How to promote the sustainable use of water: The Sao Marcos Basin Case Study

Flavio M. Menezes[1], Morganna W. Capodeferro[2], Juliana J. Smiderle[3], Pedro E. Guimarães[4]

ABSTRACT: The conflicting demands for water from irrigating perennial crops, generating power, and supplying humans and livestock have placed many river basins around the world under stress. These conflicts are being and will continue to be exacerbated by the impact of climate change. Here we expound a methodology, based on economic theory, that allows the estimation of the implicit value of the water for irrigation purposes. In turn, these implicit values can be employed to determine the amount to be charged for water to promote sustainable outcomes. The methodology is developed and applied in the context of Brazil's Sao Marcos River Basin, where agriculture and hydroelectricity generation activities compete for the existing water resources. We show that current water charges would have to increase by over 270 times to reduce the water consumption in the basin to a sustainable level.

Water is essential to life and civilization. While the supply of basic water to humans and livestock is vital to their survival, water is also vital to maintain downstream river health, which sustains fish and wildlife and protects ecosystem services[1]. The twin forces of economic and population growth have led to a rising demand for water, especially as input for food and energy production[2,3]. Moreover, climate change, through increases in the instances of severe droughts and their intensity, will continue to disrupt supply[4,5].

The combination of increased demand for water and the impact of climate change on water supply has placed many of the world's river basins under stress. For example, recent research finds that the 10% most stressed basins include approximately 19%, 19% and 35% of global population, thermal electricity generation and irrigated calorie production, respectively[6]. It stands to reason that the (implicit) value of water varies considerably across its different uses in each river basin, but also across different river basins.

Growing different crops in a river basin requires different quantities of water per unit produced, and different crops attract distinctive market prices. Growing the same crop across distinct river basins will likely require different water quantities per unit of output as the mix of other inputs such as climate conditions and soil types change.

The water value upstream of five hydropower plants in a given river basin is higher that the water value upstream of four of the hydropower plants. The water upstream of

[1] Professor of Economics, The University of Queensland.
[2] COPPE and FGV CERI
[3] Poli/UFRJ and FGV CERI
[4] EPGE and FGV CERI

five plants can be used to generate electricity through five powerplants, while the same amount of water upstream of four plants can only be used to generate through the four plants. The (implicit) value of the water used to generate electricity across different river basins will vary according to the economic value associated with water use in each basin.

Our contribution is to describe a methodology that allows the estimation of the implicit value of the water in some of its uses. This methodology is based on economic theory and the notion that businesses, such as commercial farms, choose inputs to maximize profits. The methodology is developed and applied in the context of Brazil's Sao Marcos River Basin, where agriculture and hydroelectricity generation activities compete for the existing water resources.

Understanding and measuring the implicit water value across different uses and basins is crucial for determining the most cost-effective way to promote sustainability.

SMRB water conflict background

SMRB is a small river basin that is part of the Paranaiba River Basin (**Fig. 1**). The Paranaiba River Basin plays an increasingly important role in logistics as it connects the Southeast and Midwest regions of Brazil. The Basin accounts for a significant amount of hydroelectricity generation.

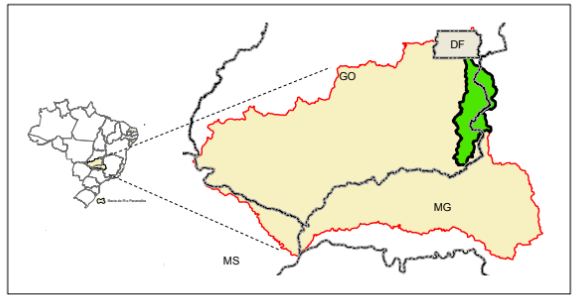

Fig. 1 The Sao Marcos River Basin's Location. The red line shows the Paranaiba River Basin and the green area the Sao Marcos River Basin (ref.[7]).

The Sao Marcos River is a federal river, located on the state border between Goias and Minas Gerais. As a federal river, it is managed by the National Water Agency (NWA). In the SMRB, there are also some tributaries that are managed by the states. The presence of state and federal management bodies in the basin adds complexity to resource management. This is especially relevant in the SMRB, which is characterized by over-use of water resources by agriculture.

The SMRB is rapidly expanding their agricultural frontier. The upstream area (Alto Sao Marcos) has a well-developed agricultural sector focused on grain and fresh produce production[8]. The basin has also strong agroindustry activities mostly related to the sugarcane supply chain[7]. In 2018, the two municipalities with the highest concentration of irrigated area in the basin, Cristalina (in the state of Goias) and Unaí (in the state of Minas Gerais), generated approximately US$ 610 million in grain production (soybeans, beans, corn), potatoes and high-valued crops such as garlic and coffee. In the national context, these two municipalities ranked 11th and 24th, respectively, in terms of the value of agricultural production[9].

Recent data shows that in 2017 there were approximately 111,933 hectares of irrigated area and 1,369 central pivots in the SMRB[10]. Central pivots are the most widely used irrigation technique in the region[8], which made the basin the second largest central pivot irrigation scheme in Brazil[11]. From this total irrigated area, 87,486 hectares (78%) and 1,076 central pivots are located in Alto São Marcos (upstream from the Batalha HPP - *Fig. 2*).

The large areas occupied by these pivots and the circular characteristics of these structures have enabled NWA to follow the evolution of the irrigated area in the region since 2010 through satellite images (**Fig. 4a**).

The irrigated areas grew at record rates between 2010 and 2014, with an increase of about 4,775 hectares per year in Alto São Marcos. This unprecedented growth was likely related to the worldwide increases in food prices. Moreover, if the growth rates observed in the period 2014-2017 are maintained in the 2017-2020 period, we estimate that there will be 92,526 hectares of irrigated area in Alto São Marcos by the end of 2020 (**Error! Reference source not found.a**). We note that irrigated agriculture has expanded despite the water restrictions that were imposed due to the presence of Batalha HPP, which is located downstream from most of the basin's irrigators. This will be discussed next.

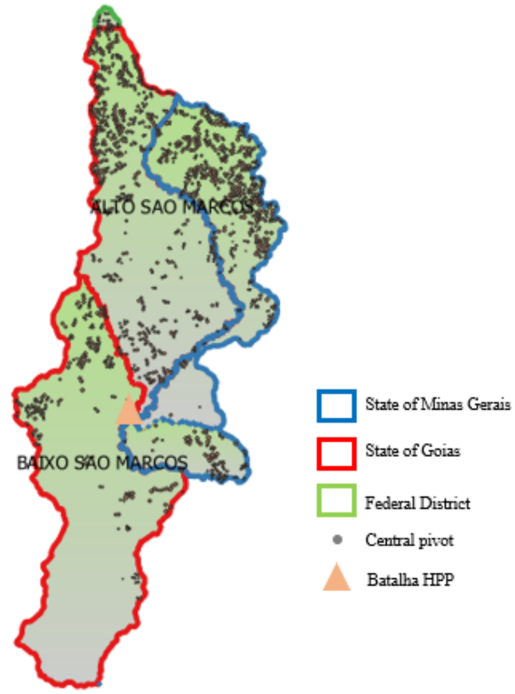

Fig. 2| The Sao Marcos River Basin division and central pivot location

The Batalha HPP is a hydroelectric power plant located on the Sao Marcos River, on the border between the municipalities of Cristalina, in the state of Goiás, and Paracatu, in the state of Minas Gerais. The Batalha HPP has 52.5 MW of installed capacity and started operating in 2014. The plant's electricity generation was contracted at auction at approximately US$ 60 per MWh[12]. Since it began operation, the plant has generated enough energy to supply about 6 million residential consumers[13,14]. Despite its relative low power capacity, Batalha HPP's reservoir regulates the river flow and allows for energy gains through the cascade of plants along São Marcos, Paranaíba and Paraná rivers (**Fig. 3**).

All HPPs in the cascade (including the Batalha HPP) account for a combined 26,442.3 MW of installed capacity, and are capable of producing 1.52 KWh per m^3 of water[15].

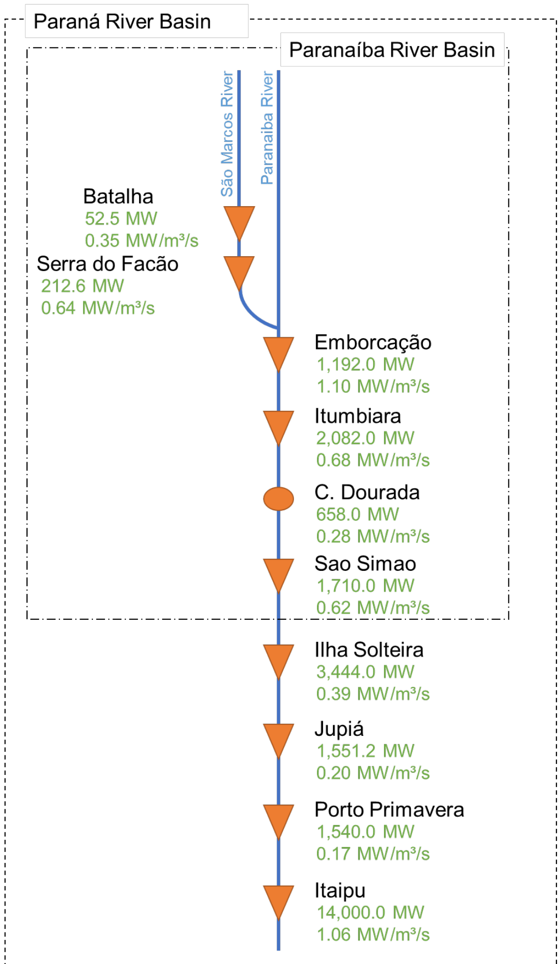

Fig. 3| HPPs located in the Paranaíba River Basin [16].

The conflict over water use in the SMRB has its origins in the regulatory approval processes for the construction and operation of Batalha HPP, which required two key permits: a permit to access water issued by the NWA and a permit to generate electricity from the National Electric Energy Agency (NEEA). However, as described below, the regulatory processes are convoluted and lack internal consistency.

The NWA approved Batalha HPP's pre-permit in 2005, allowing access to all the affluent flow minus a share reserved for irrigation. In that same year Furnas-Centrais Elétricas[17] won the concession to construct and operate Batalha HPP conducted by NEEA and, in 2008, the NWA converted the pre-permit into a water permit, maintaining the same conditions established in the pre-permit. The water permit defined the share allowed for irrigation purpose as **Fig. 4b** shows.

By 2010, the monitoring of irrigated areas conducted by the NWA revealed that the current consumption upstream from the Batalha HPP had already approached the limit that was only to be reached at the end of the concession period in 2040. Of course, less water available for Batalha HPP also meant less water for the downstream HPPs.

To address the upcoming conflict in water use, the NWA estimated that irrigation had a higher value use than hydroelectricity generation, suggesting potential gains from reallocating water in favor of agriculture[15]. The NWA proceeded to issue the SMRB Water Resource Framework, which recommended the allocation of water for irrigation[18], and led to the Batalha HPP's permit downward revision in 2010[19]. The NWA increased the upstream consumption flow's limit, as presented in **Fig. 4c.**

The reduction in Batalha HPP's water allocation resulted in a reduction in its physical guarantee; the expected amount of electricity supplied by each plant, weighted by its value to the system[20]. This reduction, however, did not breach electricity sector legislation. According to the permit revision conducted in 2010, the allowed maximum reduction of physical guarantee would occur only in 2040. (Error! Reference source not found. **c**).

Even with such reallocation in favor of irrigators, the demand for water from irrigators in the medium to long-run will still outstrip the total amount allocated[16]. To solve this longer-term excess demand crisis, the Paranaíba River Basin Committee (PRBC) – a multi-jurisdictional committee with representatives from water users and the broader society, who have the ultimate responsibility for defining water allocations priorities – intervened. The PRBC decided that irrigation would have priority use upstream from the Batalha HPP[21].

In practice, this meant a reallocation of water for the benefit of agriculture. However, Batalha HPP's permit has not been revised yet, and so the issue is yet to be resolved.

The description above highlights how the often-conflicting interests of different parties influence water allocation and economic outcomes. Ultimately this political economy leads to unsustainable water allocations. The key issue then for policymakers is to develop sustainable water allocation mechanisms that are cost-effective and can resolve the over-use problem. One such mechanism is water pricing, which is discussed in the next section.

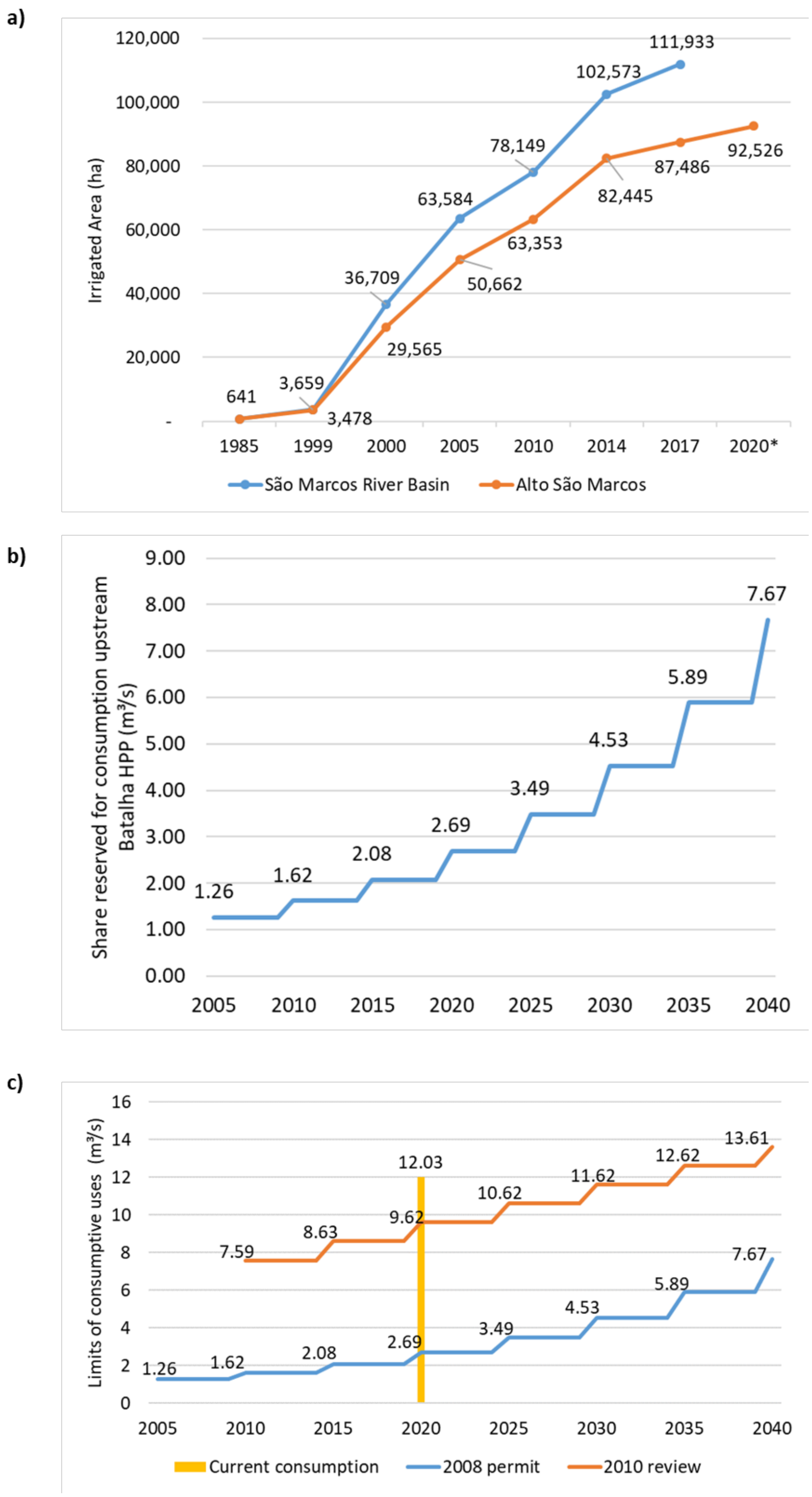

Fig. 4| SMRB water conflict background. a) Evolution of the irrigated area in SMRB. b) Share reserved for consumption upstream from Batalha HPP (ref. [31]). c) Limits of consumptive uses upstream from Batalha HPP. We estimate current consumption based on the 2020 irrigated area estimation and the average irrigator consumption (ref. [15]).

Water charges in the Paranaíba River Basin

In 2016 the PRBC proposed water charges for the federal components of the Paranaíba River Basin. However, users only began to be charged for the abstraction of water and effluent discharge in 2018. The amount paid for the abstraction of water is calculated using a formula that multiplies the following elements: (i) the Unitary Public Price (UPP); (ii) a weighting between the measured volume abstracted and the volume allocated to the user through a permit; and (iii) a k coefficient, which varies according to the quality of the water abstracted and the user sector.

There are two issues concerning the setting of UPP. First, prices are set by river basin committees generally based on an assessment of the impact these prices will have on water users' costs[22]. That is, affordability is favored over valuing the resource. Second, the decision regarding the UPP value is predominantly political, and not technical[22]. Committees' membership includes water users, who have the incentive to keep prices low.

The PRBC proposed progressive UPP values. In the first two years, the UPP for water abstraction would be equal to US$ 0.004 for m^3 of abstracted water. This value would increase yearly after the second year until the fifth year, reaching US$ 0.0063 for m^3 of abstracted water[23]. Nevertheless, the progressivity of UPP values has only changed slightly over the years, reaching already in 2020 the value of US$0.0061 for m^3 of abstracted water[24,25].

For the agriculture sector, the k coefficient is equal to 0.10. If the abstraction is done in a private reservoir or if the reservoir was built with the irrigator's own resources, the k coefficient changes to 0.07. This implies that the current charge paid by irrigators can be as little as US$ 0.0004 for the m^3 of water abstracted. In practice, the application of the k coefficient implied that while irrigators represented 90% of the users subject to water charge in the basin in 2018, they accounted for only 8% of the amount collected[26].

Not only are the price levels inadequate – as irrigators account for a disproportionally low fraction of the revenue collected, but the price structure is also flawed. When water is scarce, efficiency requires that water is allocated to the highest-value user. The existing charges, however, do not distinguish between its various uses. This means that when water is scarce, at current prices, some users are abstracting too much water from an efficiency perspective, and other users are abstracting too little.

In other words, by reallocating water from low-valued users to high-value users, we can increase the total value of what is produced using the same total amount of water. As the Parnaiba River Basin is one of the leading food producing hubs in the country[8], the potential gains from reallocating water to high-valued users is high. The next section shows how to determine a water charge to promote the efficient use of water.

Estimating the implicit value of water value

In what follows we estimate the implicit value of water for irrigated agriculture in the Alto São Marcos. That is, we estimate the value of water charges upstream from Batalha HPP that should be charged. These charges would reduce water consumption to the level of the total amount under permits in an efficient way.

To estimate the water value for each irrigator located in the Alto São Marcos, we adopted the residual imputation approach[27]. This is the most frequently used approach to estimate the shadow pricing for irrigation water. The NWA has also adopted a similar approach to estimate the water value in the upstream area of SMRB[15].

In the residual imputation approach, the unit water value is the difference between the revenue and the expenses of the crop production divided by the water consumption. The method we propose in this paper differs from the one used by the NWA in terms of the methodology used to calculate each user's revenue and expenses. The study conducted by the NWA considers the possibility of producing in dryland during the rainiest periods and its implications in the calculation of the water value. In our analysis we consider that all production depends on irrigation. Our contribution is in the use of more basin-specific sources for revenue and cost estimates. While the NWA study was based on data from the Preto River Basin, which is located close to the SMRB, we explored production cost data from the municipalities of Cristalina and Unaí – two of the municipalities with the highest concentration of irrigated area in the basin. Moreover, we used energy tariff data from the state of Goiás, where most of the basin is inserted, instead of data from the Federal District, like the NWA used.

We estimate the water value for 21 irrigators located in the Alto São Marcos who hold permits. The reason for limiting the analysis to these irrigators is that data in rivers managed by state agencies within the Basin is not available.

We estimate water value per m^3 considering the 2019 annual production of irrigators in three production cycles of the following crops: corn, beans and/or soybeans. The results will be discussed later in the paper.

Estimating economic loss in the SMRB

This section estimates the economic loss that would result from restricting the expansion of irrigated agriculture so as not to surpass the allocation as defined in the permit revision of 2010. If irrigated agriculture continued to expand without water restrictions, this could result in higher income produced in the basin, including more jobs. These foregone benefits may be larger than the value of the hydroelectricity that could be generated. Our analysis compares the implicit water value for irrigation with that for electricity generation.

We consider the "marginal cost of operation" (MCO) as the estimate of water value for electricity generation. The MCO measures the cost of generating one additional MW by the next lowest cost power plant if there is no water to generate electricity from a given power plant. As Batalha HPP is upstream of other power plants, the MCO reflects the fact that if there is no water to generate an additional MW of electricity from Batalha HPP, then there is also no water to generate additional MWs from the cascade of plants. (**Fig. 3**).

The methodology we adopt to calculate the water value for electricity generation differs substantially from that used by the NWA, which used the revenues and expenses of power generating companies located in the cascade of plants as variables. However, the hydrothermal-eolic Brazilian energy system is interconnected, providing energy transfer between generation subsystems. Thus, the value of water to the sector includes the appropriate reduction in operating costs (MCO) and an increase in energy security to the whole system from the availability of water. This value far exceeds the private benefits to the power plant owner of additional water which were measured by the NWA.

We compute the economic losses in the basin by computing the volume of water that would have to be shifted from agricultural production to power generation, and the values associated with the various uses of water.

Results and discussion

Based on the implicit water value for irrigation (**Table 1**) we construct the factor demand curve for water in the Alto São Marcos (**Error! Reference source not found.a**). This curve indicates the demand for water as a function of its price given current market conditions such as crop prices and production costs. For illustration purposes, we also present in **Fig.5.a** the maximum value charged for the agriculture sector (when k is equal to 0.10) as defined by PRBC. We note that even the user with the lowest willingness to pay for water would still be willing to pay more than the current charge.

We estimate that currently there are 92.526 hectares of irrigated area in Alto São Marcos (**Fig. 4a**). This corresponds to 12.03 m^3/s of water consumption, assuming that the average irrigator consumes 0.13 L/s per hectare[28], and an annual volume of 379,378,080 m^3. Batalha HPP's permit predicted that by 2020 this consumption should be limited to 8.63 m^3/s or 272,155,680 m^3 per year. Therefore, in order for water use in the basin to be in line with the permit, irrigators would have to reduce their consumption by 28.3%.

From the estimated demand curve, we infer that to reduce demand by 28.3% on federal rivers in the Basin, the volume of water would need to be rationed to 15,446,38 m^3. Users that are not willing to pay the amount that is associated with this volume on the demand curve (that is, US$ 0.16/m^3) would be rationed. We note that this price is almost 270 times the amount currently charged for irrigators in the region (when k=0.10). According to our analysis, a water charge of US$ 0.16/m^3 would lead to water being used by the most efficient users and consumed at sustainable levels.

By estimating the value of water for energy production and the water value for irrigation from 2010 to 2019, we conclude that agriculture was the highest value use for four of the ten years. That is, mostly water is more valuable when used in agriculture (**Fig. 5b**). We note that due to a reduction in commodity prices and an increase in production costs, the average of the water value for irrigation was negative in 2018. This highlights the relevance of market conditions in determining the efficient use of water.

Importantly, if the volume of water that has been used above the Batalha HPP permit limit since 2010 (**Fig. 5c**) were reallocated to the electricity sector, the economic loss would have been approximately US$ 101 million for the ten-year period. This corresponds to 17% of the value of the annual production of the two largest municipalities in the SMBR. That is, the award of the permit to Batalha HPP came with significant societal costs, which were only avoided by the use of water in an unsustainable way.

In the absence of mechanisms to compensate the power plant for its voluntary relinquishment of the permit, a water charge of US$ 0.16/m^3 would ensure that the future water use by irrigators would be constrained to the overall limits, and limited to their most (constrained) efficient use. That is, such price represents the least cost way, in terms of efficiency, for rationing water to irrigators so as to achieve a sustainable level of water consumption.

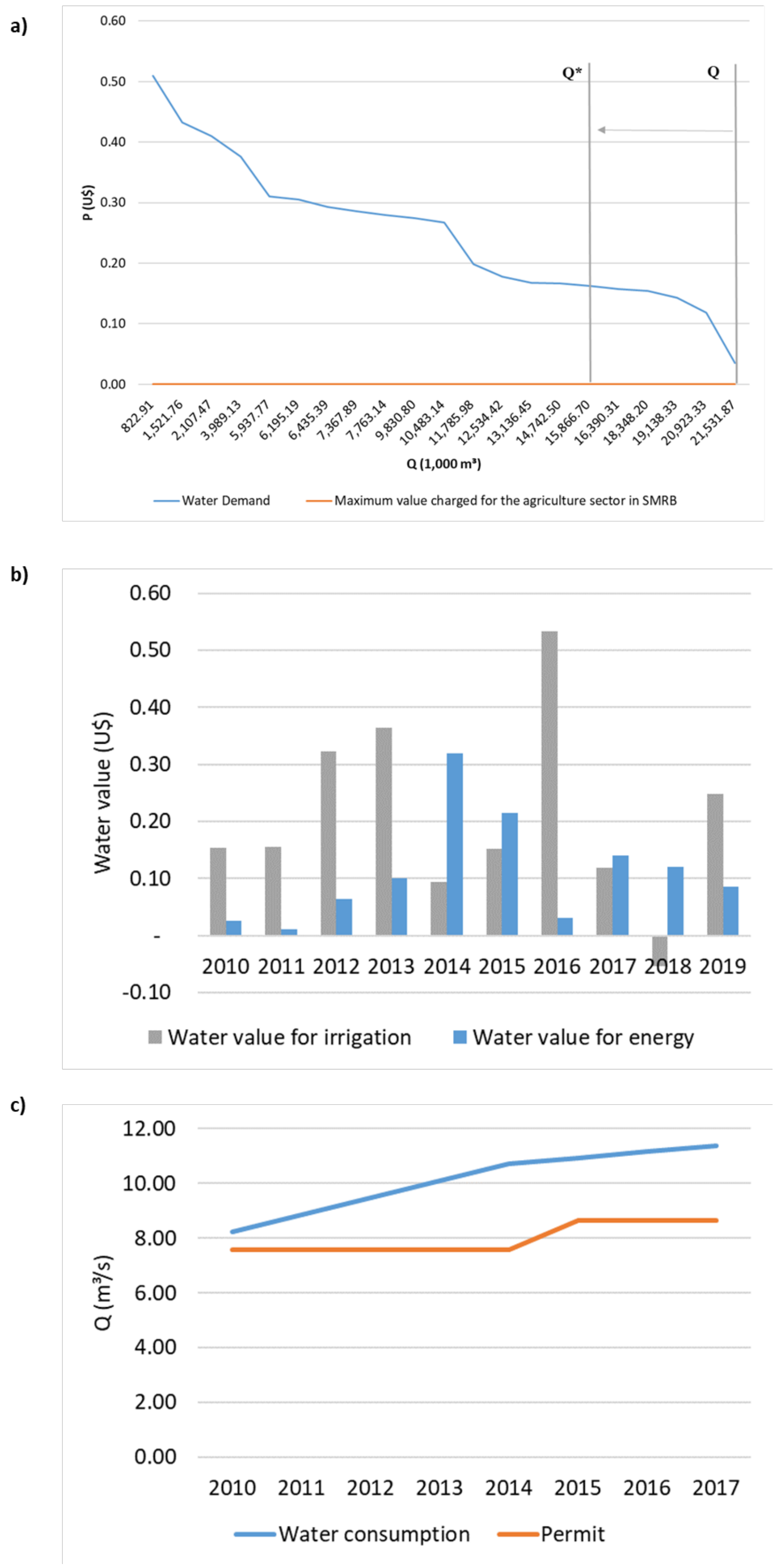

Fig. 5| *Results. a)* *Theoretical factor demand function for water in the Alto São Marcos.* ***b)*** *Water value for irrigation and energy production from 2010 to 2019.* ***c)*** *Real consumption of water upstream from Batalha HPP and limits of consumptive uses defined in Batalha HPP's permit (ref.*[19]*).*

Conclusion

Existing conflicts over water use in river basins around the world are likely to be exacerbated due to climate change. The Sao Marcos Case study highlights the inherent difficulties in operating complex regulatory arrangements aimed at achieving sustainable water consumption levels. Such arrangements are prone to capture by water users, administrative errors, and political interference. Market instruments, including prices, albeit not perfect, have a better shot at promoting sustainability.

Methods

The residual imputation approach for estimating the implicit water value starts with the maximization of an irrigator's profit[27]:

$$\max_{(x_1,\dots,x_n,x_w)} \left\{ P \cdot f(x_1,\dots,x_n,x_w) - P_w \cdot x_w - \sum_{i=1}^{n} P_i \cdot x_i \right\} \quad (1)$$

Where P represents the price of the crop; f is the production function; P_i is the price of the production factor i; x_i represents the quantity of production factor i (e.g., labor, land, etc.); P_w is the price of water; and x_w is the amount of water.

Assuming that crops and all production factors markets are perfectly competitive, prices may be treated as constants. Thus, by applying the first order condition for each production factor, we obtain:

$$P_w = P \cdot \frac{\delta f}{\delta x_w} \quad (2)$$

$$P_i = P \cdot \frac{\delta f}{\delta x_i} \quad (3)$$

That is, the competitive price of water or any other production factor is equal to its marginal productivity.

If the production function f is homogeneous in the first degree (i.e., f(tx)=tf(x)), we can apply Euler's theorem (compute the first derivative with respect to t and evaluate it at t=1). So, the production function can be written as:

$$f(x_1,\dots,x_n,x_w) = x_w \frac{\delta f}{\delta x_w} + \sum_{i=1}^{n} x_i \cdot \frac{\delta f}{\delta x_i} \quad (4)$$

Multiplying (4) by P and substituting it with (2) and (3), we may obtain:

$$P_w = \frac{P \cdot f(x_1,\dots,x_n,x_w) - \sum_{i=1}^{n} P_i \cdot x_i}{x_w} \quad (5)$$

To estimate the first element of equation 5, representing the irrigator's gross revenue, we use the information in the irrigators' permits about their annual production, including the number of productive cycles in each year. In general, we observe the alternation between the planting of legumes (for example, bean) and the planting of grass (for example, corn) in the region. In some instances, we had to adapt the information presented in the permit and assume the sequencing of the productive cycles. This was necessary in cases where the permit indicated the production of only one crop and at the same time the use of irrigation throughout the year. In these cases, it was assumed that the irrigator had 3 production cycles with soybean, bean, and corn rotation.

Based on the production cycles, we calculated the income of these irrigators by considering the productivity and price for each crop. Average productivity for the region is estimated at 10,250 kg per hectare for corn; 3,000 kg per hectare for beans and 3,300 kg per hectare for soybeans[15]. The average prices of these products in the state of Goias in 2019 were US$ 0.83 for bean, US$ 0.13 for corn and US$ 0.31 for soybean[29]. We chose the state of Goias as the representative of the basin because approximately 72% of the basin's area is within the limits of that state (**Error! Reference source not found.**). The irrigator's revenue was then calculated by multiplying these variables by the irrigated area indicated in each permit.

We then used the average costs of production in 2019 in the municipalities of Cristalina, in the state of Goiás (for bean and soybean) and of Unaí, in the state of Minas Gerais (for corn), both located in the SMRB, to estimate the second element of equation 5, representing the irrigator's cost. For beans the costs of production were estimated in US$ 1,248.25 per hectare, for corn US$ 1,122.40 per hectare and for soybean US$ 812.87 per hectare[30]. These costs include seeds, fertilizers, planting and harvest expenses.

We consider that on average one irrigated hectare consumes 531 kWh of energy[15]. A typical irrigator in the region lifts the water to an average gross manometric height of 188 meters[15], and thus 531 kWh allows irrigator to transport on average 1,040 m^3 of water. The cost of electricity was based on the average rate charged in the "irrigated rural" category in 2019 by the largest electricity distributor in the region, CELG-D. (US$106.53 per MWh[14], or US$ 56.97 per hectare, or US$ 54.96/1,000 m^3).

The implicit water value for irrigation was calculated from the irrigator net revenue and the volume of water used annually by them, according to their permits.

We estimate the value of water for electricity generation as follows:

$$Water\ value(energy) = MCO\ \left(\frac{R\$}{MWh}\right) x\ productivity\ \left(\frac{MWh}{m^3}\right) \quad (6)$$

The comparison between water values for irrigation and energy production in the period between 2010 and 2019 was made varying the prices and production costs in irrigation (**Supplementary Table 1**) and the average MCO in those years (**Supplementary Table 2**). We calculated the value of water in all years for the same irrigators, assuming that the same permits would be in effect. Thus, for example, we assumed that the permits issued in 2017, were a renewal of existing permits to existing irrigators.

The economic loss was calculated for each of the years when the water value for irrigation exceeded the value for electricity production. Year by year we multiplied the volume of water used in excess by agriculture by the difference between the water value for the electricity sector and the average water value for irrigation (**Supplementary Table 3**). The total economic loss if permits were enforced was calculated by adding the economic losses in each year throughout the analyzed period as in Equations 7 and 8.

$$WL_{year} = \left(V_{abst} - V_{permit}\right) x\ \left(\frac{1}{n}\sum_{i=1}^{n} WV_{irrig} - WV_{elect}\right) (7)$$

Where: WL_{year}= economic loss in a year;

V_{abst} = abstracted volume in that year;

V_{permit}= allocated volume in that year (permit);

n= quantity of irrigators who have water permits issued by the NWA;

WV_{irrig}=water value for irrigation in that year; and

WV_{elect}= water value for electricity generation.

$$WL_{total} = \sum_{i=year} WL_{year}\ ;\ year = 2010;\ 2011;\ 2012;\ 2013;\ 2016;\ 2019. \quad (8)$$

Data availability

The data that support the analysis developed in this study are available within the paper and its Supplementary Information files.

References

1. Postel, S. L. *Securing water for people, crops, and ecosystems: New mindset and new priorities*. *Natural Resources Forum* vol. 27 (2003).

2. Veldkamp, T. I. E. *et al.* Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. *Nat. Commun.* **8**, 1–12 (2017).

3. Boretti, A. & Rosa, L. Reassessing the projections of the World Water Development Report. *npj Clean Water* **2**, 1–6 (2019).

4. Easterling, D. R. *et al.* Climate extremes: Observations, modeling, and impacts. *Science* vol. 289 2068–2074 (2000).

5. Grafton, R. & Garrick, Dustin & Horne, J. *Water Misallocation: Governance Challenges and Responses*. https://www.researchgate.net/publication/331297130_Water_Misallocation_Governance_Challenges_and_Responses (2017).

6. Qin, Y. *et al.* Flexibility and intensity of global water use. *Nat. Sustain.* **2**, 515–523 (2019).

7. Agência Nacional de Águas. *Plano de recursos hídricos e do enquadramento dos corpos hídricos superficiais da bacia hidrográfica do rio Paranaíba.* http://cbhparanaiba.org.br/_download.php?file=aHR0cDovL2NiaHBhcmFuYWliYS5vcmcuYnIvdXBsb2Fkcy9kb2N1bWVudG9zL1JldW5pb2VzX1BsZW5hcmlhcy8yMDEyLzEwUmV1bmlhb09yZGluYXJpYTEzZTE0LjEyLjEySXR1bWJpYXJhR08vUFJIUGFyYW5hYmFkb3NMdWl6Sm9ieS5wZGY= (2013).

8. Agência Nacional de Águas. Subsídios para a discussão da compatibilização da geração de energia hidrelétrica com expansão da agricultura irrigada na bacia do rio São Marcos. (2014).

9. Instituto Brasileiro de Geografia e Estatística. Produção Agrícola Municipal. https://sidra.ibge.gov.br/tabela/5457 (2018).

10. Agência Nacional de Águas & Empresa Brasileira de Pesquisa Agropecuária. Metadados Agricultura Irrigada por Pivôs Centrais no Brasil. https://metadados.ana.gov.br/geonetwork/srv/pt/main.home?uuid=e2d38e3f-5e62-41ad-87ab-990490841073 (2019).

11. Agência Nacional de Águas & Embrapa Milho e Sorgo. *Levantamento da agricultura irrigada por pivôs centrais no Brasil (1985-2017)*. (ANA, 2019).

12. Elétrica, C. de C. de E. CCEE - Informações ao mercado. http://www.ccee.org.br/portal/faces/pages_publico/o-que-fazemos/infomercado?_adf.ctrl-state=1cqtdwjv8v_1&_afrLoop=1576090523714178#!%40%40%3F_afrLoop%3D1576090523714178%26_adf.ctrl-state%3D1cqtdwjv8v_5 (2020).

13. Operador Nacional do Sistema

Elétrico. Resultados da Operação - Histórico da Operação. http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/geracao_energia.aspx (2020).

14. Agência Nacional de Energia Elétrica. Relatório do Sistema de Acompanhamento de Informações de Mercado para Regulação Econômica. http://relatorios.aneel.gov.br/_layouts/xlviewer.aspx?id=/RelatoriosSAS/RelSAMPRegiaoEmp.xlsx&Source=http%3A%2F%2Frelatorios.aneel.gov.br%2FRelatoriosSAS%2FForms%2FAllItems.aspx&DefaultItemOpen=1: (2020).

15. Agência Nacional de Águas. Nota Técnica n° 103 /2010/GEREG/SOF-ANA. (2010).

16. Agência Nacional de Águas. Sistema Nacional de Informação de Recursos Hídricos. http://portal1.snirh.gov.br/ana/apps/webappviewer/index.html?id=5094e51beb90418aab741d9dc56ddeb9 (2019).

17. Eletrobras Furnas. *Demonstrações financeiras e relatório da administração*. https://www.furnas.com.br/Upload/12-sub-254053496-relatorio_adm_2018.pdf (2018).

18. Agência Nacional de Águas. Resolução n° 562, de 25 de outubro de 2010. (2010).

19. Agência Nacional de Águas. Resolução n° 564, de 25 de outubro de 2010. (2010).

20. Hochstetler, R. L. ‘ Physical Guarantee ’ Apportionment Based on Marginal Benefit. *XIV Symp. Spec. Electr. Oper. Expans. Plan.* (2018).

21. CBH Paranaíba. Deliberação n° 70/2016. (2016).

22. [OECD], O. for E. C. and D. *OECD Studies on Water Water Charges in Brazil*. http://dx.doi.org/10.1787/9789264285712-en (2017) doi:10.1787/9789264285712-en.

23. CBH Paranaíba. Deliberação n° 61/2016. (2016).

24. Conselho Nacional de Recursos Hídricos. Resolução n° 192, de 19 de dezembro de 2017. (2017).

25. Agência Nacional de Águas. Cobrança - Informações gerais - Paranaíba. https://www.ana.gov.br/gestao-da-agua/cobranca/paranaiba/informacoes-gerais (2020).

26. Agência Nacional de Águas. *Cobrança pelo uso de recursos hídricos*. http://biblioteca.ana.gov.br/asp/download.asp?codigo=139784&tipo_midia=2&iIndexSrv=1&iUsuario=0&obra=82407&tipo=1&iBanner=0&iIdioma=0 (2019).

27. Young, R. A. *Measuring economic benefits for water investments and policies (World Bank Technical Paper No. 338)*. *World Bank Technical Paper* vol. 338 http://ideas.repec.org/p/fth/wobate/338.html (1996).

28. Agência Nacional de Águas. Nota Técnica n° 104 /2010/GEREG/SOF-ANA. (2010).

29. AGROLINK. AGROLINK - Cotações de commodities agrícolas, com preços atualizados diáriamente em todos os

estados brasileiros. https://www.agrolink.com.br/cotacoes/historico/go/soja-em-grao-sc-60kg (2020).

30. Abastecimento, C. N. de. Planilhas de Custos de Produção - Séries Históricas. https://www.conab.gov.br/info-agro/custos-de-producao/planilhas-de-custo-de-producao/itemlist/category/414-planilhas-de-custos-de-producao-series-historicas (2019).

31. Agência Nacional de Águas. Resolução n° 489, de 19 de agosto de 2018. (2008).

Author contributions

F.M.M. and M.W.C. designed the study. M.W.C. and J.J.S. performed the analyses. P.E.G. modelled the economic problem. F.M.M., M.W.C. and J.J.S. analysed the results and wrote the manuscript.

Competing interests

The authors declare no competing interests.

Table 1. Variables used for calculating the water value for each irrigator located in Alto São Marcos.

Irrigator	**Permit Resolution**	**Annual Volume (m^3)**	**Irrigated Crop**	**Irrigated Area (ha)**	**Productive Cycle**	**Gross Revenue (US$)**	**Production Expenses (US$)**	**Net Revenue (US$)**	**Water Value (US$/$m^3$)**
18	1296/2018	822,914.40	bean, soybean*	172	3	1,032,765.09	613,450.75	419,314.34	0.51
10	1468/2017	698,850.00	corn, bean	125	3	793,124.10	490,774.72	302,349.38	0.43
3	1005/2015	585,702.00	bean, soybean	165	2	580,607.51	340,784.10	239,823.41	0.41
4	212/2016	1,881,659.00	corn, bean	260	3	1,649,698.13	941,448.40	708,249.72	0.38
15	691/2018	1,948,642.00	corn,bean, soybean	426	3	2,068,775.96	1,463,286.98	605,488.98	0.31
12	2210/2017	257,418.00	corn,bean, soybean	34	3	215,729.75	137,191.44	78,538.32	0.31
1	402/2015	240,200.00	corn, bean, soybean	50	3	242,814.08	172,378.61	70,435.47	0.29
6	647/2016	932,500.00	corn, bean, soybean	190	3	922,693.50	656,123.70	266,569.80	0.29
8	318/2017	395,250.00	corn,bean, soybean*	79	3	383,791.93	273,318.51	110,473.43	0.28
11	1492/2017	2,067,660.00	corn, bean	250	3	1,586,248.20	1,018,372.56	567,875.64	0.27
14	304/2018	652,344.00	corn, bean	77	3	488,564.45	314,510.94	174,053.51	0.27
2	452/2015	1,302,841	corn,bean, soybean*	197	3	958,629.99	700,036.93	258,593.06	0.20
9	816/2017	748,440	corn,bean, soybean*	104	3	505,053.28	372,223.67	132,829.62	0.18

Irrigator	Permit Resolution	Annual Volume (m^3)	Irrigated Crop	Irrigated Area (ha)	Productive Cycle	Gross Revenue (US$)	Production Expenses (US$)	Net Revenue (US$)	Water Value (US$/$m^3$)
16	1044/2018	602030.03	corn, bean, soybean	80	3	388,502.53	287,771.81	100,730.72	0.17
7	781/2016	1606050	corn,bean, soybean*	213	3	1,034,387.98	766,365.31	268,022.67	0.17
21	1996/2018	1124200	corn, bean, soybean	146	3	709,017.11	526,584.85	182,432.26	0.16
20	1673/2018	523612	corn,bean, soybean*	67	3	323,428.35	240,802.42	82,625.94	0.16
17	1156/2017	1957890	corn,bean, soybean*	245	3	1,187,360.85	885,984.72	301,376.13	0.15
19	1439/2018	790128	corn,bean, soybean*	94	3	454,062.33	341,087.91	112,974.41	0.14
5	263/2016	1785000	corn, bean, soybean	185	3	899,383.35	687,698.85	211,684.50	0.12
13	65/2018	608540	corn, soybean	130	3	306,158.41	285,033.07	21,125.34	0.03

*adapted information

Supplementary Information

Supplementary Table 1. Variables modified for each year to calculate the evolution of the water value for irrigation *(ref.*[14,29,30]*)* .

Year	Crop	Crop prices (US$/kg)	Production costs (US$/ha)	Cost of electricity (US$/1,000m³)
2010	soybean	0.15	429.97	18.31
	bean	0.45	601.46	
	corn	0.07	575.45	
2011	soybean	0.17	412.89	26.63
	bean	0.38	611.30	
	corn	0.10	630.78	
2012	soybean	0.24	409.24	26.25
	bean	0.66	650.21	
	corn	0.10	701.84	
2013	soybean	0.24	496.83	25.81
	bean	0.40	779.12	
	corn	0.09	912.81	
2014	soybean	0.24	496.83	28.52
	bean	0.40	779.12	
	corn	0.09	912.81	
2015	soybean	0.25	610.00	48.93
	bean	0.61	908.47	
	corn	0.10	1040.55	
2016	soybean	0.30	633.41	43.51
	bean	1.10	957.71	
	corn	0.16	1059.77	
2017	soybean	0.26	668.60	48.45
	bean	0.58	934.81	
	corn	0.10	1114.77	
2018	soybean	0.31	814.80	69.71
	bean	0.41	1179.01	
	corn	0.12	1152.65	
2019	soybean	0.31	812.87	54.96
	bean	0.83	1248.25	
	corn	0.13	1122.40	

Supplementary Table 2. MCO (US$/MWh) per year

year	MCO (US$/MWh)
2010	17.34
2010	6.82
2010	42.13
2010	65.99
2010	210.16
2010	141.06
2010	20.74
2010	92.18
2010	79.17
2010	55.93

Supplementary Table 3. Average water values for irrigation computed for the 21 irrigators from 2010 to 2019.

Year	Average water value for irrigation (US$/m³)
2010	0.15
2011	0.15
2012	0.32
2013	0.36
2014	0.09
2015	0.15
2016	0.53
2017	0.12
2018	- 0.05
2019	0.25