

WATER METERING INSTITUTIONS, SCARCITY SIGNALS, AND IRRIGATION EFFICIENCY: ECONOMIC IMPLICATIONS FOR WATER PRODUCTIVITY IN SOUTH AFRICA

INSTITUTIONS DE COMPTAGE D'EAU, SIGNAUX DE RARETÉ ET EFFICACITÉ DE L'IRRIGATION : IMPLICATIONS ÉCONOMIQUES POUR LA PRODUCTIVITÉ DE L'EAU EN AFRIQUE DU SUD

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ABSTRACT

Water scarcity in South Africa requires irrigation water to be used productively and economically efficiently. Recent legislation requires irrigation water abstractions to be measured and reported, but water user associations can transmit this measurement requirement through different metering institutions. This paper investigates how direct volumetric metering and indirect area-based metering affect irrigation behaviour, water productivity and the economic value of improved irrigation application uniformity. A nonlinear mathematical programming model is developed to optimise irrigation scheduling and crop allocation under water quota constraints for a 30.1 ha centre pivot. Crop responses to water stress are represented using FAO 56 soil water balance calculations, FAO 66 normalised water productivity principles and an AquaCrop-consistent biomass and harvest-index framework. Application efficiency is represented with different Christiansen uniformity levels by using multiple water budgets to capture distributional losses. The results show that metering institutions change how scarcity signals enter the farm objective function. Under indirect area-based metering, water charges are linked to crop area and estimated crop water requirements rather than measured abstraction. The marginal cost of an additional millimetre of water is therefore weak, and irrigators mainly respond to quota reductions by reducing irrigated area. Under direct volumetric metering, the water constraint is enforceable at the level of actual abstraction and the shadow value of water becomes explicit. Irrigators then use deficit irrigation and retain more irrigated area, improving water productivity and reducing income losses. The findings show that improved irrigation technology alone is insufficient to improve water productivity unless institutions effectively transmit water scarcity to irrigators.

Keywords: Water scarcity; mathematical programming; crop water requirements; income losses; water productivity.

RESUME

En raison de la rareté de l'eau en Afrique du Sud, il devient nécessaire d'utiliser l'eau d'irrigation de manière productive et économique. La législation récente exige que les prélèvements d'eau d'irrigation soient mesurés et déclarés, mais les associations d'usagers de l'eau peuvent transmettre cette exigence de mesure par le biais de différentes institutions de comptage. Cet article examine la manière dont le comptage volumétrique direct et le comptage indirect basé sur la surface affectent le comportement d'irrigation, la productivité de l'eau et la valeur économique de l'amélioration de l'uniformité des applications d'irrigation. Un modèle de programmation mathématique non linéaire est développé pour optimiser la programmation de l'irrigation et l'allocation des cultures sous contraintes de quotas d'eau pour un pivot central de 30,1 ha. Les réponses des cultures au stress hydrique sont représentées à l'aide des calculs de bilan hydrique du sol FAO 56, des principes de productivité hydrique normalisée

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FAO 66 et d'un cadre d'indice de biomasse et de récolte cohérent avec AquaCrop. L'efficacité de l'application est représentée avec différents niveaux d'uniformité de Christiansen en utilisant plusieurs bilans hydriques pour prendre en compte les pertes de distribution. Les résultats montrent que les institutions de comptage modifient la façon dont les signaux de rareté entrent dans la fonction d'objectif de la ferme. Dans le cadre du comptage indirect basé sur la surface, les taxes d'eau sont liées à la superficie cultivée et aux besoins en eau estimés des cultures plutôt qu'au prélèvement mesuré. Le coût marginal d'un millimètre supplémentaire d'eau est donc faible, et les irrigants répondent principalement aux réductions de quotas en réduisant la superficie irriguée. Dans le cadre du comptage volumétrique direct, la contrainte de l'eau est applicable au niveau de prélèvement réel et la valeur d'ombre de l'eau devient explicite. Les irrigants utilisent alors l'irrigation déficitaire et conservent davantage de superficie irriguée, ce qui améliore la productivité de l'eau et réduit les pertes de revenus. Les résultats montrent que l'amélioration de la technologie d'irrigation ne suffit pas à elle seule pour améliorer la productivité de l'eau, à moins que les institutions ne transmettent efficacement la rareté de l'eau aux irrigants.

Mots-clés : Rareté de l'eau; Programmation mathématique; Besoins en eau des cultures; Pertes de revenus; Productivité de l'eau.

INTRODUCTION

Water scarcity in South Africa requires irrigation institutions to promote both productive and economically efficient water use. Irrigated agriculture supports food security and rural development, but it is also the largest user of surface and groundwater. Improving irrigation efficiency therefore depends not only on better technology, but also on whether institutional arrangements transmit water scarcity to irrigators in a way that changes decisions on water applications, crop area and technology adoption (DWS, 2022; DWS, 2023b).

Recent reforms require irrigation water abstractions to be measured and reported. In practice, however, measurement can be implemented through different institutions. Direct volumetric metering measures actual abstraction at the farm level, while indirect area-based metering reconciles quotas using estimated crop water requirements and reported crop areas. These arrangements differ fundamentally in how water scarcity enters the farm decision problem and, consequently, how irrigators respond to a reduction in available water.

Ex-ante modelling is needed because farmer responses to water policy are not limited to reducing water use. Irrigators may adjust the intensive margin, by changing water applications per hectare, or the extensive margin, by changing the irrigated area. They may also adopt more efficient irrigation technology. These responses determine water productivity: the amount of crop output and economic return generated from the water abstracted or depleted. Modelling both margins is therefore essential for evaluating whether metering reforms improve water productivity or simply shift water savings into expanded production.

Existing water programming models often struggle to represent deficit irrigation and water productivity realistically. Yield reductions are determined by soil water content relative to crop-specific thresholds and by the growth stage in which stress occurs (Allen et al., 1998). FAO 66 further emphasises that biomass production should be linked to transpiration, not total evapotranspiration, because soil evaporation is non-productive water use (Steduto et al., 2012). A model of water productivity must therefore separate productive transpiration from non-productive evaporation and distributional losses. The objective of this paper is to develop and apply a nonlinear water productivity programming model that predicts irrigator responses to water metering institutions.

The model is used to compare direct volumetric and indirect area-based metering, evaluate low and high irrigation application uniformity, and assess how these choices affect irrigation behaviour, water productivity and farm-level economic returns under water scarcity.

MODELLING APPROACH

The model represents a profit-maximising irrigator operating a 30.1 ha centre pivot. Maize yield is linked to irrigation scheduling through a daily soil water balance. The soil water component follows FAO 56 dual crop coefficient logic to distinguish crop transpiration from soil evaporation (Allen et al., 1998). Biomass accumulation follows the FAO 66 and AquaCrop principle that normalised water productivity links biomass to transpiration rather than total evapotranspiration (Steduto et al., 2009; Steduto et al., 2012; Raes et al., 2023). Final yield is calculated with a harvest-index framework, and the model is calibrated to reproduce non-stressed AquaCrop biomass and yield.

Application non-uniformity is included by replicating the water budget for field portions receiving below-average, average and above-average water applications. Low and high uniformity systems are represented using different Christiansen uniformity levels (Christiansen, 1941). This procedure captures the fact that poor uniformity can force farmers to apply additional water to protect under-irrigated areas, while over-irrigated portions generate non-productive losses. Consequently, irrigation efficiency affects both water productivity and the economic return to technology adoption.

The economic model distinguishes income from crop yield and costs related to area planted, irrigation applications, electricity and water charges. The central policy mechanism is how measured water use enters both the objective function and the water-allocation constraint. The same physical production technology can therefore generate different behaviour because the metering institution determines whether water is treated as a variable input whose cost changes with actual application depth, or as an area-related charge linked to listed hectares.

Under direct volumetric metering, measured water use equals the actual irrigation depth applied multiplied by the irrigated area. The water tariff enters the objective function as a variable cost per cubic metre, and the allocation constraint limits actual abstraction. Each additional millimetre increases the marginal cost of irrigation and uses water that could otherwise support area expansion. This creates a positive shadow value of water under scarcity and encourages deficit irrigation where the value of saved water exceeds the yield loss (Tsur and Dinar, 1997; Scheierling, Young and Cardon, 2004; Grafton, Chu and Wyrwoll, 2020).

Under indirect area-based metering, measured water use is calculated as irrigated area multiplied by the crop water requirement used by the water user association. The water charge therefore varies with hectares irrigated, but not with the actual depth applied. Once a hectare is listed, an additional millimetre affects pumping and application costs but not the water tariff or measured quota use. The allocation constraint is consequently satisfied primarily by changing hectares, which weakens the scarcity signal and can reduce incentives for water productivity improvements (Jones, 2000; Lika, Galioto and Viaggi, 2017; Dono, Giraldo and Severini, 2010).

The baseline assumes a water listing of 30.1 ha and a maize water requirement of 638 mm/ha listed. For area-based charges, measured water use is 30.1 ha multiplied by 638 mm, irrespective of actual diversions. For volumetric charges, the same allocation limits actual diversions directly. This difference explains why the metering rules produce different intensive and extensive margin responses and different incentives to improve water productivity. The model is solved for water allocations between 520 and 700 mm/ha listed to derive response functions

Baseline outcomes are calculated for the current allocation and then compared with a 10% curtailment. The modelling framework can incorporate weather-state variation; the shortened conference paper focuses on the institutional mechanism and the representative response functions that explain how scarcity signals filter through to water productivity and economic returns.

RESULTS AND DISCUSSION

Technology-specific production functions

Both the low and high uniformity centre pivots achieve a maximum maize yield of approximately 17 ton/ha. However, the low-uniformity system requires about 640 mm to reach this yield, while the high-uniformity system requires about 600 mm. The 40 mm difference is non-productive water use caused by distributional losses. The result is important for water productivity: improved uniformity produces the same crop output with less applied water because a larger share of the applied water contributes to transpiration and biomass accumulation.

Response functions under volumetric and area-based charges

Under volumetric water charges, the farmer responds to the scarcity value of water. For the low-uniformity system, water allocations above about 640 mm/ha listed represent water-abundant conditions: the whole 30.1 ha is irrigated and application rates do not increase further. Between about 580 and 640 mm/ha listed, land is limiting and the farmer uses additional water to increase application rates. Below about 580 mm/ha listed, water becomes the limiting resource and the farmer reduces irrigated area while maintaining an application rate that remains economically viable. The high-uniformity system follows the same logic, but reaches the water-abundant point at about 599 mm because it produces the same yield with less water.

Area-based charges create a different response because the charge is linked to hectares planted rather than actual irrigation diversions. The marginal factor cost of applying an additional millimetre is therefore limited to pumping and application costs. The farmer consequently applies irrigation close to the water-abundant optimum and responds to reduced quota allocations mainly by reducing hectares. Improved uniformity still raises physical water productivity by lowering the water required per hectare, but the private financial incentive is weaker because the farmer is not rewarded directly for abstracting less water than the area-based estimate.

Baseline outcomes

The baseline results illustrate the importance of distinguishing actual and measured water use. With area-based charges, both uniformity levels are measured as using the full allocation of 192 038 m³ because the full 30.1 ha is irrigated. Actual use differs: the low-uniformity system abstracts 1 545 m³ more than measured, while the high-uniformity system abstracts 11 364 m³ less than measured. With volumetric charges, measured and actual use are equal, so the farmer is financially rewarded for the lower water requirement of the high-uniformity system. This difference explains why metering institutions influence the economic value of water productivity improvements.

Table 1. Baseline outcomes for volumetric and area-based water charges

Indicator	Unit	Volumetric charges	Volumetric charges	Area-based charges	Area-based charges
		Low uniformity	High uniformity	Low uniformity	High uniformity
		Low	High	Low	High
Irrigation application	mm	638.00	598.91	643.13	600.25
Hectares planted	ha	30.10	30.10	30.10	30.10
Maize yield	ton/ha	16.99	17.00	17.00	17.00
Water use: actual	m ³	192 038	180 272	193 583	180 674
Water use: measured	m ³	192 038	180 272	192 038	192 038
Margin above specified costs	R	506 894	513 593	507 215	510 435
Electricity costs	R	37 357	34 529	37 658	34 573
Water tariff	R	52 964	49 719	52 964	52 964

Direct responses to a 10% water allocation reduction

When the allocation is reduced from 638 to 574 mm/ha listed, volumetric charges encourage a combination of lower application rates and small area reductions. The low-uniformity system reduces application rates by 58 mm and area by 0.30 ha, while the high-uniformity system reduces application rates by 15.8 mm and area by 0.46 ha. Yield reductions are small because the production function is flat near maximum yield, but the water saved has value under volumetric metering. This is the mechanism through which direct metering promotes deficit irrigation and improves economic water productivity.

Under area-based charges, the same 10% curtailment produces almost no change in application rates. The direct response is a 3.01 ha reduction in irrigated area for both uniformity levels. Profit losses are much larger than under volumetric charges because the farmer sacrifices crop area rather than using water productivity gains from small yield reductions and lower application depths. The result shows that indirect metering can discourage the intensive-margin adjustments needed for efficient deficit irrigation.

Table 2. Direct margin responses to a 10% reduction in the water allocation

Indicator	Unit	Volumetric charges	Volumetric charges	Area-based charges	Area-based charges
		Low uniformity	High uniformity	Low uniformity	High uniformity
		Low	High	Low	High
Irrigation application	mm	-58.0	-15.8	0.2	0.6
Hectares planted	Ha	-0.30	-0.46	-3.01	-3.01
Maize yield	ton/ha	-0.4	-0.2	-	-
Water use: actual	m ³	-19 204	-7 438	-19 294	-17 904
Water use: measured	m ³	-19 204	-7 438	-19 204	-19 204
Margin above specified costs	R	-21 354	-16 469	-49 934	-50 377
Electricity costs	R	-3 864	-745	-4 554	-4 111
Water tariff	R	-5 296	-2 051	-5 296	-5 296

Indirect responses from improving application uniformity

Improving application uniformity reduces the water needed to sustain yield. Under volumetric charges, changing from low to high uniformity allows the farmer to comply with the 10% curtailment mainly through a 54.85 mm reduction in application depth and a small 0.46 ha area reduction. The margin above specified costs decreases by R 9 770, much less than the direct low-uniformity response. Under area-based charges, the same technology improvement reduces actual water use by 30 814 m³, but the farmer still reduces area by 3.01 ha because the measured quota is area-based. The water productivity benefit is therefore not fully converted into a private financial benefit.

Table 3. Indirect margin responses when changing from low to high uniformity

Indicator	Unit	Volumetric charges	Area-based charges
Irrigation application	mm	-54.85	-42.29
Hectares planted	ha	-0.46	-3.01
Maize yield	ton/ha	-0.15	0.00
Water use: actual	m ³	-19 204	-30 814
Water use: measured	m ³	-19 204	-19 204
Margin above specified costs	R	-9 770	-47 158
Electricity costs	R	-3 573	-7 197
Water tariff	R	-5 296	-5 296

Responses to institutional change

Changing from area-based to volumetric metering alters the incentive structure. Farmers are no longer only constrained by listed hectares; they face the direct opportunity cost of each cubic metre abstracted. The low-uniformity system responds with a 63.13 mm reduction in application depth and only a 0.30 ha reduction in area. The high-uniformity system reduces application depth by 17.09 mm and area by 0.46 ha. Despite small yield losses, margins decrease less than under area-based curtailment because the farmer retains productive area and uses water more efficiently. Institutional reform therefore changes both water productivity and the source of returns to irrigation efficiency.

Table 4. Responses to a 10% curtailment when changing from area-based to volumetric charges

Indicator	Unit	Direct responses	Direct responses	Indirect response
		Low uniformity	High uniformity	Low to high
		Low	High	Low to high
Irrigation application	mm	-63.13	-17.09	-59.98
Hectares planted	ha	-0.30	-0.46	-0.46
Maize yield	ton/ha	-0.40	-0.16	-0.16
Water use: actual	m ³	-20 749	-7 840	-20 749
Water use: measured	m ³	-19 204	-19 204	-19 204
Margin above specified costs	R	-21 675	-13 310	-10 091
Electricity costs	R	-4 166	-789	-3 875
Water tariff	R	-5 296	-5 296	-5 296

PRACTICAL IMPLICATIONS

The results support the argument that irrigators should increasingly manage irrigation water to maximise profit and water productivity rather than simply meet crop water requirements. The metering rule filters through the objective function by changing the marginal cost of actual water application. Area-based metering encourages farmers to view water reductions as area reductions because the water charge is attached to hectares. Volumetric metering makes the scarcity value of water explicit and creates an incentive to use deficit irrigation where yield losses are small relative to water and cost savings.

The analysis also shows why FAO 56 and FAO 66 concepts are important for policy modelling. Water productivity cannot be evaluated from applied water alone, because some water becomes productive transpiration while some is lost as evaporation, drainage or non-uniform over-application. By separating soil evaporation from transpiration and linking biomass to normalised water productivity, the model identifies whether metering institutions improve productive water use or merely change measured abstractions.

The practical policy implication is that compulsory direct measurement should not be implemented as an isolated administrative reform. It should be accompanied by decision-support information for irrigators on deficit irrigation, crop water productivity and the economic value of improved uniformity. Catchment managers should also consider rebound effects because field-level water savings may be used to expand irrigated area if saved water remains available to the same irrigator (Wheeler et al., 2020).

CONCLUSIONS

This paper developed a nonlinear water productivity programming model to evaluate how water metering institutions affect irrigation behaviour and economic returns. The model links FAO 56 soil water balances, FAO 66 normalised water productivity principles, AquaCrop-consistent biomass and harvest-index calculations, irrigation application uniformity and a farm-level profit objective. This structure allows the analysis to show how scarcity signals enter the objective function and translate into intensive and extensive margin responses.

- High application uniformity improves physical water productivity by reducing the water required to reach near-maximum maize yield from about 640 mm to 600 mm.
- Indirect area-based metering weakens the scarcity signal because water charges are linked to hectares and estimated crop water requirements. A 10% allocation reduction therefore leads mainly to extensive-margin responses, with a 3.01 ha reduction in irrigated area.
- Direct volumetric metering internalises scarcity by linking measured use and water charges to actual abstraction. Farmers respond by reducing application rates, retaining more irrigated area and using deficit irrigation to improve economic water productivity.
- Improved application uniformity has greater private value under volumetric metering because farmers are financially rewarded for lower actual water use. Under area-based metering, physical water savings are not fully reflected in the objective function.
- Direct metering can create rebound risks where saved water is used to expand irrigation. Water productivity policy should therefore evaluate field-level efficiency together with catchment-scale consumptive use.

The study demonstrates that institutional arrangements for water measurement shape farmer behaviour, the economic value of irrigation technology and the water productivity outcomes of irrigation policy. Technology improvements are most effective when metering institutions transmit scarcity signals clearly to water users.

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