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IWRM Incorporating Water Use and Productivity Indicators of Economic Clusters Using a Hydro-Economic SDSS

Gerald Norbert Souza da Silva [1,*], Márcia M. G. Alcoforado de Moraes [2], Laíse Alves Candido [3], Carlos Alberto G. de Amorim Filho [4], Nilena B. M. Dias [5], Marcelo Pereira da Cunha [6] and Lourdinha Florêncio [3]

1 Civil Engineering Department, Federal University of Paraiba, João Pessoa 58033-455, Brazil
2 Economic-Integrated Management Research Group, Department of Economics, Federal University of Pernambuco, Recife 50740-600, Brazil
3 Civil Engineering Department, Federal University of Pernambuco, Recife 50740-530, Brazil
4 Department of Economics, Federal University of Pernambuco, Recife 50740-600, Brazil
5 Department of Energy, School of Mechanical Engineering, University of Campinas, São Paulo 13083-860, Brazil
6 Institute of Economics, University of Campinas, Campinas, São Paulo 13083-857, Brazil
* Correspondence: gerald.silva@academico.ufpb.br; Tel.: +55-83999929405

Abstract: IWRM should include the integration of management instruments towards intersectoral efficient water allocation. A platform linking economywide and network-based models, available from a Spatial Decision Support System (SDSS), was used to analyze allocation decisions in 4-interlinked basins in Northeastern Brazil during a period of water scarcity. The SDSS can integrate water allocation issues considering hydrologic and socioeconomic aspects. In this study, we applied a normalized concentration index and exploratory spatial data analysis to socioeconomic data to identify job hotspots in economic sectors. Hydro-economic indicators were determined and used as economic weights of those hotspots and individual users for water allocation. This innovative method of allocation simulates the use of economic instruments. Removing the weights, the use of non-economic instruments is also simulated. The economic allocation transfers water from agriculture and industry to the services sector compared to the non-economic. This is justified given the low indicators of the main sectors of agriculture and industry in the region: sugarcane cultivation and the sugar–alcohol industry. Moreover, regional transfer results show that without using economic criteria and maintaining the current distribution network, there is a transfer of water stored in drier to humid regions. These results can support the decision-making process by defining effective management instruments.

Keywords: IWRM; hydro-economic allocation; integrated economic modeling; spatial decision support system; hotspot analysis; hydro-economic indicators

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Citation: Souza da Silva, G.N.; Alcoforado de Moraes, M.M.G.; Candido, L.A.; de Amorim Filho, C.A.G.; Dias, N.B.M.; Pereira da Cunha, M.; Florêncio, L. IWRM Incorporating Water Use and Productivity Indicators of Economic Clusters Using a Hydro-Economic SDSS. *Hydrology* **2023**, *10*, 72. https://doi.org/10.3390/hydrology10030072

Academic Editor: Abdullah Gokhan Yilmaz

Received: 15 February 2023
Revised: 9 March 2023
Accepted: 16 March 2023
Published: 22 March 2023

1. Introduction

Current considerable investments in water infrastructure worldwide should be able to benefit from a definition of public policies that increase the efficiency of water use. The identification of an optimal (efficient) economic allocation in this context assumes a central role: once implemented, efficient allocation can transfer scarce resources between economic sectors, adding value to society, guaranteeing access to the less fortunate, and protecting the environment [1]. Achieving water efficiency is not a trivial task and will largely depend on the credibility of institutions, laws, planning, and regulations using effective water management instruments, especially economic ones. These instruments need to be designed and evaluated using economic theory through analytical tools, such as economic models and decision support systems. They can simulate the real system and how the water allocation changes when the water management instruments proposed are in place and enable the evaluation of these instruments and their resulting allocations by measuring allocation impacts, namely: economic, environmental, productivity, and equity.

Clear analysis of allocation impacts driven by water management instruments must be available to decision-makers, especially in developing countries where institutions are not strong, political power is unbalanced, and the availability and diversity of water uses are uncertain. The water allocation challenge among uses, especially in a context of uncertainty and water scarcity, is so important that some authors have suggested that the definition of IWRM should be changed to Integrated Water Resources Allocation and Management, IWRAM [2] to highlight the need for allocation studies. Models can use different criteria to identify the optimum water allocation among users and measure the direct economic impacts of this distribution [3–5] when integrated with regional economic models, such as Input–Output Models (IOMs).

Decision-makers often remain ill-informed about the water allocation trade-offs and are ill-equipped to deal with a range of plausible outcomes. Multi-discipline tools and integrative skills extending from basin to regional levels are needed to address the IWRAM challenges and to adapt to these challenges as they evolve.

A platform linking a network-based system model to an economywide model, made available in a spatial decision support system (Hydro Economic Allocation System—HEAL) [6], is a tool able to integrate water allocation issues from local to regional levels considering hydrological and socioeconomic aspects. Integrated models have been developed for four interlinked basins in Northeastern Brazil (NE) and applied to these basins during a period of water scarcity. A normalized concentration index method [7] and exploratory spatial data analysis [8] were carried out using socioeconomic data generated by an IOM regionalized for the study area in the base year to identify employment hotspots (statistically significant clusters) of a given economic sector. The integrated platform, then, identifies water use and regional socioeconomic values (jobs and GDP) and combines this information to develop Sustainable Development Goal 6 (SDG6) indicators [9,10], Water Use Efficiency (WUE) and Water Intensity (WI), and productivity indicators [11], Labor Productivity (LP) and Unit Labor Costs (ULC), for each cluster identified in the study area.

These indicators were used as weights, resulting in a final index per cluster, which was then used to prioritize the water allocation for each cluster. In addition to prioritizing the regional clusters, the indices obtained from the weighted averages were also calculated for each sector and municipality and used as weights in the water allocation process of their associated demand user nodes.

This strategy of allocation using SDG6 and productivity indicators are able to simulate an economic allocation and, thus, the use of water economic instruments in different ways. Furthermore, by removing the weights and priority for clusters, we can simulate non-economic (hydrological) allocation and regulatory management instruments and compare the effects of these two types of water instruments for the same study area and period.

The HEAL system, in its current version, was able to provide model results representing both different configurations of water allocation strategies in an interactive and automated way through a user-friendly interface. These results can provide assessments of the effects of the application of management instruments in different settings and under different water availability conditions. These models can be built in different ways, for example, by modifying optimization criteria of water allocation to reflect the interests of the stakeholders and decision-makers themselves in a participatory modeling approach [12].

These results should be able to support the decision to define the management instruments in a transparent and accessible way, contributing to adaptive governance, especially in regions with water scarcity and increasing water transfer needs, as is the case in NE Brazil. Moreover, the Brazilian water law, enacted in 1997 (Law No. 9433 [13]), requires decentralized governance, which means it requires the participation of civil society. Full exercise of citizenship with respect to water management and the laws and regulations that attend it cannot be achieved without scientific data that provides the information and transparency needed for intelligent and equitable decision-making.

2. Materials and Methods

Observations of the most recent severe drought period (2012–2018) in Northeast Brazil and the recent literature on IWRM [5] show that water resource allocation under scarcity might not only provide water security for the basic needs but also the regional economy, supporting local productive arrangements as a fundamental mechanism for regional development. To enrich the debate with analytical results about the benefits/damages of water resources allocation, both for the population and for economic sectors, we developed a methodology described below and applied it, using the spatial decision support system (HEAL system), in an important study area within the state of Pernambuco, Northeastern Brazil.

2.1. The Study Area

The four interlinked basins in Northeastern Brazil are key river basins in the state of Pernambuco (Figure 1). According to Silva [14], the 3 largest basins (Capibaribe–Ipojuca–Una), with 18,000 km^2, represent almost 20% of the area of the state, according to the Brazilian Institute of Geography and Statistics (IBGE). The basins comprise two climate zones, the *Zona da Mata* (humid coastal area) and the *Agreste* (semiarid region). The Agreste is characterized by irregular rainfall and a rate of annual precipitation by potential evapotranspiration of 0.7.

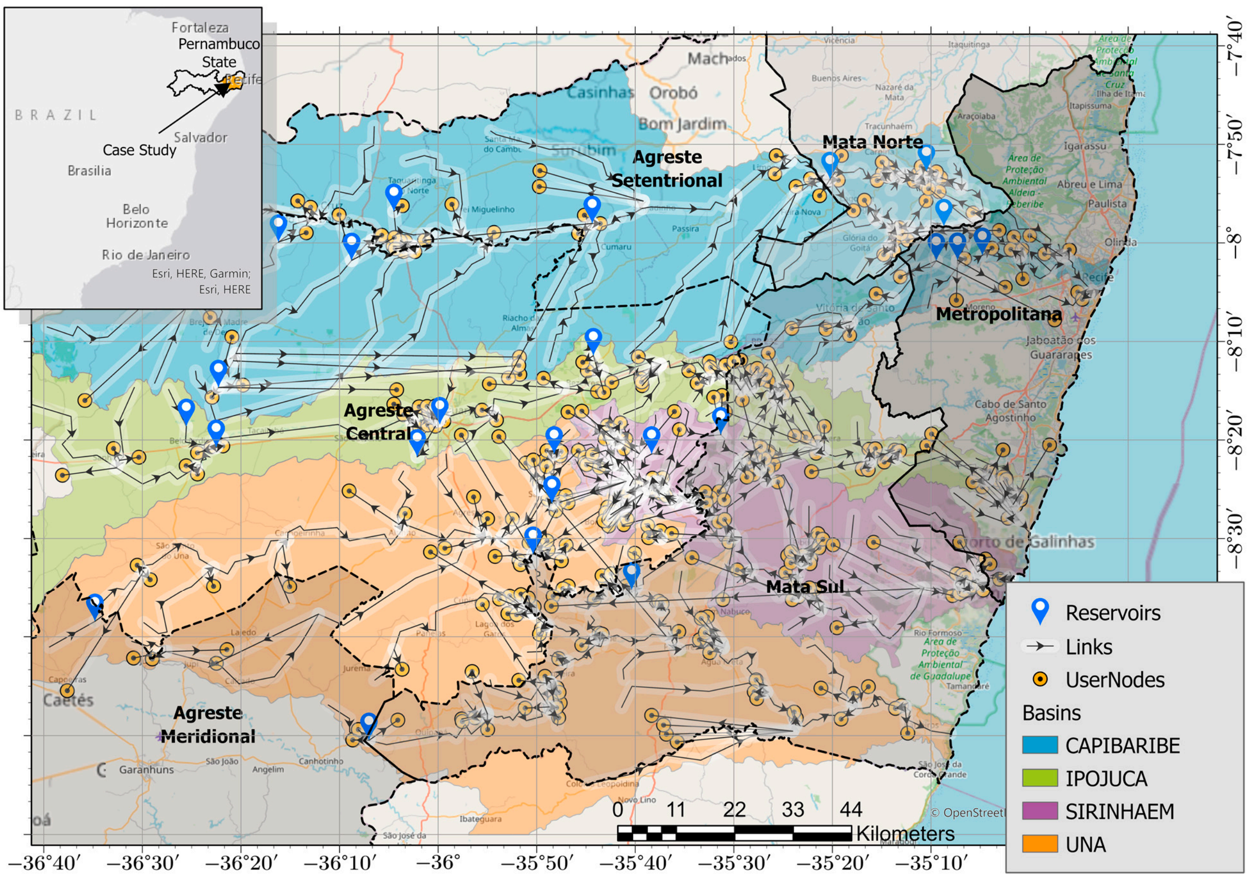

Figure 1. Case study area showing network, basins, and development regions.

An extended drought period affected the semiarid Agreste region and economy between 2012 and 2018, considered the worst in the past hundred years [15]. A technical study by the National Confederation of Municipalities (CNM) estimated drought-related losses in the Northeast between 2012 and 2017 at BRL 147 billion [16]. The main water sources of the Agreste region during drought periods are surface reservoirs. By 2017, around 60 cities within the Agreste region had suffered a collapse of their water systems and started to have their supply made by water trucks [15]. The hydro-infrastructure includes an estimated surface storage capacity of 1050 Mm^3 during the simulation period, mainly located in the Agreste region, with nearly no groundwater storage capacity.

For example, in the Agreste region, the lack of water has had a strong negative impact on the textile industry. Even though it is an efficient sector in the use of water, with high productivity rates, the water crisis hit it hard since production depends directly on laundries and print shops without a water allocation policy to protect the sector [15]. It is important to point out that not only the reduction in availability, but also the water distribution policies among economic sectors during scarcity defines the socioeconomic impacts associated with the water crisis.

Previous results of integrated modeling [17] applied to the same study area have shown that regulatory water instruments in current use have failed to differentiate water allocations between users, economic sectors, or regions according to the efficiency of their water use. This has resulted in greater economic and social losses. The basins should benefit from the development of public water policies that improve management and provide adequate incentives to sectors and agents that use water more efficiently, have higher rates of productivity and show resilience and sustainability in water use. These water policies are even more important when considering that the basins will receive water from the Transboundary Water Transfer Project of the São Francisco River (PISF) [6] because there is no guarantee that the resource will be distributed efficiently. Water from this system must be pumped over long distances at a high cost of energy and money. Furthermore, it will reduce the discharge of the São Francisco River. Thus, water becomes more expensive, reinforcing the idea that the management of these water resources must be made in a clear and intelligent manner.

The basins of the present study are within six Development Regions (DRs) in the state of Pernambuco: Metropolitana (Metropolitan Region of Recife), Zona da Mata Norte, Zona da Mata Sul, Agreste Setentrional, Agreste Central, and Agreste Meridional (State Law 12.427/2003 [18]). The reason for this division is to promote the reduction of disparities within the different regions of the state, allowing regional development within the state through local opportunities through this territorial framework. Figure 1 presents the parts of the DRs that are part of the study area.

As seen in Figure 1, the entire DR of Mata Sul is part of the study area, as well as a good part of Agreste Central and Agreste Setentrional. These last 2 DRs have, respectively, 88.46% and 73.68% of their municipalities within the area of the basins studied. On the other hand, the DRs of Agreste Meridional and Mata Norte have a smaller portion of their municipalities within the study area, approximately 40%.

The Agreste Central occupies the second position among Pernambuco's DRs in terms of population concentration (11.92%) and GDP (8.11%), second only to the Metropolitan Region. The Gross Value Added (GVA) in this region is divided into 78.67% from the service sector, 13.16% from industry, and 8.17% from agriculture. Two other DRs, Mata Sul and Agreste Setentrional, have a GVA composition similar to that from Agreste Central. Together, they have 14.33% of the population and 8.79% of the state's GDP. The GVA of the Mata Norte has a higher percentage from industry (19.35%) and agriculture (16.06%) compared to the other DRs mentioned above. On the other hand, the Agreste Meridional has the lowest percentage from industry (7.77%) of all the DRs in the state, but it is the second highest in the service (79.56%) and fourth highest in agricultural (12.67%) sectors. In terms of population and GDP in relation to the others, these last two DRs have together, respectively, 13.86% and 8.27% [19,20].

2.2. Hotspot Analysis, Water Use and Productivity Indicators and the Cluster Ranking Index

Figure 2 shows the used sources of data and the developed methods used to identify and then prioritize the main productive arrangements, especially those essential to maintain important economies on a regional level.

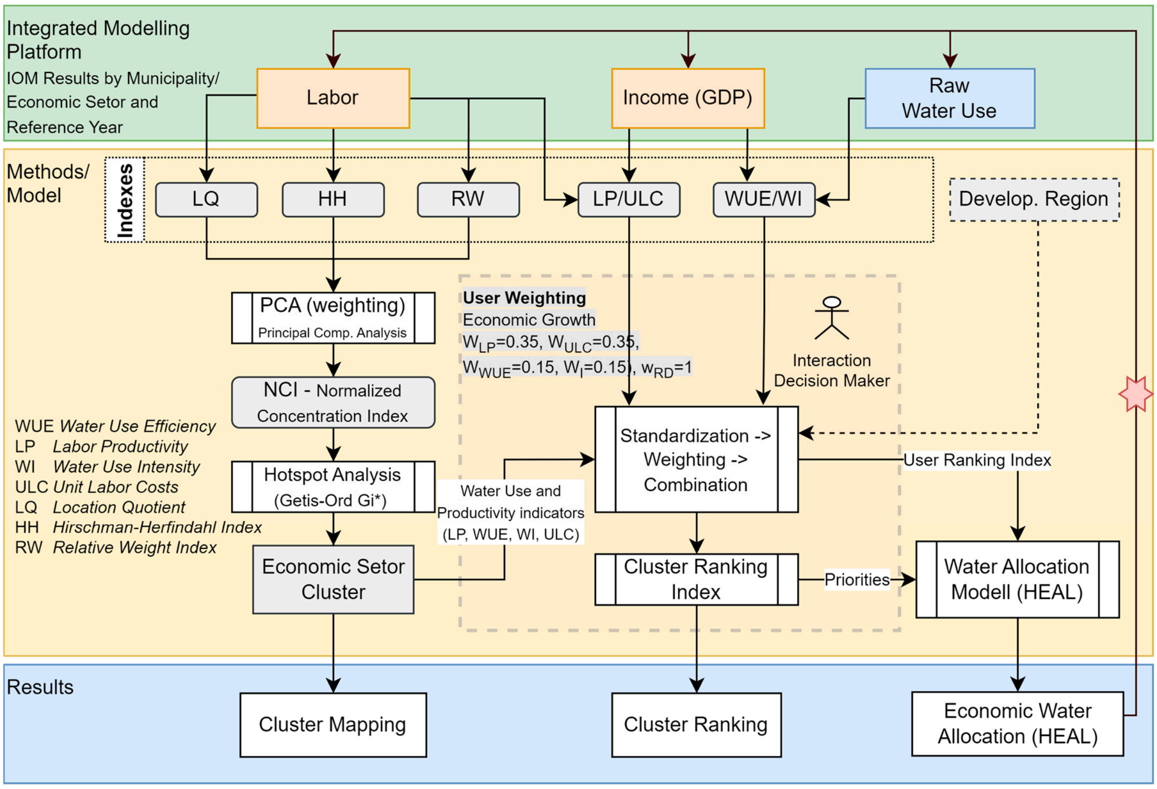

Figure 2. Materials and methods.

Labor, GDP, and raw water uses are the main data inputs for the analysis. These were obtained from the integration of the network-based water model with the IOM [17] which made it possible to identify the raw water used as well as the GDP and the number of jobs generated, by both the economic sector and the municipality in the study region for the reference year, 2011. The year chosen was a wet year, coming right before the beginning of the drought that occurred between 2012 and 2018 in the state. The IOM covered 76 economic sectors within 75 regions (the rest of Brazil, the rest of the Northeast, Bahia, and the rest of PE, with 68 municipalities and 3 municipal clusters belonging to the 4 interlinked basins—Capibaribe, Ipojuca, Una, and Sirinhaém).

This interregional IOM was developed for this study area based on the Brazilian IOM for 2011. In its basic form, an IOM consists of a system of linear equations, each describing the distribution of the production of an economic sector to all sectors of the economy. Raw water was introduced into the IOM through the integrated platform to help understand the nature of direct and indirect linkages between sectors and water allocation.

This raw water use employed by the IOM is simulated by the network-based model for the reference year (2011) based on the water permits related to demand user nodes associated with their economic activity (economic sectors). As the reference year was a wet year in the region, it was possible to obtain, through the allocation of the network-based model, following operational rules in place at the time, a satisfactory estimate of the water use values per user, considering the water demands of the users were met.

To identify productive arrangements, we chose to conduct a hotspot analysis of economic sectors in the municipalities. This analysis provides spatial analysis and identification of geographical clustering. The hotspot analysis uses the Getis-Ord Gi* statistic [8] to identify statistically significant economic clusters based on the concentration index available for all municipalities. The chosen method (Getis-Ord Gi*) can capture a local group of municipalities (polygons) within a given confidence limit by using z-scores and p-values. This method identifies municipalities with high economic activities in each sector spatially by looking at each municipality within the context of its neighbors. For example, a municipality with a high value is economically important but may not be statistically significant; this municipality would not be considered to have a high economic value unless it were surrounded by other municipalities with high economic values to make it significant. The regional sum for municipalities (with neighbors) is compared proportionally to the sum of all municipalities in the study area. When the regional sum is different from the expected sum, an economic cluster is established.

The criterion used to obtain these regional economic hotspots, is the normalized concentration index [7]. The Normalized Concentration Index (ICN), calculated for all economic sectors in each of the municipalities in the study area, is the linear combination of indicators of specialization, concentration, and relative importance of sectoral employment, characteristics of productive clusters. The three indexes that, together, take these points into account are the modified Hirschman–Herfindahl Index (HH), the Location Quotient (QL), and the Relative Weight Index (PR). Thus, to calculate the ICN, a linear combination of the three standardized indexes analyzed for each economic sector and municipality in the study area was performed. The specific weights of each of the indexes in each of the productive sectors were obtained by applying principal components analysis to provide proper scaling of the indexes (HH, QL, and PR) to avoid distortions of the indexes and the resulting ICN.

Once these normalized concentration indexes were estimated, they were used in the exploratory analysis of spatial data to identify the hotspots or economic clusters. The hotspots thus represented a set of municipalities with a concentration of jobs in a specific economic sector of the study area. After identifying the hotspots or economic clusters, their water use and productivity indicators were measured and combined to obtain a cluster ranking index.

The water use indicators chosen were associated with goal 6.4 of the Sustainable Development Goals (SDGs) of the United Nations, following recommendations of the FAO (Food and Agriculture Organization of the United Nations) [9,10] to measure Water Use Efficiency (WUE) and Water Intensity (WI) in each cluster. The WUE is obtained considering the ratio between the GDP (Gross Domestic Product in USD) of a sector or region and the region's consumption of raw water (m^3). Therefore, the WUE (USD/m^3) indicates the monetary value generated by the volume of water used. The higher the value of this indicator, the greater the efficiency in the use of water in the sector or region. On the other hand, the WI measures the ratio between the volume of water used in a given economic activity and the GDP generated by it. It thus represents the volume of water used for each monetary unit generated in the year (m^3/USD). The lower the value of this indicator, the better [10,21]. Thus, these two indicators can support managers in monitoring goal 6.4 (FAO 2018), as this goal is associated with an increase in the efficiency of water use in all sectors, as well as a substantial reduction in situations of water stress.

The productivity indicators were those presented in the OECD productivity statistics database and obtained for the identified hotspots: Labor Productivity (LP) and Unit Labor Costs (ULC). The LP is measured as the GDP at market prices per person employed. The ULC measures the average cost of labor per unit of output produced. These indicators are useful for understanding the sources of growth in an economy through the contributions from labor, capital, and the efficiency with which these inputs are used in the production process [11]. Measurement of these indicators for each hotspot, that is, for each economic sector within the associated municipalities that concentrates employment in the study area, makes it possible to evaluate and compare them related to their importance in the promotion of productivity growth in the region. This latter is considered a key source of economic growth and improvements in living standards.

All these four indicators, water use efficiency, water use intensity, labor productivity, and unit labor costs, were standardized on a scale from zero to one to prevent the difference in scalar magnitudes from affecting the calculation of the index. It should be noted that, for some indicators, in the definition of the maximum and minimum values for standardization, the lower and upper outliers observed in the distribution of their values were excluded.

These outliers were identified using the interquartile range (IQR). Values less than the first quartile minus 1.5 times the IQR or values greater than the third quartiles plus 1.5 times the IQR were considered "outliers". In the first case, the value zero was assigned to the "outlier", and in the other situation, the value one.

Those two types of standardized indicators were combined using a weighted average to obtain a unique index, then used for ranking the hotspots. Weights of 0.35 were considered for each of the 2 productivity indicators and 0.15 for each of the 2 water use indicators.

Obtaining such indicators was only possible due to the platform that integrates models, which manages to associate water use with socio-economic data (jobs and income). Other indicators can be obtained and used, as well as different weights for each one can be chosen by managers. The SDSS foresees the development of new functionalities in a friendly interface that allows the user to generate other hydro-economic indicators, as well as change the weights of each one to obtain new results that can support the allocation decision in situations of scarcity.

2.3. Network-Based Hydro-Economic Optimization Model for Water Allocation

In the integrated platform, each user that demands the allocation of water in the network-based model is associated with the economic sectors of the regionalized IOM and a region/municipality in the study area. Therefore, the water allocated in the different scenarios can be measured by both economic and geographical means. Moreover, the economic sectors were aggregated into three major sectors, seeking to follow the FAO recommendations [10] (see Supplementary Material Table S1), and the municipalities were aggregated into Development Regions (DRs) of the state. The aggregation of the economic sectors used the sectors listed in the International Standard Industrial Classification of All Economic Activities (ISIC, Rev. 4): Irrigated Agriculture (ISIC A, excluding forestry and fishing); MIMEC (ISIC B, C, D, and F); and Services (ISIC E and G to T). Sector E includes the treated water production and distribution sector. The aggregation of the municipalities used the 12 DRs described in Section 2.1, established according to Pernambuco State Law 12.427/2003 [18].

To analyze and improve the economic outcome under water stress conditions, hydro-economic spatial statistics were used to provide a decision criterion for water allocation.

The network-based water optimization models utilize a composition of nodes and links that can represent spatially the main components of a raw water distribution system. This spatial location of water supply and water demands can integrate hydrological and economic information. All components of water balance, such as inflows, evaporation, demands, return coefficients, and reservoir volumes and releases, are represented in the network. Derived from that network, the prescriptive or optimization models maximize or minimize a specific objective function to provide values of the decision variables, considering all water balance components related to the horizon under analysis to support the allocation of water resources. In these basin-level optimization models, the hydrological interactions between the main sources of water and their uses are described in less detail than in the most traditional water management models: the descriptive ones. Wurbs [22] reports that most optimization models calculate the values of decision variables, including reservoir releases, to optimize the objective function without directly considering, in a comprehensive way, the operating rules of the system.

The objective functions of these network-based optimization models, in general, seek to express planning and management goals, as this way, the results can assist in the identification of optimal policies. When considering an economic objective as the criterion to be maximized, an economically efficient allocation is identified, which implies a maximum benefit or well-being for all users who use the available water resources. Optimization models in which the objective function is hydrology-inferred are those where the decision in the intersectoral allocation is derived from hydrological specifications.

2.4. Water Allocation Scenarios

The optimization model uses preemptive goal programming, a stepwise optimization approach with distinct Objective Functions (OF), fixing water allocation for specific uses in each step of the optimization process. We analyzed the trade-off between water user allocation and reservoir storage. An increase in stored water represents an increase in water security for prolonged drought periods. The reservoir objective uses a threshold for the respective OF, in which various combinations were analyzed, and two scenarios were selected for the detailed analysis of the intersectoral and reservoir trade-offs and the impact of economical weighting techniques. Figure 3 shows the Pareto efficiency regarding two main objective functions: reservoir storage and user allocation for this case study.

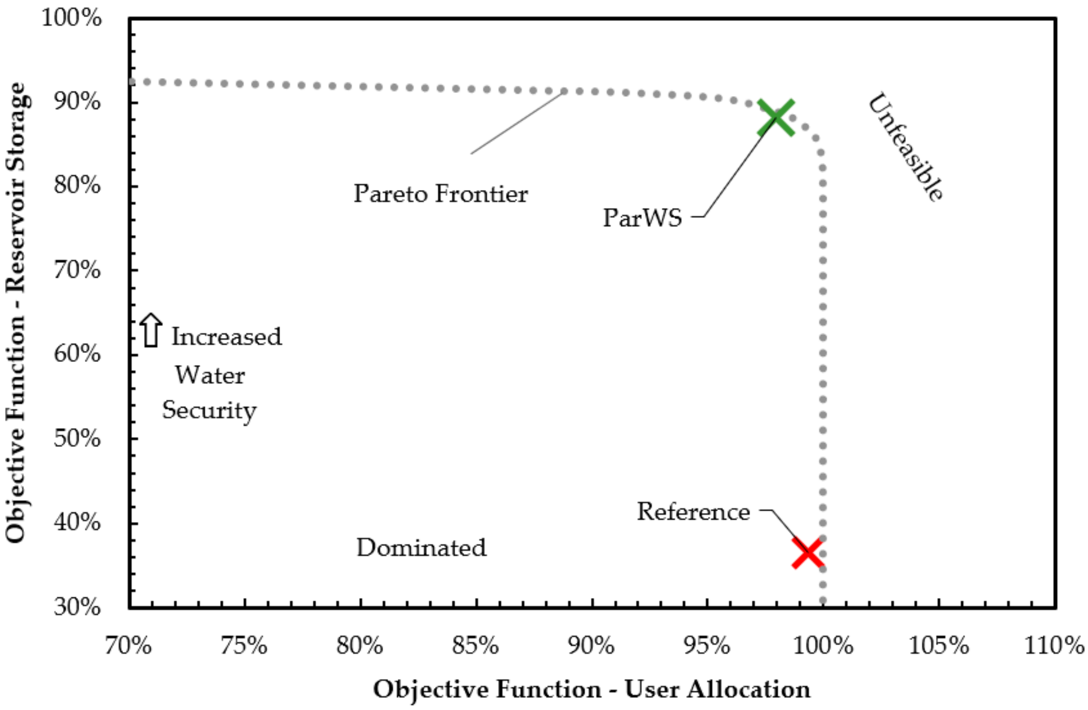

Figure 3. Objective functions within the Pareto efficiency of two objective functions: reservoir storage and user allocation. Reference scenario (red X) and ParWS—Pareto Frontier with Water Security (green X).

The first scenario, so called Reference, simulates previous examples of water storage to represent similar reservoir management as observed in the past. Equation (1) was used as primary objective function with S_{obs} being the monthly observed storage, while water allocation for priority uses and all remaining users were the subsequent OFs (Equations (2) and (3) with weighting $w_d = 1$)).

$$\min_{S_R \epsilon reservoir} \sum \frac{S_{Obs}}{S_{max}} - \frac{S_R}{S_{max}}, \ subject\ to: \quad S_R \in reservoir \tag{1}$$

The second scenario represents increased reservoir storage on the Pareto Frontier resulting in increased Water Security (ParWS) by using a threshold for reservoir storage (sum of reservoir storage > 88%) for the simulation period. This new scenario would guarantee meeting water user demands at a level very close to that of the reference, but with much higher storage values, thus representing a dominant solution in relation to the Reference. Additionally, for the ParWS scenario, economic cluster ranking (Equation (4)) and weights (w_d) are applied as described above (Equation (3)), creating the main sub-scenario with Economic weighting (ParWS + Eco). In this third scenario, after the first OF (Equation (2)), cluster index ranking was applied to the optimization model by prioritizing the allocation of water to the highest-ranked hotspots (see Equation (4) and Section 3.1). In addition, the indices obtained from the weighted averages w_d were calculated for each sector and municipality and used as weights in the allocation process of their associated demand-user nodes (Equation (3) and Section 3.1). At the end, after user allocation, Equation (5) maximizes the stored water in all reservoirs.

Priority for public supply, with q_d—water demand and q_a—water allocated in m^3/s

$$\min_{q \epsilon public supply} \sum (q_d - q_a)^2 \tag{2}$$

Water allocation (q_a) for all other users with weights (except public and cluster supply)

$$\min \sum w_d * (q_d - q_a)^2 \tag{3}$$

Allocation for economic clusters (except public supply)

$$\min_{q \epsilon economic\ cluster} \sum (q_d - q_a)^2 \tag{4}$$

Maximize reservoir storage S in Mm^3:

$$\max_{S_R \epsilon reservoir} \sum \frac{S_R - S_{min}}{S_{max} - S_{min}} \tag{5}$$

all subject to

$$q_a \leq q_d, d_a > 0, S_R \leq S_{max}, S_{min} \geq 88\%, S = f(inflow, evaporation, release, divert).$$

The optimization results of water allocation between sectors and DRs in the three scenarios were compared to get an idea of the different possibilities of different reallocation in the period 2011–2013, a period of scarcity in the study area. By simulating the application of different management instruments, the integrated platform can consider both water infrastructure and the effect of using differing allocation criteria. The Reference scenario simulates the allocation strategy used at the time. The water security, ParWS, scenario represents the best strategy from the hydrological point of view, considering volumes stored in the reservoirs and meeting total demands. The ParWS + Eco scenario, on the other hand, represents the economic criterion, taking into account the demands of clusters of jobs and users with higher values of efficiency in the use of water and productivity.

3. Results

3.1. Job Hotspots Characterization and Ranking

Using the method described above (Figure 2 in Section 2.2), it was possible to identify job hotspots that represent regional patterns for different economic activities. The complete list of municipalities in each hotspot and the maps can be found in the Supplementary Material Tables S2 and S3. Figure 4 below shows the hotspots identified for two employment sectors: manufacture of alcoholic beverages (Sector 18) and manufacture of apparel and accessories (Sector 21).

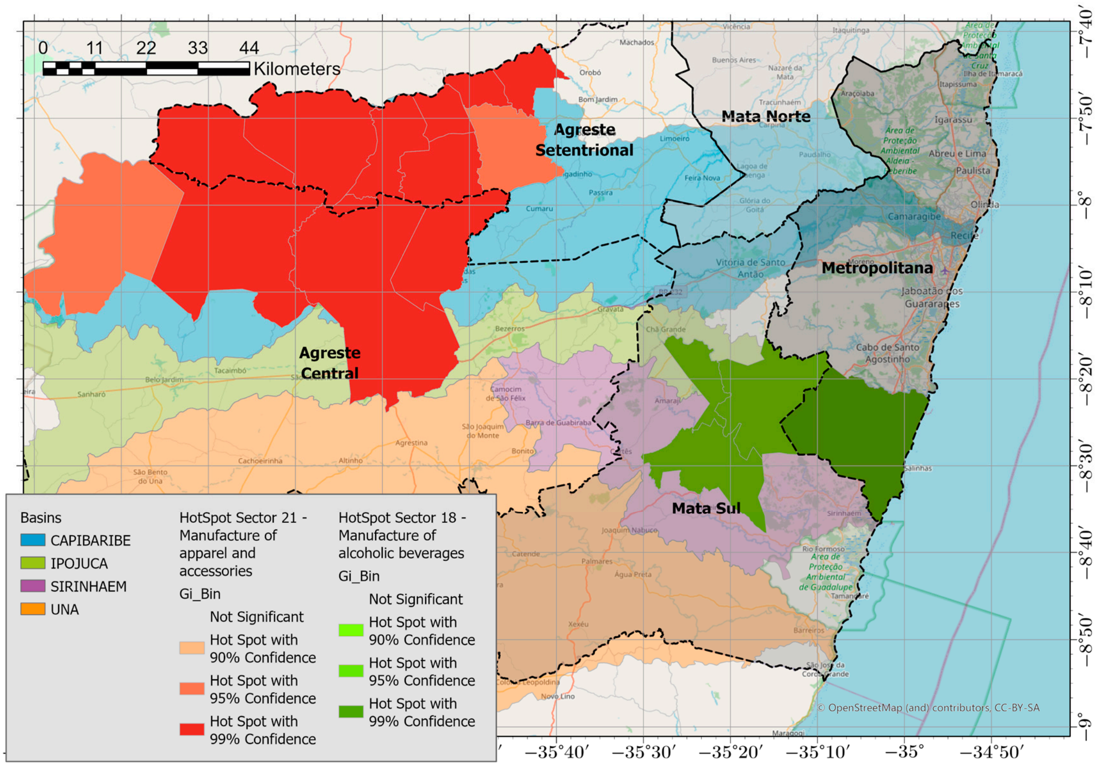

Figure 4. Results of hotspots analysis: manufacture of alcoholic beverages (Sector 18) and manufacture of apparel and accessories (Sector 21).

These hotspots are part of some local productive arrangements already known in the State of Pernambuco that have relevance and representativeness at the national level. The beverage sector is concentrated in the municipalities of DR Mata Sul, while the clothing sector is located in the Agreste region of Pernambuco.

In addition to the two job clusters (hotspots) presented here, another 55 were identified. These hotspots involved 85 municipalities and represented significant percentages in the number of jobs (32.06%) of the 4 total interconnected basins. In terms of GDP, use of raw water and treated water, the percentage values were: 35.63%, 29.37%, and 18.89% of the total study area.

Most of the economic sectors that uniquely constitute each of the employment clusters belong to the Services sector (36 of the 57 clusters). These service job clusters represent 15.35% of all jobs in the study area. The service job cluster proportions of GDP, raw water and treated water were, respectively, 23.11%, 0.02%, and 15.10% in the study area. To a lesser extent, job clusters are made up of economic sectors categorized as MIMEC (12 out of 57). MIMEC sectors were responsible for 16.60% of all jobs in the study area and agriculture (5 out of 57) for 0.1 % of jobs. MIMEC and agriculture, for GDP, the use of raw water and treated water associated with the poles in each of these sectors were the following: MIMEC (12.44%, 12.3%, and 3.78%) and agriculture (0.07%, 15.23%, and 0.0007%).

Regarding the most significant DRs within the study area, the municipalities in the Agreste Central of the interconnected basins have the most service job clusters (17 of 27 municipalities), with 18.10% of the jobs in this sector. Among the clusters identified in the DRs of Agreste Setentrional and Mata Sul, the MIMEC and agriculture sectors stand out. In the Agreste Setentrional area, 80.67% of jobs in the MIMEC sector are concentrated in the clusters identified. In Mata Sul, 73.91% of jobs are in agriculture.

After identifying the job hotspots, their water use and productivity indicators were measured. Their indicators were combined using a weighted average with weights of 0.35 for each of the 2 productivity indicators (Labor Productivity (LP) and Unit Labor Costs (ULC)) and 0.15 for each of the 2 indicators of water use (Water Use Efficiency (WUE) and

Water Intensity (WI)). This combination made it possible to rank the clusters in order to set priorities in the water allocation model. Figure 5 presents the ranking of just the hotspots of the sectors that use raw water in the study area.

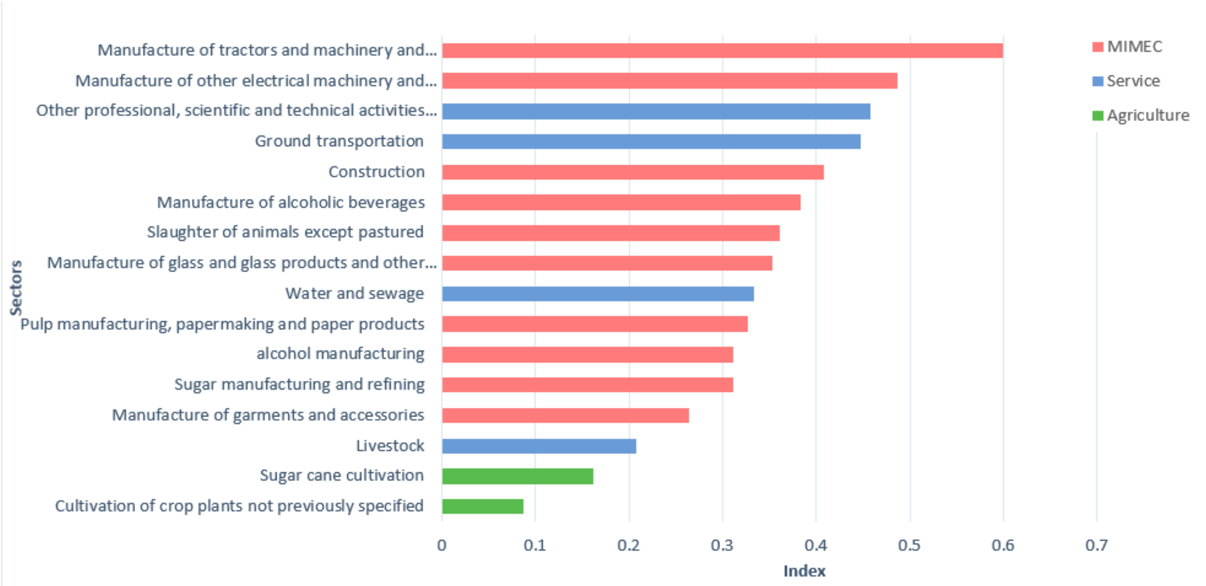

Figure 5. Ranking of the hotspots that use raw water in the study area.

It can be seen in Figure 5 that among these hotspots, the highest ranked are from the MIMEC sector, while those from the agricultural sector are at the bottom. In the allocation model, in the scenario with Economic weighting (ParWS + Eco) (see Equation (4)), the five highest-ranked hotspots, as illustrated in Figure 5, were prioritized. However, in the ranking of all 57 hotspots, which can be seen in Supplementary Material Table S4, the first 11 places are hotspots in sectors that use only treated water and are in urban centers. For this reason, as a way of prioritizing these hotspots, public supply (i.e., water for human consumption), in the ParWS + Eco scenario, was prioritized in the allocation model (Equation (2)).

Finally, according to Equation (3), under the ParWS + Eco scenario, the model allocates water to all other users considering weights (w_d) for each. These individual weights are obtained in the same way that the index for each hotspot was obtained. Table 1 presents the values of each of these indicators and the weight (w_d) obtained for some users. Values for all users can be seen in Supplementary Material Table S5.

This combination of water use and productivity indicators through the weights in the proposed scenario (ParWS + Eco) prioritizes users who, in addition to using water efficiently, also have good productivity indicators. The more efficient, less intensive users, with better productivity indicators, would have a preference for water allocations to meet their needs in situations of scarcity.

In addition, it is important to highlight that the interface of the spatial decision support system (HEAL system), currently under development, will allow the individual weights obtained for each user (w_d) to vary depending on the decision-maker's choices in relation to the weights (w_{LP}, w_{ULC}, w_{WUE}, w_I, and w_{RD}) of each of the indicators (see Figure 2 and Table 1).

Table 1. Indicators (productivity and efficiency) and weight (w_d) were obtained for municipalities and sectors. Unit Labor Costs (ULC), Labor Productivity (LP), Water Use Efficiency (WUE), Water Intensity (WI), and Weight (w_d).

User			Indicators				w_d
Development Region	**City**	**Sector**	**ULC**	**LP**	**WUE**	**(1-WI)**	
Agreste Central	Agrestina	Dairy products and other food products (Service)	0.741	0.196	0.328	0.874	0.508
		Manufacture of glass and glass products and other non-metallic mineral products (MIMEC)	0.680	0.261	0.059	0.297	0.383
	Caruaru	Manufacture of footwear and leather goods (Service)	0.818	0.177	0.856	0.952	0.62
		Manufacture of wood products (Service)	0.714	0.151	0.086	0.521	0.394
Agreste Setentrional	Limoeiro	Livestock (Service)	0.345	0.072	0.05	0.171	0.179
		Textile product manufacturing (MIMEC)	0.809	0.156	0.249	0.835	0.500
Mata Sul	Barreiros	Sugarcane cultivation (Agriculture)	0.342	0.239	0.001	0.000	0.203
	Maraial	Alcohol manufacturing—Ethanol (MIMEC)	0.761	0.353	0.000	0.000	0.390
Mata Norte	Lagoa de Itaenga	Manufacturing and refining of sugar (MIMEC)	0.736	0.379	0.000	0.000	0.390
	Carpina	Sugarcane cultivation (Agriculture)	0.342	0.239	0.000	0.000	0.203

3.2. Water Allocation Results

3.2.1. Water Allocation per Development Region and Aggregated Economic Sector

Figure 6 presents the water allocation for each development region (DR) and its aggregated economic sectors obtained by the integrated models using the HEAL system to simulate the reference year (2011). This was a wet year, just before the onset of the prolonged drought period, which lasted until 2018. The simulation was obtained using the IOM of 2011 integrated with the optimization model in the Reference scenario during the period (2011–2013), which is considered the most recent initial and crucial period of drought management. Therefore, those water allocation results are representative of the water management (water allocation policies and observed levels of reservoirs) practiced in 2011.

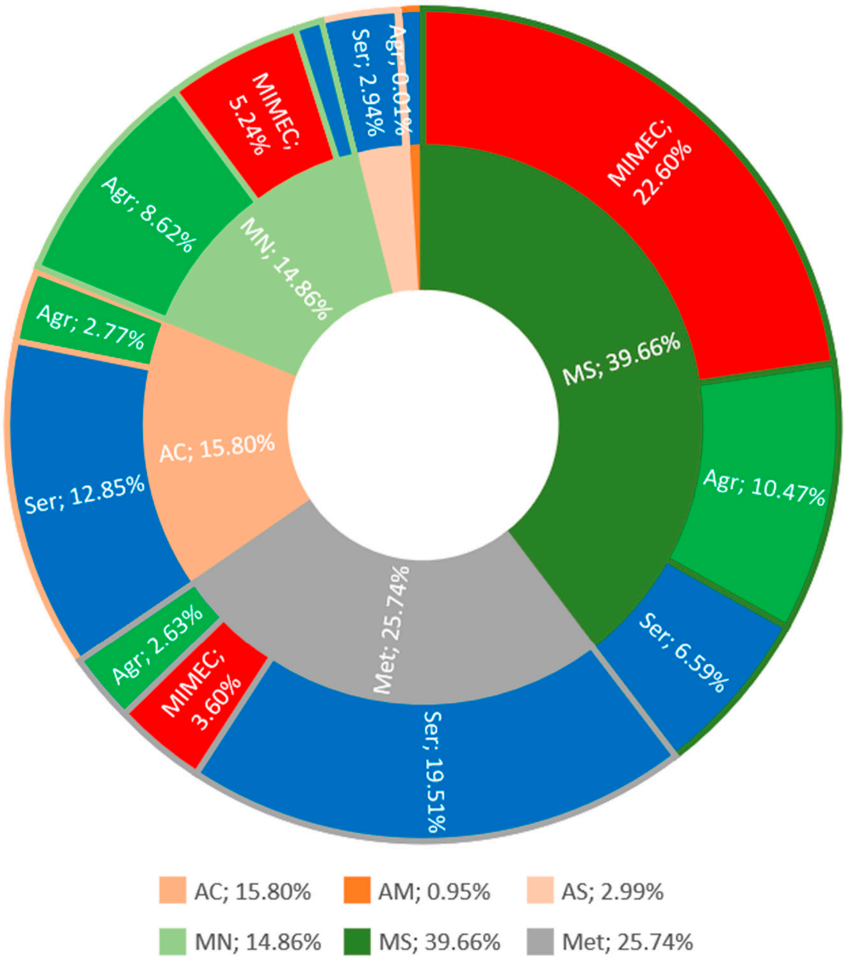

Figure 6. Water allocation per development region and aggregated economic sector obtained by the HEAL for the reference year 2011 (under water management practices at that time). Met: Metropolitana; MS: Mata Sul; MN: Mata Norte; AM: Agreste Meridional; AC: Agreste Central; AS: Agreste Setentrional.

In 2011, most of the water (54.52%) was allocated to Mata regions (Mata Norte and Mata Sul). The greatest amount of water was allocated to the MIMEC sector in the Mata Sul region (22.60%), followed by the service sector in Metropolitana (19.51%) and Agreste Central (12.85%) regions.

It is important to highlight that the industries that are supplied exclusively through water distribution companies (treated water), and therefore do not draw raw water directly from water sources, were not categorized in the MIMEC sector but as in the Service sector in our platform. We could identify the use of raw water and treated water by sector/region through the regionalized IOM used. (The sectors of the IOM in our study area and the classification made for each of the sectors in the study area, according to the aggregation of sectors described above, can be seen in Supplementary Material Table S1.)

This means that the MIMEC sector in our study represents only a part of the industrial sector, the one that uses mainly raw water as a factor of production. In a disaggregated way, the MIMEC sub-sectors “manufacturing and refining of sugar” and “alcohol manufacturing (ethanol)” are the most prominent. When analyzing only this industrial (MIMEC) sector, the sugar and ethanol activities together represent almost 97.3% of the use of raw water. Looking at the entire study area, that is, in all DRs, water use in the MIMEC sector (31.66%) is seen to be concentrated in the following DRs: Mata Sul (MS) (22.60 out of 39.66%), Mata Norte (MN) (5.24 out of 14.86%), and Metropolitana (3.6 out of 25.74%), which are non-arid regions along the coast, belonging to the so-called *Zona da Mata*.

Observing the services sector in a disaggregated way, practically all the raw water is allocated to the "water and sewage" sector—ISIC E (91.3%), which then, using it as a production factor, produces treated water for the entire region and distributes it among the other sectors. 93.79% of this treated water goes to the other sectors classified as services, including industries served exclusively by sector E, that is, treated water and distribution. The remaining 6.2% of treated water complements the supply to industries that mostly use raw water (categorized in this study as MIMEC). Less than 1% of this treated water goes to irrigated agriculture, which uses raw water almost exclusively.

Analyzing this raw water allocation (43.83%) for the services sector by DR, it is observed that, contrary to the allocation to MIMEC, there is a more balanced distribution among the humid regions (MS, MN, and Met—27.10%) and arid regions (AS, AC, and AM—16.73%). However, when analyzing each DR individually, it is evident that the services sector is the main beneficiary of allocated raw water among the arid regions: Agreste Central (AC—12.85 out of 15.80%), Agreste Meridional (AM—0.93 out of 0.95%), and Agreste Setentrional (AS—2.94 out of 2.99%). In the humid area, the services sector receives smaller percentages of raw water: Mata Norte (MN—1.01 out of 14.86%), Mata Sul (MS—6.59 out of 39.66%), and Metropolitana (19.51 out of 25.74%).

Finally, in the case of the agricultural sector, where the use of raw water is 24.51% of the total allocation in the 4 interlinked basins, 21.72% of this use is concentrated in the humid region of the state (MN—8.62 out of 14.86%, MS—10.47 out of 39.66%, and Met—2.63 out of 25.74%). Only the remaining 2.79% is allocated to the arid region (AC—2.77 out of 15.80% and AS—0.005 out of 2.99%), with practically all this water going to Agreste Central. The Agreste Setentrional receives almost no raw water (only 0.005%) and Agreste Meridional only 0.019 out of 0.95%.

In fact, the agriculture sector in the study area uses about 91.5% of its raw water for irrigated sugarcane cultivation, which is traditionally cultivated along the coast in the humid region.

3.2.2. Scenario Comparison: Hydrological and Economic Tradeoffs

Starting from the reference scenario allocation towards the Pareto Frontier (ParWS) (see Figure 3), it is possible to identify the reservoir level that could have been reached without compromising the fulfillment of other demands in 2011–2013, that is, without reducing the total volume of water allocated. This new allocation, still without weights (ParWS), would have been slightly different, with less than 1% change in sectoral shares for the overall allocation. The service sector would have suffered the most expressive reductions, of only 0.79% and 0.42% in Agreste Central and Agreste Setentrional development regions, respectively; the Metropolitana region would have had the largest increase of 0.61% (see Figure 7).

It should be noted that such reductions associated with this scenario (ParWS), which belongs to the Pareto Frontier of the two considered criteria (storage volumes and demand levels), constitute a dominant solution in relation to the reference. This solution increases the levels of the reservoirs (one of the considered optimization criteria) without significantly altering the demand fulfillment values (the other criterion). The social and economic impacts of even small reductions in meeting demands can be significant, but in this case, are not being measured by the two criteria. To do this, the reductions in allocations would need to be returned to the IOM as an exogenous shock. This is work for future research (see the link with the star symbol in Figure 2).

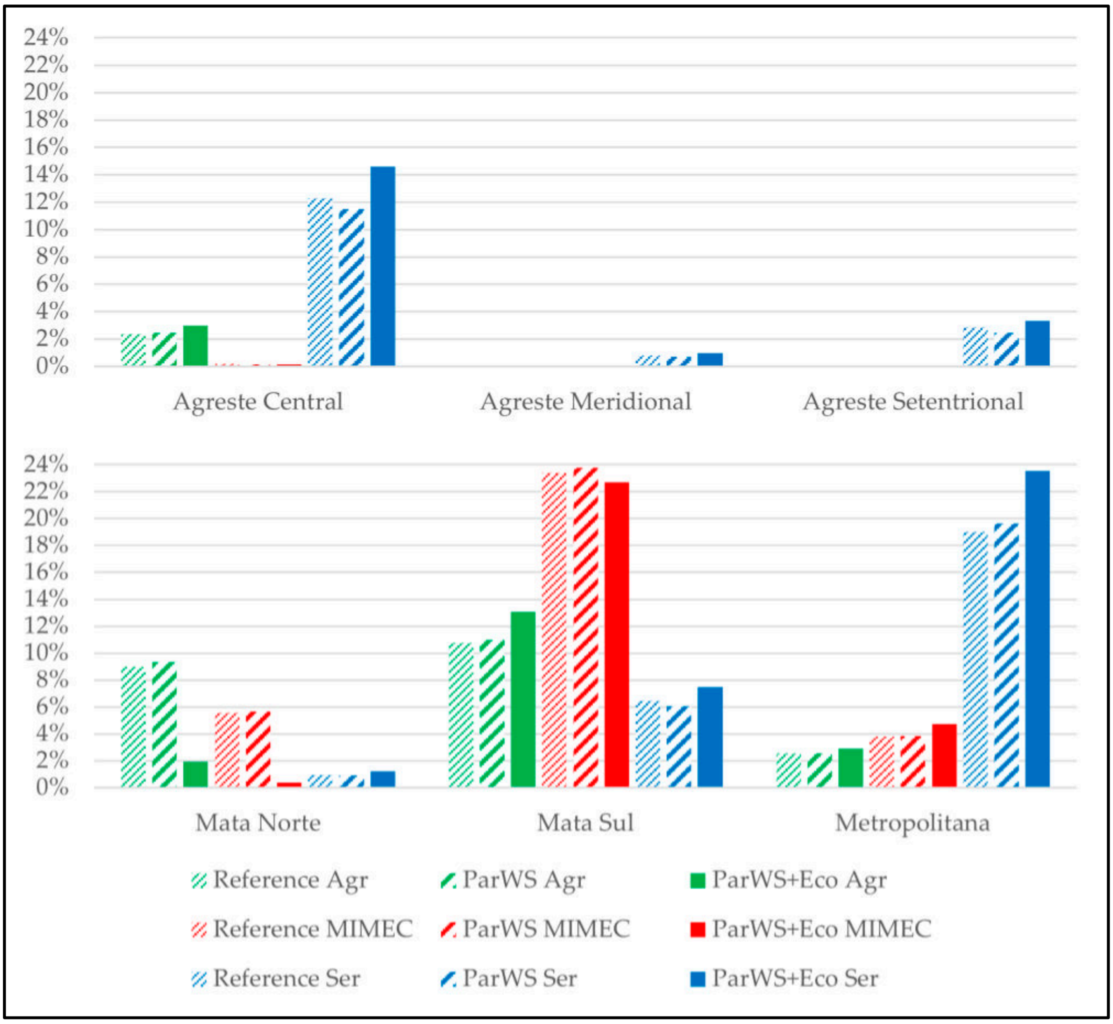

Figure 7. Aggregated economic sectors of the DR's: Reference (fine hatching), ParWS (thick hatching), and ParWS + Eco (solid color) scenarios for the sectors of agriculture (green), MIMEC (red) and service (blue).

Once the users within economic clusters were prioritized, and water use and productivity indicators were applied as weights for all other users in a scenario with the reservoir accumulation indicated by the ParWS scenario, it was possible to notice the impact of the economic criteria (ParWS + Eco) on the allocation by sector and development region for the triennium 2011–2013. Contrary to the behavior of the previous scenario (ParWS), the services sector no longer has its allocations reduced in relation to the reference scenario, neither in Agreste Septentrional nor Agreste Central, but increased by 0.91 and 3.08%, respectively. Furthermore, in the Metropolitana DR, the increase is even more expressive in this sector in relation to the previous scenario and the Reference scenario (3.90%). The Mata Norte took the biggest hit by losing water for its agriculture (7.38%) and MIMEC (5.27%) sectors followed by Mata Sul and its MIMEC sector (1.09%) compared to the Pareto Frontier scenario (ParWS). Mata Sul received more water for its agriculture (2.06%) and service (1.42%) sectors. Comparing the ParWS+Eco scenario with the Reference, the results are similar: the service sector in Agreste Septentrional and Agreste Central experiences an increase of 0.48% and 2.29%, respectively, while Metropolitana DR receives 4.51% more water. Mata Norte was also hit the hardest by losing water for its Agriculture (7.03%) and MIMEC (5.19%). Mata Sul received more water for its agriculture (2.30%) and Service (1.04%) sectors.

The scenario ParWS + Eco shows higher reservation of water when related to ParWS and especially related to the Reference scenario. In the Reference scenario, the average stored water after 2 years of drought was already below 40%. The scenarios ParWS and ParWS+Eco show much higher stored water volumes at the end of the simulation, providing water security for longer drought periods (Figure 8).

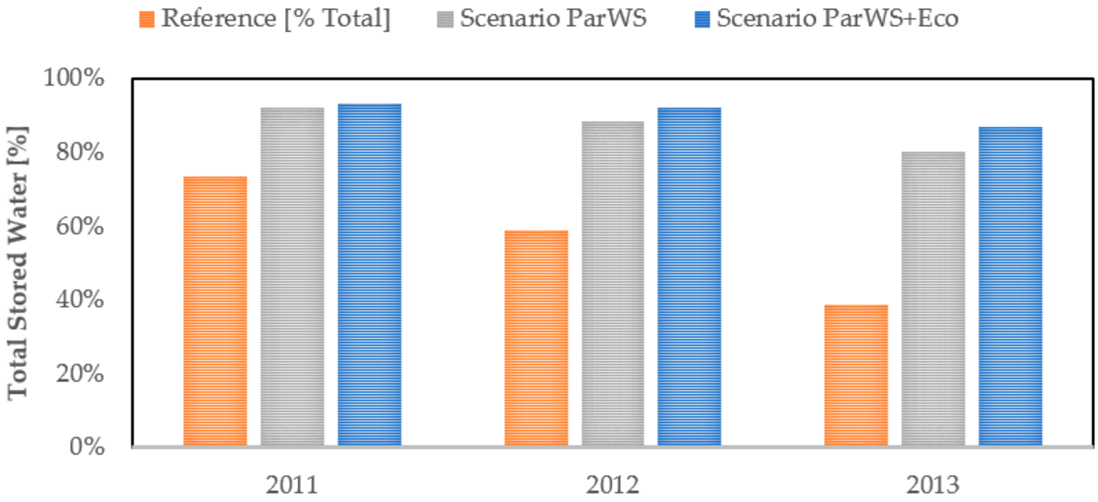

Figure 8. Total stored water for the scenarios: Reference, ParWS, and ParWS+Eco.

The difference between these (ParWS+Eco—ParWS) is that in the Eco scenario, less water is delivered to the users during the shortage, but not the same proportion for all.

The agriculture sector in Mata Norte lost the largest amount (around 121,116 thousand hm^3) and percentage of total allocated water (7.38% of its share) (Figure 9). It is important to point out that practically all the water allocated for irrigated agriculture in the 4 basins (88.6%) when the economic criterion is not used (ParWS and Ref) is distributed to the humid DRs (MN (35.2%), MS (42.7%), and Met (10.7%) under the Reference scenario). Of this total, practically all the water is in the sugarcane cultivation sector (94.3%). When applying the economic criterion (ParWS+Eco in relation to ParWS), all the reduction in the Mata Norte allocation occurs in the sugarcane cultivation sector, even in regions where there is a net increase in agriculture (MS), this sector has its allocations reduced (Table 2). In fact, the sector has both low efficiency and productivity indicators, both as a hotspot (Figure 6) and individually (Table 1), which results in a lowering of priority when it comes to economic allocation.

Still comparing ParWS+Eco and ParWS scenarios, the MIMEC sector lost large amounts of water in Mata Norte and Mata Sul regions, but this loss was experienced more in Mata Norte, as it lost 5.27% of the total share. As seen in Section 3.2.1, the MIMEC sector is concentrated in 2 DRs (approximately 71.38% of the sector water allocated to MS and 16.54% to MN) and has as sub-sectors “manufacturing and refining of sugar” and “alcohol manufacturing (ethanol)” as the most prominent activities. Hotspots of these sectors were identified in the MS, but both sectors had low rankings (Figure 5). In the case of MN, in addition to not having been identified with hotspots for sugar and ethanol activities, the efficiency and productivity indicators of these sectors in the municipalities of this region resulted in low weights.

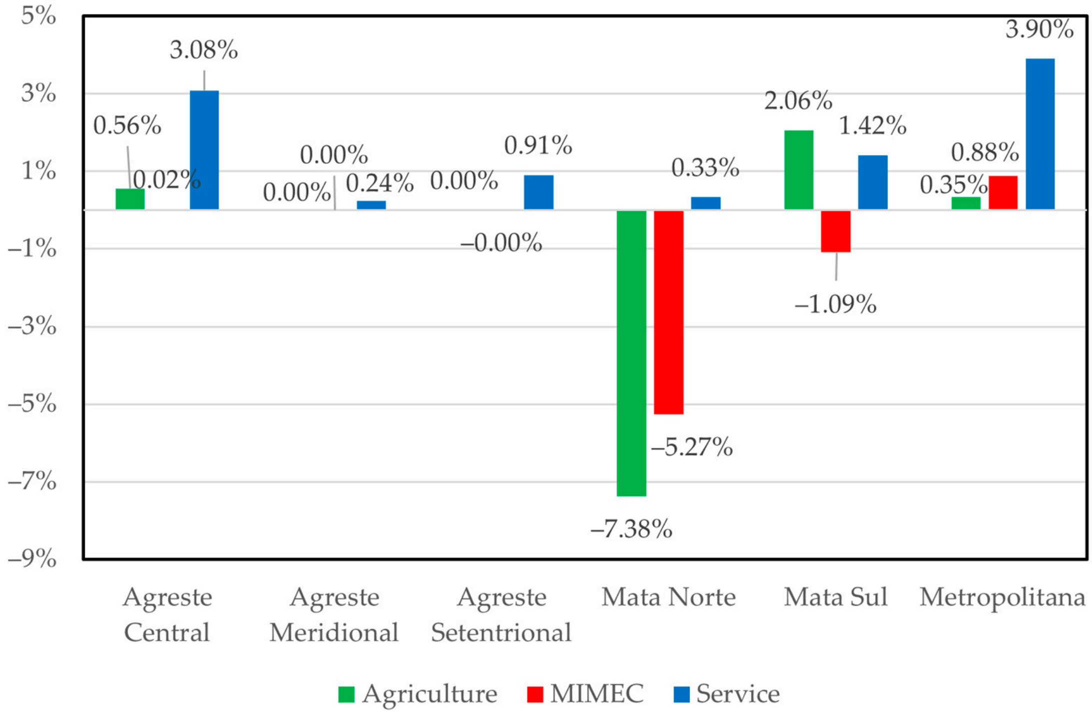

Figure 9. Percentage difference between water allocation (ParWS+Eco—ParWS).

Table 2. Difference between water allocation in the ParWS and ParWS+Eco scenarios for the agriculture sector subsectors in 10^3 Mm^3 (thousand Mm^3). The table cells received conditional formatting in an increasing color scale (red—white—green). The value in red represents the largest drop in water allocation for the agriculture sector and the green one represents the largest increase.

	Development Region Water Allocation Differences in Thousand Mm^3					
Sector	**Agreste Central**	**Agreste Meridional**	**Agreste Setentrional**	**Mata Norte**	**Mata Sul**	**Metropolitana**
Sugar cane cultivation	−59	0	0	−121,100	−1473	−1995
Other fruit growing	622	0	0	−17	69	0
Cultivation of crop plants not previously specified	512	0	2	0	326	0
Livestock	−156	0	2	0	4	0
Fishing and Aquaculture	0	0	0	0	0	0

On the other hand, the services sector gains in percentage terms in all DRs under the ParWS+Eco scenario compared to the Reference and ParWS scenarios, with the Agreste Central and Metropolitana having the highest percentage increases (see Figure 7). The ParWS increases storage levels at the expense of reducing the allocation of the service sector in the Reference scenario; under the economic criterion (ParWS+Eco), however, storage levels improve even more (see Figure 8), but no longer at the expense of reductions in the allocations to the services sector (Figure 9), which is not penalized since it has good indicators (see Table 1). Under ParWS+Eco, the agriculture sector (cane cultivation) and MIMEC (sugar and alcohol production) suffer water allocation reduction.

Looking in more detail at the network of nodes and links in the region, it can be noted that this reallocation takes place through the Carpina reservoir, located between Agreste Central and Mata Norte. When the economic criterion is included, the volume stored in the AC is greater when compared to the other two scenarios (see Figure 10), preventing the downstream release that would serve the MN users (agriculture and MIMEC) and increasing the supply to the AC service users. This attests to the possibility that without using economic criteria and without having an adequate distribution network, there could be a transfer of water stored in drier regions but used to serve humid regions.

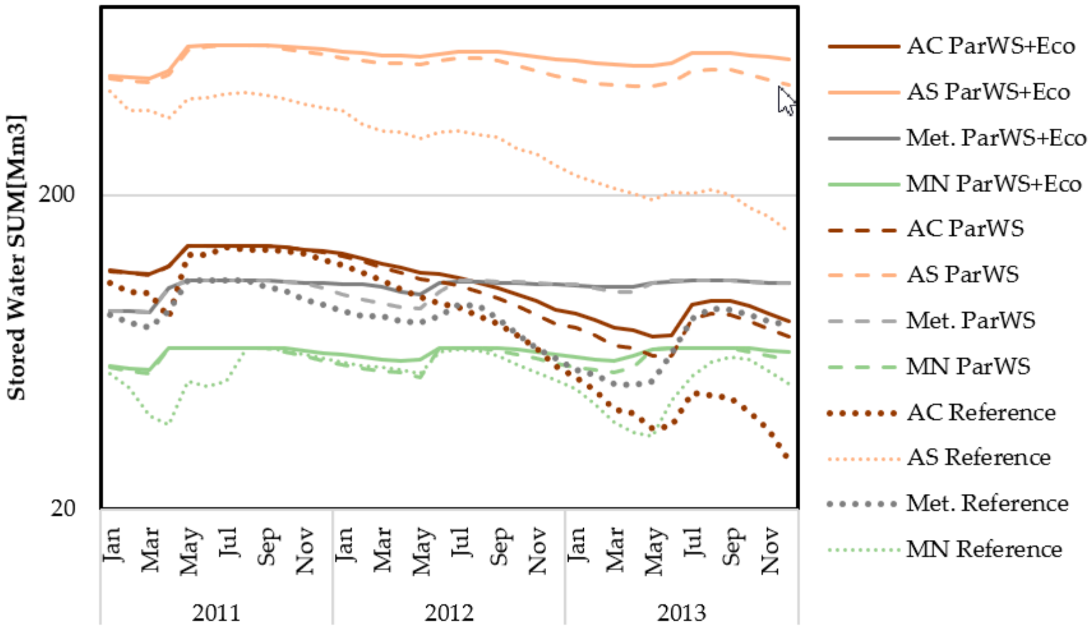

Figure 10. Monthly sum of stored water per development region and scenario in the reference period.

As the net amount of water allocated in each region changes between the two scenarios, reaching the reservoir level under the ParWS and ParWS+Eco scenarios, the percentage of water share changes among the sectors in each region. Mata Norte and Mata Sul are the only regions with noticeable percentage changes in regional water share (Figure 11). Although the volume of water reduced from the agriculture sector in Mata Norte was the greatest, it represented a reduction of only 3.97% in the regional percentage, while MIMEC lost 24.78% and service received 28.74% in the same region, highlighting the tradeoff driven by the economic criteria within the region In Mata Sul, MIMEC lost water (5.74%) to agriculture (3.28%) and service (2.46%) sectors.

Finally, looking at the entire study area and sectors aggregated according to ISIC (see Supplementary Material Table S1), one observes the global effect of economic allocation, which transfers water from agriculture and industry to the services sector (see Table 3). This is justified given the low efficiency and productivity indicators of the main sectors of agriculture and industry in the region, namely: the cultivation of sugarcane and the sugar-alcohol industry.

Table 3. Overall percentage difference in water allocation between sectors for the analyzed scenarios.

	'ParWS'—'Ref'	'ParWS+Eco'—'Ref'	'ParWS+Eco'—'ParWS'
Agriculture	0.80%	−3.62%	−4.42%
MIMEC	1.76%	−3.70%	−5.46%
Services	−2.56%	7.32%	9.87%

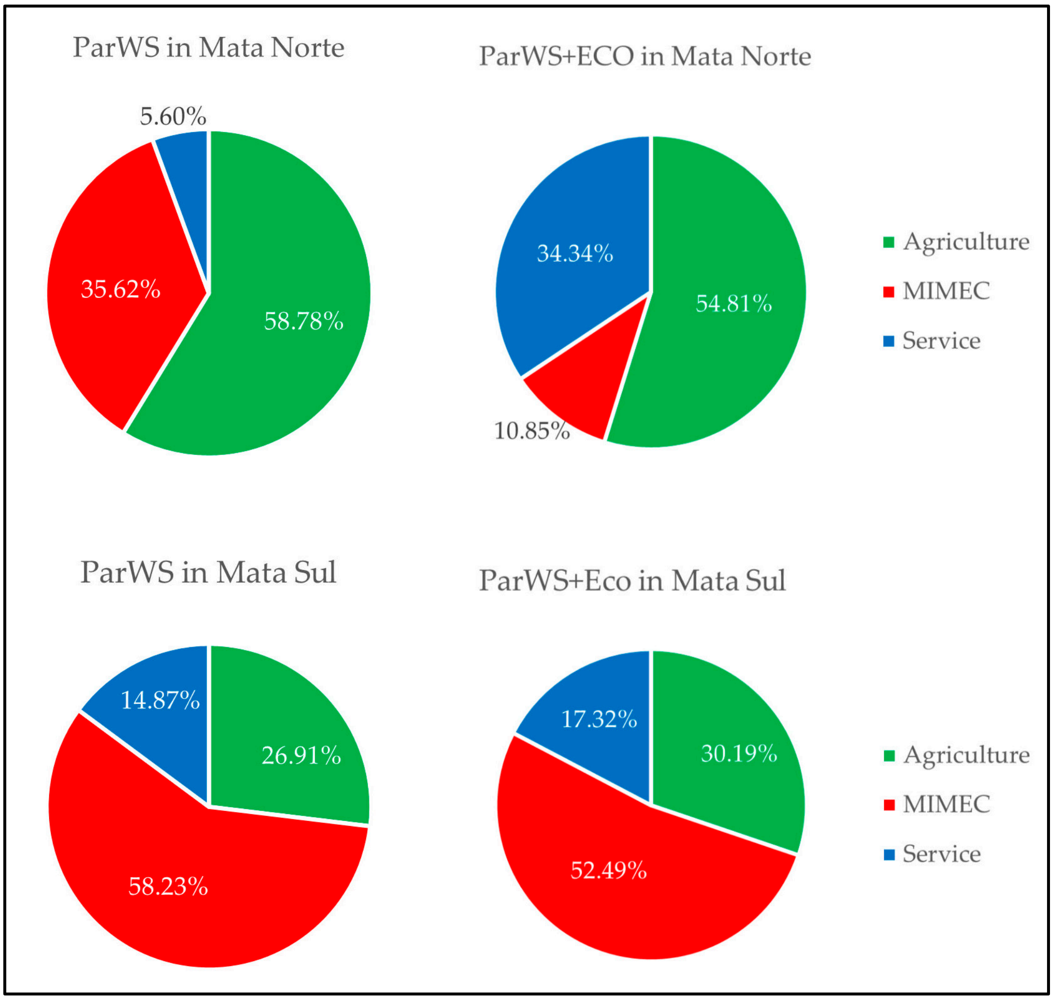

Figure 11. ParWS and ParWS+Eco water allocations for sector in Mata Norte and Mata Sul.

It is important to point out that it has not yet been possible to measure the social and economic impacts of such a transfer, which is expected to be obtained in a continuation of the research with new data from the results of the water transfers to the IOM as an exogenous shock (see star in Figure 2). Another important aspect to emphasize is that these results were based on the existing network of nodes and links in the 2011–2013 water distribution, which was not yet capable of storing or transferring large amounts of water from the humid regions to the drier regions.

4. Discussion

Decision-making on water resources needs to be supported with analytical tools to identify trade-offs between alternatives [23]. The HEAL concept is to analyze water resource management under water scarcity using true hydro-socioeconomic criteria. Water security is an ongoing mission. Understanding economic arrangements related to water supply is crucial to guarantee its best use. Our method, which identifies and prioritizes important economies on the regional level, provides support to the decision-making process of water resource allocation. This innovative approach aims to integrate socioeconomic and hydrological models with the use of hydro-economic indexes, such as employment and water use efficiency, for water resource management and particularly for the identification of optimal policies for water allocation under water scarcity scenarios using objective allocation criteria.

The results showed important trade-offs between user allocation and reservation in the distinct regions and economic sectors. For example, the semiarid Agreste region, which contains important regional economies, needs to prioritize reservoir water storage to maintain activities and employment during drought periods. This is even more necessary as the Agreste region is especially vulnerable because of the higher climate variability. The use of economic weighting favors more efficient water uses with higher employment under the proposed method (ParWS+Eco). Main tradeoffs were observed between the service sector with fewer water demands and the agriculture sector with lower economic values/employment and higher water demands, such as sugarcane cultivation. Water uses with less efficiency and less impact on employment receive major cuts in water allocation during water scarcity situations. Similar conclusions were found by [24], which pointed out the need for reallocating water from lower valued uses to higher valued uses.

Additionally, we observed for the presented scenarios a higher sensitivity to the weighting of the individual user compared to the cluster. This was due to the low number of representative users for the specific sectors and the fact that they suffered no significant cuts under the presented allocation scenarios. Increasing water stress changes this, for example, under scenarios with higher threshold values for reservoir storage. We would suggest a higher aggregation of users and economic sectors, considering different techniques of clustering, for example, by using the relation among sectors described in the IOM [25,26]. An example of this might be by grouping of service sectors with similar water efficiencies and employment.

The Reference and ParWS scenarios showed a highly downstream-oriented water allocation from the semiarid to the more humid and developed Mata region. Several circumstances contributed to this: the gravitational nature of river networks, less conservative reservoir management, higher water demands for agriculture in the humid Mata region, no incentives or indication of relevant economies/employment in the semiarid region and related water demands. Results indicate the need for more and improved water infrastructure and management instruments, supporting/encouraging the allocation of more water from the humid (Mata) region to the drier upstream region (Agreste) during drought periods. The Transboundary Project of the São Francisco River (PISF) also has a mainly downstream-oriented purpose, as water is released in the upper regions of the basins. Certainly, upstream-oriented water infrastructures will increase costs, but the opportunity cost must also be considered for the existing water uses and users under changing climate scenarios. The new possibilities for storing and transferring water between the dry and humid regions of the state through an adequate water infrastructure, that is already being built, can make possible a rational and efficient use of water and enable a sustainable economic development. For this, public allocation policies that consider water use efficiency and productivity indicators for the different economic sectors are essential.

5. Conclusions

IWRM recognizes the interconnection between people, ecosystems, and hydrology [27] linking water resources to human activities and other resources, such as forests and land use. Its objectives mirror the aims of food–energy–water (FEW) nexus studies, such as efficient resource management, synergistic thinking, and fair distribution of resources. Despite involving important economic concepts, IWRM policies are predominantly based on engineering and hydrology concepts. Particularly in countries under development, where the IWRM policies are difficult to implement [28], the importance of efficient water allocation increases and has changed the focus of IWRM to the concept of Integrated Water Resources Allocation and Management (IWRAM) [2]. As the costs and complexity of providing water grow, as well as the economy and competition for water, the benefits of water reallocation accompany this growth significantly [29].

Economics is the study of the optimal or efficient allocation of scarce resources [30] and its implications for the use of resources for society, making it, therefore, perhaps the most appropriate way to solve water allocation problems. However, unlike other common resource allocation problems in economics, water efficient allocation will require nonmarket valuation and government intervention due to its many particularities such as some of the following: supply quantity varies from year to year, economies of scale exist in distribution and storage systems, and the characterization of water as a public good for many of its uses and externalities. Even knowing that economic efficiency is not the only criterion to be considered in water allocation, and that, in general, it is not even the criterion used in allocation decisions, water decision-makers must benefit from those economic evaluation techniques, which have, in recent decades, been developed by economists for measuring the economic values or benefits associated with nonmarket allocation instruments relating to the environment and natural resources [31]. In order to be effective, government intervention should be based on water policies and instruments analyzed with economic evaluation techniques as recommended by Dublin no. 4 Principle [32].

A number of advantages of property rights and market assignments have been shown in the literature with respect to less flexible allocation systems [33].

Water allocation policies can change the way water is managed, and thus, those water productivity indicators in an economy can be improved by reallocating water from highly water-intensive economic sectors to less (low) water-intensive ones. A water-scarce regional economy based on water-intensive sectors compromises its sustainable economic development and will require well-designed policies that must provide incentives to increase water efficiency and productivity.

Our approach, integrating economic indexes and water use indexes is able to measure water efficiency and productivity of the economic uses and enables simulation of allocation strategies based on them. Results can support the design of such allocation policies and improve the sustainable management of water resources. Moreover, our integrated platform, which combines an IOM and an optimization model, has potential to give new insights, as being a different modeling approach. The platform can determine what the different allocation strategies would be in an economy on a regional level. Therefore, as a continuation of this research, the results or changes from the allocation model need to be analyzed again in the IOM model to measure the economic effects of this new economically optimized water allocation. Towards this, the reductions in allocations of the different scenarios would need to be returned to the IOM as an exogenous shock. Furthermore, additional research afford should be directed toward the further analysis of the integration of water quality indicators and external transfers.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/hydrology10030072/s1, Table S1: Sections of ISIC aggregated in three sectors, according to FAO/UN 2018, and applied in this study; Table S2: Municipalities and/or clusters in each sector's hotspot.; Table S3: Maps of municipalities and/or clusters in each sector's hotspot, Table S4: Ranking of all 57 hotspots, Table S5: Value of each indicator and the weight (wd) obtained for all users. SDG6 indicators: Water Use Efficiency (WUE) and Water.

Author Contributions: Conceptualization, M.M.G.A.d.M. and M.P.d.C.; methodology, M.M.G.A.d.M. and G.N.S.d.S.; software, G.N.S.d.S.; validation, C.A.G.d.A.F., L.A.C. and G.N.S.d.S.; formal analysis, M.M.G.A.d.M., C.A.G.d.A.F., L.A.C. and G.N.S.d.S.; investigation, M.M.G.A.d.M., C.A.G.d.A.F., L.A.C. and G.N.S.d.S.; resources, N.B.M.D.; data curation, C.A.G.d.A.F., L.A.C. and G.N.S.d.S.; writing—original draft preparation, M.M.G.A.d.M.; writing—review and editing, M.M.G.A.d.M., C.A.G.d.A.F., L.A.C., N.B.M.D. and G.N.S.d.S.; visualization, G.N.S.d.S., L.A.C. and C.A.G.d.A.F.; supervision, M.M.G.A.d.M.; project administration, M.M.G.A.d.M. and M.P.d.C.; funding acquisition, M.M.G.A.d.M., M.P.d.C. and L.F. All authors have read and agreed to the published version of the manuscript.

Funding: Financial support for this research has been provided by ANA/CAPES (16/2017) and CT-HIDRO/CNPq project (35/2013).

Data Availability Statement: Not applicable.

Acknowledgments: The English text of this paper has been revised by Sidney Pratt, Canadian, MAT (The Johns Hopkins University), RSAdip-TESL (Cambridge University).

Conflicts of Interest: The authors declare no conflict of interest.

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