure uses a genetic algorithm to simplify the optimization model by fixing the irrigation schedule of each crop and then solving for the optimal water allocation amongst crops subject to water constraints. The area-based charges results showed that when irrigation application efficiency is low, irrigators could apply more water per hectare to sustain high crop yields without being held accountable if water quotas are exceeded. In contrast, irrigators with higher application efficiency could use less water than the area-based estimated water use. The results also showed that volumetric water charges cause both intensive margin and extensive margin responses. The conclusion of whether a volumetric-based water charging system will be better than area-based water charges is not straightforward because of differentiated impacts on profitability and hydrology. While irrigators will use irrigation water more efficiently and adopt more efficient irrigation technologies, their changed behavior could impact the hydrology of the water system through reduced return flows.

Keywords Agriculture · Area-based water pricing · Volumetric-based water pricing · Irrigation · Water use optimization model · Hydroeconomic modeling

1 Introduction

South Africa is a water-scarce country with an average rainfall of 450 mm per year, which is well below the world average of 860 mm (Department of Water and Sanitation (DWS) 2022). Rainfall decreases substantially from east to west, where crop production is possible only under irrigation. In the western parts of the country, the Orange River supplies

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water to various water user associations through canals and direct water abstractions. Current water supplies are under pressure due to water reallocation reform to ensure environmental sustainability, equitable water allocation and economic development (Department of Water and Sanitation (DWS) 2022). South Africa's National Development Plan (NDP) Vision 2030 prioritizes water demand management while considering the importance of reducing water demand by 2030 to ensure a secure water future for the nation.

Little potential exists to augment the water supply through new developments (Backeberg 2014). Achieving a water-secure future, therefore, requires all water users to reduce water demand. However, the government targets irrigated agriculture as a potential water source (Department of Water and Sanitation (DWS) 2022). Irrigated agriculture uses 61% of South Africa's water, making it the largest single water-use sector. Researchers have shown that increasing water tariffs (Martínez-Dalmau et al. 2023) and volumetric water metering (Dono et al. 2010) are conducive to more efficient water use. The sector pays low water tariffs compared to other water use sectors, and water use is often not accurately measured. Thus, the government argues that current policies do not create the necessary incentives to use water efficiently and that small improvements will increase water availability. The government is revising South Africa's National Water Resources strategy to include strategic objectives and actions to reduce water demand by promoting water conservation and demand management and ensuring compulsory metering and billing (Department of Water and Sanitation (DWS) 2022). Water metering is necessary to implement demand management through increased water tariffs to increase water use efficiency. In this regard, regulations were published in February 2017 by the South African Government stating that a water user must measure the amount of water taken from a water resource and keep a record of it for at least five years (Department of Water and Sanitation (DWS) 2017). Water metering is especially problematic in areas where water abstractions are done straight from the river. Most irrigation water user associations use indirect means to estimate irrigation water use in river systems. Research by Van der Stoep et al. (2012) identified appropriate technology and devised implementation guidelines to facilitate volumetric water metering in irrigated agriculture.

Changing the water charging method (i.e., area-based vs. volumetric) impacts irrigation water use substantially since it changes the incentives to use irrigation water more efficiently (Dono et al. 2010). Lehmann and Finger (2013) argue that ex ante analysis of any water policy change is necessary to ensure that the change does not result in unintended consequences. Water programming models are popular for ex ante analysis of water policy changes (Graveline 2016). The ability of the water programming model to predict extensive margin and intensive margin responses to policy changes is critical to avoid overpredicting the impact of the change on profit and water use (Sapino et al. 2022). Deficit irrigation is an important strategy available to irrigators to reduce water applications and increase water productivity (Mukherjee et al. 2023). According to Graveline (2016), researchers have found it challenging to model intensive margin changes resulting from deficit irrigation.

The incorporation of deficit irrigation into mathematical programming models is problematic because water deficits in different crop growth stages affect crop yields differently (Doorenbos and Kassam 1979). Furthermore, crop water stress conditions are more directly related to available soil water relative to a threshold soil water content where water stress begins (Allen et al. 1998) than are irrigation water applications that augment available soil water. Consequently, soil water budget calculations are necessary to determine the onset of water stress and the duration thereof. Seasonal crop water production functions are typically used to summarize trial data related to crop responses to water deficits (Kamali et al. 2022). These functions are highly site specific and are not applicable under different situations. Foster and Brozović (2018) demonstrated that crop growth simulation models could be used to simulate the impact of various intraseasonal irrigation scheduling constraints on crop yields (i.e., seasonal crop-water production function) while considering weather variability. Sapino et al. (2022) adopted a similar approach to simulate and incorporate seasonal production functions into a positive multiattribute utility programming model to model intensive margin changes in water use in response to water pricing policies. Seasonal crop-water production functions assume technical efficiency (i.e., achieve the highest yield given seasonal water availability and system capacity constraints). A potential problem with using seasonal crop-water production functions to model farm-level water allocation between multiple crops is that the water allocation is not optimal when water availability within a specific time period within the production season is binding (Bernardo 1985). Ignoring time period-specific farm-level constraints related to pumping capacities and water supply will result in incorrect estimation of the impact of water policy changes on irrigation water use and profit.

The main objective of this research is to develop a farm-level water programming model to realistically model extensive margin and intensive margin responses resulting from deficit irrigation to the implementation of volumetric water charges. The research's novelty is developing a procedure to explicitly represent deficit irrigation in the water programming model with an irrigation crop yield simulation model. Consequently, there is no need to estimate a production function using the output from the crop yield simulation model. The model includes 16 different states of nature to prevent the optimization of unrealistic irrigation schedules when assuming perfect knowledge about future weather conditions. Furthermore, the procedure enables explicit consideration of a decision-maker's intraseasonal irrigation management choices as influenced by technical and economic factors. Incorporating a daily irrigation scheduling routine directly into the solution procedure has the benefit of determining potential changes in farm-level return flows when changing to volumetric water charges. The water programming model is solved with a hybrid solution procedure that relies on an evolutionary algorithm to optimize irrigation schedules and linear programming to allocate water between different crops.

2 Farm-level Water Programming Models

We developed two water programming models to optimize crop-specific irrigation management decisions and areas irrigated to maximize farm profit for a given water charging method (i.e., area based vs. volumetric).

2.1 Volumetric Water Charging Model

The volumetric water charging model optimizes irrigation water use while assuming that the water user association (WUA) can accurately measure the water use of irrigators to bill and control total water use. Equations (1)-(3) show the mathematical formulation of the water programming model when volumetric water charges apply:

$$\max_{A_c,M_c} E(\pi) = \frac{1}{S}\sum_{s=1}^{S}\sum_{c=1}^{C} A_c \cdot \left[\left(P_c - C_c^Y\right) \cdot Y_{cs}\left(M_c|\omega_s,\gamma\right) - \left(C_c^W + C_c^I\right) \cdot I_c\left(M_c|\omega_s,\gamma\right) - C_c^A\right] \tag{1}$$

$$\sum_{c=1}^{C} I_c\left(M_c|\omega_s,\gamma\right) \cdot A_c \leq Q \tag{2}$$

$$\sum_{c=1}^{C} A_c \leq A^0 \tag{3}$$

where $E(\pi)$ is the expected profit (R) from producing C crops with random expectation of future weather states S, A_c is the area irrigated (ha), P_c is the crop selling price (R/ton), C_c^Y is harvesting costs (R/ton), C_c^W is the irrigation water tariff (R/mm), C_c^I is the costs that vary with irrigation depth (R/mm) (i.e., electricity costs, labor costs and repair and maintenance costs), and C_c^A is the costs that vary with the area irrigated (R/ha) (i.e., machinery cost, fuel, pesticides, herbicides, etc.). Y_{cs} and I_c are the harvested crop yield (ton/ha) and applied irrigation depth (mm/ha), respectively, as a function of irrigation management decisions during the season (M_c) given random weather states (ω_s) and a fixed production technology set (γ) representing soil characteristics and irrigation technology.

An important problem with irrigation water use optimization is the assumption of perfect knowledge about future weather. The calculation in square brackets in Eq. (1) calculates each crop's gross margin per hectare as a function of irrigation management decisions for a given technology set and future weather states. Irrigation management decisions are optimized to maximize the average farm gross margin across all weather states to overcome the problem of perfect knowledge. Equation (2) constrains actual farm-level irrigation water use to the water quota of the farm (Q, measured in mm). Thus, the assumption is that the water user association could meter actual water use. Importantly, the irrigator could manage farm-level water use through intensive (i.e., M_c) and extensive (A_c) margin changes. Equation (3) constrains the area irrigated to be less than the available area (A^0).

2.2 Area-based Water Charging Model

The area-based water charging model optimizes water use, assuming the WUA bills and controls irrigation water use using indirect water metering. Indirect water metering uses the irrigated area and an estimate of crop water requirements to estimate farm-level irrigation water use. Equations (3)-(5) provide the mathematical formulations of the water programming model when area-based water charging is applied:

$$\max_{A_c,M_c} E(\pi) = \frac{1}{S} \cdot \sum_{s=1}^{S}\sum_{c=1}^{C} A_c \cdot \left[\left(P_c - C_c^Y\right) \cdot Y_{cs}\left(M_c|\omega_s,\gamma\right) - C_c^W \cdot R_c - C_c^I \cdot I_c\left(M_c|\omega_s,\gamma\right) - C_c^A\right] \tag{4}$$

$$\sum_{c=1}^{C} R_c \cdot A_c \leq Q \tag{5}$$

where R_c is the crop's irrigation water requirement (mm/ha).

Equation (4) shows that irrigation management decisions do not impact the total water charge because the WUA determines crop water use (i.e., R_c). Equation (5) shows that the WUA restricts water use by means of an indirect measurement of irrigation water use. Consequently, farmers who use less water do not benefit, while farmers who use more water are not penalized. Therefore, area-based water charges do not provide an economic incentive to change irrigation water management.

The following sections discuss the quantification of crop yield and applied irrigation water as a function of irrigation management decisions.

2.3 Crop Yield Estimation

We combined daily soil water budget calculations from Allen et al. (1998) with the Stewart relative evapotranspiration formula (Stewart et al. 1977) to estimate crop yield as a function of irrigation management decisions. Nonuniform irrigation water applications complicate crop yield estimations because a portion of the field receives more than the intended irrigation depth, while others receive less (Autovino et al. 2016). Increasing irrigation application depths to improve crop yields on the under-irrigated parts will increase deep percolation in the other parts. Estimating crop yields using multiple water budgets with different irrigation depths provides a straightforward means to model inefficiencies resulting from nonuniform irrigation applications (Venter and Grové 2016; Grové 2019). We used three water budgets with average, below-average, and above-average water applications to explicitly model the impact of nonuniform irrigation application on crop yield. Equations (6)-(7) show the crop yield calculation procedure:

$$Y_{cs}\left(M_c|\omega_s,\gamma\right) = \frac{1}{3}\sum_{b=1}^{3} Y_{cs}^{P} \cdot \prod_{g=1}^{4}\left[1 - ky_{cg}\left(1 - \frac{\sum_{d\in g} \frac{RWC_{csdb}(M_c|\omega_s,\gamma)}{TRWC_{csd}} \cdot ETm_{csd}}{\sum_{d\in g} ETm_{csd}}\right)\right] \tag{6}$$

$$RWC_{csdb}\left(M_c|\omega_s,\gamma\right) = min\left|\begin{array}{c} RWC_{csdb-1} - ETa_{csdb} + P_{sd} + I_{cdb}\left(M_c|\omega_s,\gamma\right) + TR_{cdb} \\ TAM_{cd} \end{array}\right. \tag{7}$$

where crop yield is dependent on the daily (i.e., d) water budget calculation, Y_{cs}^{P} is the potential crop yield in a specific weather state (ton/ha), ky_{cg} is the crop growth stage-specific crop yield response factor (dimensionless), RWC_{csdb} is the root water content as a function of irrigation management decisions (mm), $TRWC_{csd}$ is the threshold water content when water stress begins (mm), ETm_{csd} is the potential evapotranspiration (mm), ETa_{csdb} is the actual evapotranspiration (mm), P_{sd} is precipitation (mm), I_{cdb} applied irrigation depth (mm) as a function of the decision-maker's irrigation management decisions, TR_{cdb} is the increase in root water content from root growth (mm) and TAM_{cd} is the upper bound of the total available water in the soil.

The numerator in Eq. (6) shows that the crop's potential evapotranspiration rate decreases if the root water content falls below a threshold. Domínguez et al. (2012) provided a procedure to calculate the threshold water content as a function of crop characteristics and atmospheric evaporative demand. The Stewart model combines evapotranspiration deficits in different crop growth stages such that the combined effect of these deficits results in a more than proportional crop yield reduction. Consequently, the model is nonlinear. Equation (7) shows that irrigation management decisions influence root water content through irrigation application. Percolation of water out of the root zone occurs if the addition of precipitation or irrigation applications results in a root water content that exceeds the maximum available water content of the soil. The upper level of the root water content is therefore constrained to the maximum available water content of the soil with a MIN function (Allen et al. 1998). Consequently, the water budget calculations are discontinuous, rendering standard mathematical programming optimization algorithms inappropriate for solving the water programming models. Evolutionary algorithms provide an alternative optimization procedure to mathematical programming approaches to optimize complex irrigation problems (Banadkooki et al. 2020).

3 Hybrid Solution Procedure

Cai et al. (2001) developed a hybrid method that combines an evolutionary algorithm with linear programming to solve complex water resource allocation models. The hybrid method identifies and fixes a set of "complicating" variables to produce a model that is much easier to solve. We apply the hybrid method to solve the two water programming models. Careful inspection of our models shows that knowledge of the irrigation management decisions results in a linear programming model with the area irrigated as the decision variable. The linear programming model optimizes the irrigated area conditional on each crop's assumed irrigation management decisions. An evolutionary algorithm iteratively evolves irrigation management decisions to improve the objective function of the linear programming model to achieve optimal water allocation between crops for a near-optimal irrigation schedule. Thus, the complexity of the water yield relationship does not matter since the evolutionary algorithm optimizes the intensive margin responses.

An essential step in applying the evolutionary algorithm to optimize irrigation scheduling is transforming irrigation management decisions into actual water applications. A popular method to define the timing of irrigation events is to specify the soil water depletion level when irrigation is triggered, while irrigation system application rates constrain irrigation depths (Foster and Brozović 2018). Alternatively, the evolutionary algorithm could directly generate irrigation dates and corresponding irrigation depths when optimizing irrigation decisions (Wang et al. 2020). We choose to generate irrigation schedules directly with the evolutionary algorithm because it is easier to relate them to time-of-use electricity tariffs that incentivize irrigation on days when electricity charges are low compared to soil water depletion levels.

4 Data and Application

The water programming models were solved for a representative farm size in the Vanderkloof WUA, where farmers irrigate their fields directly from the Orange River. The Vanderkloof WUA uses water quotas to control water abstraction. At the beginning of the new production year, irrigators must provide the WUA with a production plan indicating the different crops and areas irrigated. The WUA uses this information and crop water use estimates to reconcile planned water abstractions with the water quota. The crop water requirements used by the Vanderkloof WUA for maize, popcorn, and wheat are 638, 528 and 560 mm/ha, respectively (Van Heerden et al. 2001), while the water tariff is R1.72/m^3 (Griekwaland-Wes Korporatief (GWK) 2020).

The farm has a listed irrigated area of 230 ha with a water quota of 11000 m^3 per listed hectare. Production possibilities include irrigated maize, wheat and popcorn. The production area of popcorn is restricted to 30 ha due to contractual agreements with the buyer. All the crops are irrigated with center pivot irrigation with an application rate of 12 mm/day and assuming two application efficiency scenarios. The uniformity was assumed to be 83% for the low application efficiency scenario and 90% for the high application efficiency scenario. The soil in the area is a relatively homogeneous sandy loam with a water-holding capacity of 100 mm/m (Van Heerden et al. 2001). The information needed for irrigation scheduling and crop yield estimation was taken from SAPWAT (Van Heerden and Walker 2016). Irrigation costs were estimated using the procedure outlined by Meiring (1989) using the Ruraflex electricity tariff structure. Production costs were taken from the production cost guide compiled by the local cooperative (Griekwaland-Wes Korporatief (GWK) 2020).

The water programming models were developed in Microsoft Excel®. The hybrid solution procedure was implemented using Microsoft Visual Basic for Application (VBA®).

5 Results

The first part of this section discusses the economic and irrigation water use impacts of changing from area-based charges to volumetric-based charges. The second part discusses the potential hydrological effects due to the implementation of volumetric-based charges.

5.1 Economic and Irrigation Water Use Impacts of Changing to Volumetric-based Charges

The Vanderkloof WUA uses an area-based water charging system to control irrigation water use. Therefore, the area-based charging system is considered the baseline in this study. The results of the optimized economic indicators and irrigation water use for the baseline situation are presented first before discussing the changes resulting from changing to volumetric-based charges.

5.1.1 Area-based Charging Baseline Situation

Area-based water charging is an indirect means of determining a farmer's irrigation water use based on the area that the farmer irrigates and the official crop water requirements as determined by the Vanderkloof WUA. Irrigation water users must provide the WUA with their production plan to reconcile planned irrigation water use with their water quota and determine the farm's total water charge. During the production season, the WUA verifies the actual areas irrigated through ground inspections. The WUA does not distinguish between the irrigation water use of a specific irrigation technology (e.g., pivot irrigation) with different water application efficiencies. However, actual irrigation water use may differ substantially between the same irrigation technology with different water application efficiencies. The first part of Table 1 shows the optimized economic indicators, irrigation water use and areas irrigated for scenarios where irrigation application efficiencies are either low or high and water charging is area-based.

According to the WUA in Vanderkloof, all farms, irrespective of irrigation water application efficiencies, use 638 mm/ha to produce maize, 560 mm/ha to grow wheat, and 528 mm/ha to grow popcorn. Consequently, farmers with different irrigation water application efficiencies will plant 173 ha of maize, 234 ha of wheat and 30 ha of popcorn with a water quota of 2,574,000 m^3.

Table 1 Comparison between area-based and volumetric-based water charges for high or low irrigation efficiencies

		AREA-BASED CHARGES (BASELINE)			VOLUMETRIC-BASED CHARGES		
		Irrigation Application Efficiency			Irrigation Application Efficiency		
				High	Low	High	High
		Low	High	Changes relative to	Changes relative to baseline		
				Low	Low	High	Low
Expected Total Gross margin	R	3,747,843	3 911,352	163,509	-19,125	86,764	250,273
Expected Production Income							
Maize	R	5,738,013	5,900,516	162,503	-5,216	909,335	1,071,838
Wheat	R	9,026,171	9,018,765	-7,406	-999	-5,621	-13,027
Popcorn	R	832,108	836,977	4,869	-21,380	-4,249	620
Expected Electricity cost	R	539,613	476,457	-63,156	-43,862	756	-62,400
Expected Water tariff cost	R	441,991	441,991	-	-	-9,514	-9,514
Irrigation water use							
Water User Association							
Maize	mm/ha	638	638	-	-	-	-
Wheat	mm/ha	560	560	-	-	-	-
Popcorn	mm/ha	528	528	-	-		-
Total	m^3	2,574,000	2,574,000	-	28,246	196,320	196,320
Actual irrigation water use							
Maize	mm/ha	823	770	-53	-113	-108	-161
Wheat	mm/ha	495	432	-63	-10	-8	-71
Popcorn	mm/ha	691	594	-97	-100	-9	-106
Total	m^3	2,790,873	2,523,234	-267,693	-216,873	-4,638	-272,277
Hectares Irrigated							
Maize	ha	173	173	-	5	31	31
Wheat	ha	234	234	-	-	-	-
Popcorn	ha	30	30	-	-	-	-

The exchange rate as of 30 November 2022: R 1 = 0.0583 USD

The results show that the actual irrigation water use is substantially different from the irrigation water use anticipated by the WUA.

The actual water use of farms with low irrigation application efficiency is 2,790,873 m^3, which is 218,873 m^3 more than the allocated water quota of the farm. Low irrigation application efficiency results in water applications of 823 mm/ha for maize, 495 mm/ha for wheat and 691 mm/ha for popcorn. Increasing irrigation application efficiency reduces water application per hectare by 53 mm, 63 mm and 97 mm for maize, wheat and popcorn, respectively, which causes total water use to decrease by 267,639 m^3. The reduction in water use is to such an extent that the total water use of farms with high application efficiency is 50,766 m^3 (2,574,000–2,523,234) less than the water quota. Differences in the actual water use between farms with low and high water application efficiency are the main cause of differences in the profitability of these farms.

The results show that a farm with high water application efficiency has an expected total gross margin of R3,911,352, which is R163,509 higher than that of a farm with a low water application efficiency. The higher expected gross margin results from lower water application in general and intensive margin changes in water applications that cause crop yields to change. Lower water application reduces electricity costs by R63,156. Intensive margin changes in water applications allocates more water to the production of maize, resulting in higher crop yields per hectare; therefore, the expected production income of maize increases by R162,503. Compared to a low irrigation efficiency farm, intensive margin changes in water applications on wheat and popcorn do not substantially change production income. The expected water cost of both farms is the same (R441,991) because, according to the WUA, the farms use the same amount of water.

5.1.2 Changing to Volumetric-based Water Charging

The implementation of volumetric-based charges requires that the WUA can measure water abstraction accurately. Consequently, the water bill is for the irrigator's actual water use. The second part of Table 1 shows the changes in the optimized economic indicators, irrigation water use and areas irrigated relative to the baseline when irrigation application efficiencies do not change and volumetric charges are applied. However, the table includes a scenario to show the impact of implementing volumetric charges when a farm with low irrigation application efficiency under area-based charging changes its irrigation application efficiency to high under volumetric-based charging.

When changing to volumetric-based charges, a farm with low irrigation application efficiency has to reduce its actual water use by 216,873 m^3 to not exceed its water quota. Even though the farm's irrigation water use is within the water quota, the farm's irrigation water use would exceed the water quota by 28,246 m^3 if area-based charging is applied. Volumetric charges create an economic incentive for irrigators to make intensive margin changes, resulting in an increase in the area under irrigation. The modeling results showed that irrigation water application per hectare is reduced by 113 mm, 10 mm, and 100 mm for maize, wheat and popcorn, respectively, while the area of maize is increased by 5 ha. Reduced irrigation water application per hectare results in lower crop yields per hectare, reducing the production income of all crops. The reduction in electricity costs by R43,862 does not offset the reduction in production income; therefore, the total gross margin of the farm is reduced by R19,125.

The impact of volumetric-based charging on the profitability and irrigation water use of a farm with high irrigation application efficiency is in direct contrast to that of a farm with low irrigation application efficiency farm. The farm with high irrigation efficiency will practice deficit irrigation to a larger extent on maize (i.e., 108 mm) and use the saved water to irrigate 31 ha more maize. Irrigation of a larger maize area increases the production income of maize (i.e., R909,335) without substantially increasing electricity costs (i.e., R756). Consequently, the expected gross margin of the farm increases by R86,764 when implementing volumetric water charges. Interestingly, the actual water abstraction of the farm with a high irrigation application efficiency, which was already lower than the quota, is further reduced by 4,638 m^3. Therefore, irrigators maximize profit rather than crop yield. The implication of the lower water abstraction for the WUA is that their income will decrease by R9,514 compared to a situation where the water quota would have been exceeded by 196,320 m^3 if area-based charges were applied.

A farm with low irrigation application efficiency could increase its profitability by R250,273 by improving its irrigation application efficiency under volumetric charges. Changing to a higher application efficiency requires intensive and extensive margin changes to realize a higher total gross margin. Intensive margin changes require a reduction in irrigation water application per hectare by 161 mm, 71 mm, and 106 mm for maize, wheat and popcorn, respectively, while the irrigated area of maize will increase by 31 ha. The impact of intensive margin reductions in irrigation water use is dominant, resulting in a decrease in actual irrigation water of 272,277 m^3.

5.2 Potential Hydrological Externalities

Changing to a volumetric water charging system may result in externalities. Deep percolation occurs when irrigation water application exceeds the soil's field capacity and indicates potential expected return flows in our analyses.

The first part of Table 2 shows the total water abstracted, the potential expected return flow and the net irrigation water use for farms with low and high application efficiencies when applying an area-based charging system. The farm with a low application efficiency abstracts 2,790,873 m^3 water, of which 692,063 m^3 potentially returns to the system as return flow. Thus, only 2,098,809 m^3 of water (i.e., net irrigation) is effectively removed from the system. Changing from a low to a high application efficiency is hydrologically

Table 2 Expected changes to farm-level hydrology when moving to volumetric-based charges

		AREA-BASED CHARGES (BASELINE)			**VOLUMETRIC-BASED CHARGES**		
		Irrigation Application Efficiency			Irrigation Application Efficiency		
				Low	Low	High	High
		Low	High	Changes relative to	Changes relative to baseline		
				High	Low	High	Low
Total abstraction (A)	m^3	2,790,873	2,523,234	-267,639	-216,873	-4,638	-272,277
Total potential expected return flow (B)	m^3	692,063	442,311	-249,752	-133,915	-41,770	-291,522
Net irrigation use (A-B)	m^3	2,098,809	2,080,923	-17,887	-82,957	37,132	19,245

beneficial since the net irrigation water use of the farm decreases, thereby increasing water availability by 17,887 m^3.

Changing from an area-based charging system to a volumetric system would reduce water abstraction and potential return flows. When the irrigation application efficiency remains low, implementing volumetric charges has a beneficial hydrological impact since net irrigation is reduced by 82,957 m^3. However, rebound effects occur when the irrigation application efficiency is high because potential expected return flows decrease by more than the total water abstraction. Consequently, net irrigation water use increases by 37,132 m^3 and 19,245 m^3, respectively, compared to the baseline high and the baseline low conditions.

6 Discussion

The results on irrigation water use showed a discrepancy between the amount of water billed by the WUA and the optimized water extraction by the farmers when area-based charging was applied. Irrigators with lower irrigation application efficiencies could apply more water per hectare to sustain high crop yields without being held accountable for exceeding their water quota because policing of water use is performed on hectares planted with a specific crop. Consequently, no incentive exists to conserve water, and more water is applied to the crops in most cases. On the other hand, irrigators with higher application efficiencies could use less water than the area-based estimates of the WUA. These irrigators forgo the opportunity to plant additional hectares while not exceeding their water quota if accurate water metering is enforced. Increasing irrigation application efficiency will always increase profitability since less water is required to produce the same crop yield. A concern with increasing efficiencies is the rebound effect, whereby increases in efficiency result in increased water resource depletion (Wheeler et al. 2020). The results showed that rebound effects are not a concern under area-based charges if irrigation application efficiency increases because irrigators are not allowed to make extensive margin changes.

Changing to a volumetric water charge that assumes that irrigation water use can be accurately metered and enforced changes the way irrigators value their water because the opportunity costs of their irrigation water use increase. Irrigators adopt deficit irrigation and use the saved water to profitably irrigate larger areas without exceeding their water quota. Implementing volumetric charging forces irrigators with low efficiencies to adopt more efficient technology because their farm gross margin is reduced if they do not adopt more efficient technology. Controlling irrigation water use through water metering causes rebound effects if farmers adopt more efficient irrigation technology since the saved water from improved efficiencies and deficit irrigation is used to irrigate larger areas. In such cases, return flows decrease because the water quota caps water abstraction, while consumptive water use increases due to an increase in irrigated areas.

7 Conclusions

An area-based water charging system that uses indirect water use measurements to control irrigation water use does not promote efficient water use because irrigators are not allowed to value water according to its true scarcity value. The conclusion of whether a volumetric-based water charging system will be better than area-based water charges is not straightforward because of differentiated impacts on profitability and hydrology. From a profitability perspective, volumetric-based water charges benefit irrigators using irrigation water more efficiently and volumetric-based charges incentivize irrigators with low efficiencies to adopt more efficient irrigation technologies. From a hydrological impact perspective, equating reduced water abstraction under volumetric-based water charges to water saving will be fatal without considering the impact on the broader hydrology through reduced return flows that may cause rebound effects. Furthermore, the rebound effects of volumetric-based water charges are more directly related to extensive margin changes than intensive margin changes.

8 Recommendations for Policymakers

Currently, the government emphasizes that irrigated agriculture should use water more efficiently since the belief is that small efficiency gains will result in large water savings because the sector is the largest water user. However, reduced water abstraction may not result in water savings because return flows might also be reduced. Detailed hydrological impact studies are therefore necessary to determine the impact of irrigators' responses on hydrology before implementing a policy to increase water use efficiency in the sector.

Changing to a system whereby control of irrigation water use is achieved through water metering will increase the scarcity value of water, which will trigger intensive margin responses and the adoption of more efficient irrigation technology, resulting in more efficient irrigation water use. If metering is not accompanied by measures to control consumptive use (i.e., extensive margin responses), water metering is likely to result in rebound effects.

The biophysical module in this study uses the FAO56 water budget calculations to simulate crop water use while using relative evapotranspiration to estimate crop yield. The hybrid solution procedure adopted in this research enables the incorporation of crop growth models such as AquaCrop (Steduto et al. 2012) into the analyses, thereby improving the crop yield response to water deficit estimates.

This study assumed that the farm decision-maker is risk neutral. However, the literature has shown that the decision-maker's attitude toward risk influences his intensive and extensive margin responses. Future research should therefore investigate how risk-averse decision-makers respond to volumetric-based charging.

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Data Availability The data are available from the corresponding author upon request.

Declarations

Consent to Publish All authors agree to publish the paper in the journal and the paper has not been submitted for consideration in other journals.

Conflict of Interest The authors declare no conflict of interest.

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